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TITANIUM DIOXIDE PHOTOCATALYSIS: AN ADVANCED OXIDATION PROCESS TO IMPROVE AIR QUALITY

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Abstract *- Despite recent advances in clean energy technology, air pollution continues to pose a major threat to the environment and human health as a whole. Densely populated cities from Beijing to Los Angeles struggle to mitigate the detrimental effects of smog from car exhaust and industrial factories, and airborne-bacterial accumulation on household surfaces and building facades carry serious potential health risks. However, over the past several decades scientists and engineers have made major strides in the development and implementation of titanium dioxide photocatalysis as a viable solution to the crisis of air pollution. This specialized advanced oxidation process harnesses the energy from ultraviolet radiation to initiate redox reactions on the compound's surface that convert pollutants in the atmosphere into non-hazardous materials that are easily broken down by the environment. This paper will begin by introducing and explaining the concept of advanced oxidation processes and how they treat air pollution. Then it will narrow in scope to discuss titanium dioxide photocatalysis and examine the potential it has in combating the environmental air crisis by explaining the complex chemistry involved in the reaction process. Finally, the paper will focus on the implementation of the specific technology of titanium dioxide nanoparticle coatings and their various environmental and health benefits.*

Key Words - advanced oxidation process, air quality, chemical engineering, nanogel coatings, organic pollutants, photocatalysis, titanium dioxide nanoparticles

THE AIR POLLUTION EPIDEMIC

Although the many industrial advances achieved throughout the 19th and 20th centuries have spurred economic success and social progress worldwide, the byproducts of such processes have often been proven to negatively impact the environment and human health as a whole. Automobiles, manufacturing plants, and the meat industry, for example, are some of the largest contributors to air contamination. The processes they entail release harmful chemicals such as sulfur dioxide (SO_2), nitrogen oxides (NO_x), ground-level ozone (O_3), and volatile organic compounds (VOCs) into the atmosphere, putting the human respiratory and cardiovascular systems at risk while also poisoning wildlife and water sources [1]. As urban areas expand and industrialization soars to new highs, the concentrations of these toxins in the air will only increase unless serious action is taken.

In 2013, the World Health Organization officially declared outdoor air pollution a carcinogen, attributing an annual three million deaths worldwide to long-term exposure [2]. Figure 1 depicts the number of deaths due to air pollution in 2010, as well as the alarming rate at which lives could be lost if action is not taken. The majority of these deaths were due to lung cancer [1].

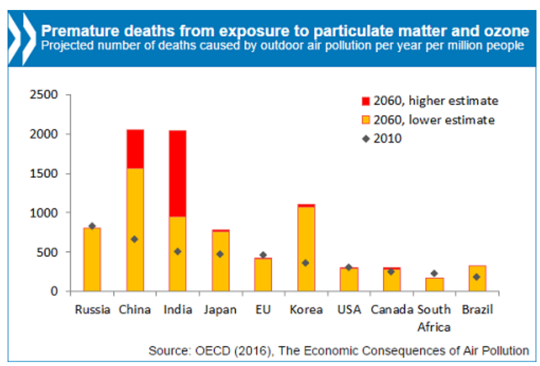

FIGURE 1 [1]
Deaths caused by air pollution in 2010, as well as projected number of air-pollution caused deaths in the year 2060.

While lung cancer is commonly associated with heavy smoking, it can be caused by frequent inhalation of large concentrations of any toxic particulate matter, most of which comes from factories that burn fossil fuels. Many cases of pollution-related cancers are linked to regions with dense manufacturing zones, such as China, India, and Eastern Europe [1]. Additionally, air pollutants have been proven to exacerbate pre-existing asthma since these tiny particles inflame air passages, making it much more difficult to breathe [3].

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The environment also suffers heavily from poor air quality, made evident by the increased cases of acid rain, smog in major urban areas, and the rapid depletion of the ozone layer in recent decades. As shown in Figure 2, the concentration of sulfur dioxide, along with other toxic gases, has dramatically increased since the Industrial Revolution of the 19th century.

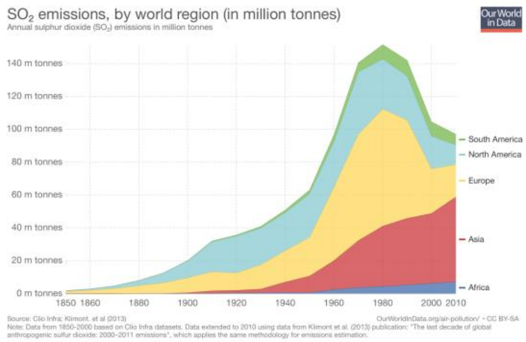

FIGURE 2 [1]
Global SO_2 emissions by continent

This is a direct result of the burning of fossil fuels in manufacturing processes that release large amounts of nitrogen oxides and sulfur dioxide into the atmosphere, which react with water vapor to produce acidic pollutants. According to the Department of Environmental Protection, this toxic precipitation damages trees, acidifies soil and water sources, and erodes man-made structures like buildings and statues [4]. Additionally, smog has become an urgent problem in many urban areas due to significant emissions from automobiles and factories. In addition to impairing eyesight, smog is composed of tiny particles that are hazardous to human and animal health when inhaled [5]. Finally, the stratosphere's ozone layer absorbs harmful ultraviolet radiation, combating the rise in atmospheric temperature. However, air pollutants are destroying this protective layer at an alarming rate, which exposes the surface of the earth to larger amounts of UV radiation [4]. These harmful rays can lead to higher risk of skin cancer and damage delicate crops [4].

In recent years, engineers and scientists have been developing sophisticated chemical processes, known as advanced oxidation processes (AOPs), which have the potential to significantly reduce the concentration of harmful contaminants in the air. Engineers have a responsibility to improve the quality of life of the general population while remaining environmentally conscious and creating sustainable solutions to the world's most pressing issues. As such, the further development and implementation of AOPs should be prioritized within the scientific community. Furthermore, society as a whole should recognize the direct impact of this technology on public health and the environment, and support efforts to make AOPs more widely available for commercial and industrial uses. The success of advanced oxidation processes will pave the way to a greener and healthier future.

REDUCING AIR CONTAMINATION THROUGH ADVANCED OXIDATION PROCESSES

Eliminating air pollution is a colossal undertaking, but new purification methods are currently being developed that make the task more feasible. Advanced oxidation processes utilize strong oxidizing agents such as water or common catalysts such as titanium dioxide to generate free radicals that react with pollutants in the air [6]. This technology is pertinent to the scientific community since it is one of the few methods that can successfully remove toxic organic contaminants from the air by transforming them into substances that can be easily broken down by the environment. In general, there are two main types of AOPs - dark and light. Most companies implement the latter due to its various advantages.

Advantages of Light-Driven AOPs

Light-driven AOPs rely on light sources to trigger their chemical reactions. In addition to destroying pollutants in the air, there are many other favorable aspects of this type of AOP. One of the most advantageous characteristics of this light-based mechanism is its low installation cost due in part to its self-sufficiency. In addition, these AOPs can play a large role in water purification, acting as a precursor to the biological treatment of water with bacteria and other microorganisms [7]. These processes can also be executed on a large or small scale, allowing them to be easily introduced to developing countries that often struggle to access technology which can combat pollution [6]. There are several light sources that can be used to initiate light-driven AOPs, the most common of which is ultraviolet radiation (UV) as it comes from the sun. The photons in UV rays strike a catalyst's surface and excite electrons to generate strong oxidizing agents, which in turn react with harmful organic compounds in the surrounding air such as sulfur dioxide and nitrogen oxides [8]. The most widely used catalyst for this type of process is titanium dioxide (TiO_2), which is the focus of this paper.

TITANIUM DIOXIDE PHOTOCATALYSIS - A SPECIFIC FORM OF ADVANCED OXIDATION PROCESS

The application of titanium dioxide in light-based AOPs is known as titanium dioxide photocatalysis. The term photocatalysis refers to any chemical reaction in which light is used to activate a substance that lowers the activation energy required for the reaction to occur, thereby increasing the rate of reaction. These substances are known as photocatalysts, and are not consumed as the reaction proceeds [9]. TiO_2 is the most commonly used photocatalyst due to a combination of unique characteristics. It is available in high abundance, chemically stable, non-toxic, relatively inexpensive, and possesses a rather strong oxidative ability [10]. The development of TiO_2 photocatalysis was facilitated decades ago through research on the use of TiO_2's semiconductor properties in photoelectrochemistry. The year 1977 witnessed the first use of titanium dioxide to decompose cyanide in water, a discovery that opened the door to further research into the compound's environmental applications [11]. It is now widely known among the scientific community that TiO_2 functions as an excellent photocatalyst in AOPs to breakdown harmful organic and inorganic compounds. The next section will discuss the complex chemistry that takes place when TiO_2 is used in photocatalysis.

Band Theory and the TiO_2 Photocatalytic Process

A rudimentary understanding of the concept of quantum mechanics and band theory is necessary in order to grasp the elaborate chemistry involved in titanium dioxide photocatalysis. Within an atom, electrons occupy different regions of probability density known as orbitals, which have discrete amounts of energy associated with them. When atoms combine to form compounds, their orbitals overlap, thus providing electrons with more available energy levels to occupy. In compounds, the proximity of these energy levels establish a continuous band in which electrons can move [12]. Electron mobility is contingent on the width of these bands and the distances between them, known as band gaps. The band gap is an energy threshold that separates the valence band, which is the highest state in which electrons are normally located, from the conduction band, which is the next empty region that electrons can occupy [12]. The size of the band gap is largely linked to the conductivity of the substance, as shown in Figure 3.

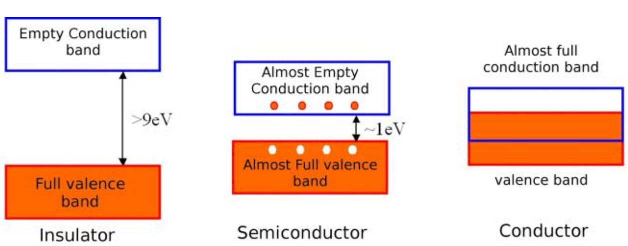

FIGURE 3 [14]
Comparison of band gaps in insulators, semiconductors, and conductors, with band gap energy estimates in electron-volts (eV)

Conductors have a complete overlap of the valence and conduction bands, allowing their electrons to flow freely without any absorption of energy. Insulators, on the other hand, have relatively large band gaps, making it extremely difficult for electrons to obtain enough energy to jump to the conduction band. By comparison, the band gap of a semiconductor such as titanium dioxide is rather narrow, so less energy is required to excite the electrons enough to leap into the conduction band.

The ability of a substance to conduct electricity is reliant not only on the distance between bands, but on how fully the electrons occupy them. Insulators for example have either both their valence and conduction band fully occupied, or empty energy bands. Consequently, there are no electrons able to travel between bands, and the lack of electron motion results in the lack of conductivity [13]. Based on this idea, then, conductors and semiconductors must have vacancies in their energy bands to allow electrons to travel between them [13]. In the next section, it will be clear why vacancies within these energy bands are necessary.

UV-Ray Absorption, Generation of Free Radicals, Redox with Pollutants

As previously mentioned, titanium dioxide photocatalysis is initiated when ultraviolet radiation strikes the semiconductor's surface and excites electrons within the material. Why does TiO_2 respond so keenly to UV photons? The answer lies in band theory. The ultraviolet radiation that is not absorbed by the ozone layer, known as UVA, varies in energy from 3.10 eV to 3.94 eV. Anatase, one of TiO_2's naturally occurring crystal structures, possesses a band gap energy of about 3.20 eV, which lies directly within the range of UV rays that touch Earth's surface. Within femtoseconds, the electrons in anatase can easily cross the band gap when excited by ultraviolet radiation [14]. For this reason, anatase is the most commonly selected form of titanium dioxide in photocatalysis.

The heart of the photocatalytic process lies at the atomic level. When ultraviolet radiation hits the surface of the titanium dioxide photocatalyst, the energy from the light's photons is absorbed by the electrons in the valence band. When this absorbed energy exceeds the band gap threshold, the excited electrons will vacate the valence band by jumping across the gap into the empty conduction band [10]. These electrons leave behind positively charged "holes" in the valence band they once occupied. This process is described in the equation below,

$$TiO_2 + h\nu \rightarrow e_{cb}^- + h\nu_{vb}^+ \qquad [8]$$

in which $h\nu$ represents UV radiation, and e_{cb}^- and $h\nu_{vb}^+$ are electrons that jump to the conduction band and holes in the valence band, respectively [8]. The holes and electrons will either recombine or diffuse to the surface of the semiconductor. Recombination of holes with electrons is not favorable since redox reactions will not occur. However, anatase and rutile, another common form of TiO_2 used in photocatalysis, possess crystal lattice structures that promote charge separation so the holes and electrons will not readily recombine [8]. Once diffused to the semiconductor-air interface, the electrons and positive holes function as reactive species, capable of being “trapped” by adsorbed water and oxygen molecules and undergoing redox reactions to generate the extremely reactive hydroxyl radical (OH•) and superoxide radical (O_2^-•), as depicted in the following formulas:

$$h\nu_{vb}^+ + H_2O_{adsorbed} \rightarrow OH\bullet \qquad [8]$$

$$e_{cb}^- + O_2 \rightarrow O_2^- \bullet \qquad [8]$$

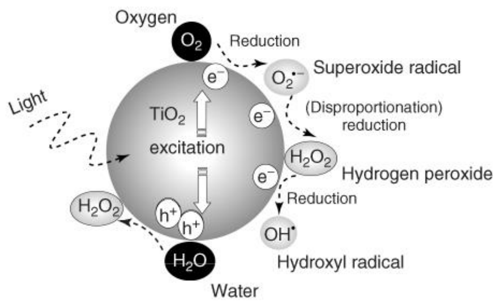

FIGURE 4 [15]
Illustration of electron promotion and hole formation, reduction reactions with water and oxygen to form radicals

Figure 4 serves as an excellent visual representation of what occurs at the atomic level when TiO_2 absorbs UV radiation. The next section will delve into the chemistry behind TiO_2 photocatalysis’ destruction of pollutants in the air.

Reaction of TiO_2 and Common Air Pollutants

The highly reactive free radicals generated during photocatalysis are capable of initiating powerful reactions with harmful organic toxins and microbes found in the surrounding atmosphere. Upon encountering bacteria, the small radicals “attack” the larger microorganism, surrounding and decomposing it into harmless substances such as water and carbon dioxide that can then be released into the environment. When the contaminant in question is a chemical contaminant, the radical and the compound undergo a redox reaction. The hydroxyl radical possesses a very high reduction potential of +2.8 volts (V), indicating its strong tendency to be reduced, or acquire an electron in a redox reaction [16]. This makes sense, since by definition free radicals are extremely unstable species with a single unpaired electron and will readily react to pair this lone electron, thereby forming a much more stable species. In redox reactions with a toxin, the hydroxyl radical oxidizes the pollutant molecule, effectively dismantling it into substances that can be easily broken down by the environment [16]. For example, when a nitrogen oxide, such as NO_2, comes in contact with the UV-irradiated TiO_2 surface applied to concrete, it is transformed into nitric acid (HNO_3). The alkaline nature of the concrete will neutralize the acid, allowing it to be safely washed away [17]. From here, the implementation of titanium dioxide photocatalysis in industry and public welfare must be considered.

TITANIUM DIOXIDE COATINGS: A SELF-CLEANING SOLUTION TO AIR POLLUTION

Titanium dioxide coatings are a revolutionary technology which take advantage of the nature of TiO_2 nanoparticles and their interaction with UV radiation. The nature of this compound lends itself to sustainability, defined by Andrew Beattie from Investopedia as “meeting the needs of the present without compromising the ability of future generations to meet theirs” [18]. The properties of TiO_2 contribute to environmental sustainability in particular. The definition decrees that a resource must be renewable in order to be environmentally sustainable. In this case, TiO_2 is naturally occuring in materials such as rutile, which is a metal ore that can be mass produced. In fact, a company called White Mountain Titanium Corporation is expected to produce 112 million tons of rutile, from which TiO_2 will be synthesized [19]. Additionally, the catalytic nature of the compound means it is not consumed while removing pollutants from the air. Since TiO_2 can be mass produced and is not depleted during a reaction, it can be considered an inexhaustible resource, thus contributing to environmental sustainability.

Titanium dioxide is incorporated into various types of coatings which can be applied in many situations as an effective tool to remove volatile organic compounds (VOCs) and other toxic compounds from the surrounding environment, among other benefits. Any compound containing carbon is considered an organic compound, and substances which evaporate easily are described as volatile. As such, VOCs are organic compounds which eventually are converted to gases and vapor. The burning of fuels such as gasoline, wood, coal, or natural gas is the main contributor to global VOC emissions [20].

As explained in the previous section, once the surface of the TiO_2 comes into contact with UV rays, it is able to react with VOCs in the air and convert them into nontoxic substances such as water and carbon dioxide. This is superior in relation to other pollution control methods which often simply collect contaminants and store them elsewhere, essentially relocating the toxins instead of disposing of them. TiO_2 photocatalysis is favorable in that the VOCs are legitimately eliminated and transformed into harmless substances.

Additionally, since it is considered a catalyst, TiO_2 itself is not physically consumed during the reaction. Rather, it is the holes and excited electrons generated by the process discussed in the previous section which undergo a reaction with the compounds in the air. Therefore, once TiO_2 is initially incorporated into the coatings, the product is considered self-sufficient in that it requires no maintenance. The coatings will continue to extract and convert toxic substances from the air without interference as long as they are exposed to natural light.

Green Millennium: Guiding Us Towards A Cleaner Future

Leading the charge in the war against air pollution with the development of their unique TiO_2 coatings is a company known as Green Millennium. This division of the Japanese photocatalytic research institution Saga-KON Corporation was founded in 2003 and is currently based in California [21]. Green Millennium strives to "develop, market, distribute, and globalize a wide range of high quality nano photocatalytic coating products" [21]. The company has been achieving this goal by perfecting their production of aqueous metal oxide photocatalytic coatings, distinguishing Green Millennium from other companies that manufacture TiO_2 in its conventional, less efficient powdered form [21]. Their coatings possess the properties discussed in the previous section that enable them to purify the surroundings based on the conditions in which they are implemented.

Green Millennium's Manufacturing of Titanium Dioxide Photocatalytic Coatings

TiO_2 is arguably the most valued white pigment in the coatings industry because its ability to scatter and reflect light allows for a brighter, whiter color [22]. Particle size determines how refractive a substance is, since the higher the angle at which light bounces off a surface, the more the light is bent. The larger the particle size, the more light is reflected. For this reason, most companies in the coatings business produce TiO_2 in solid, powder form to allow control of particle size and, consequently, the level of refraction in their coatings [22].

However, in powder form TiO_2 can form white deposits, hindering its reactive properties and rendering it useless in coatings meant to clean the air. For this reason, TiO_2 is manufactured in aqueous form for use in photocatalytic coatings. This state ensures an even distribution of particles throughout the coating and prevents the formation of deposits, which extends the product's life and furthers its self sufficiency. For this application, the aqueous form of TiO_2 is superior to the powder form in various ways. The powder form is milky white, deteriorates over time (as a result of formation of deposits), and has an acidic pH level which means it can only be applied to acid-proof surfaces [22]. On the other hand, the aqueous form is relatively transparent (allowing it to be applied to a wider variety of surfaces such as glass), does not form deposits, and has a neutral pH meaning it can be used on almost all organic or inorganic materials, regardless of their resistance to acidity [22]. The precise manufacturing process of aqueous TiO_2 is patented, but clearly contributes to the remarkable properties of these "intelligent" coatings.

The application process begins by ensuring that the substrate (the surface on which the coating is applied) is hydrophilic, meaning that it possesses the tendency to mix well with water. A sample of the substrate is then collected to test its compatibility with the TiO_2 coatings. The surface of this sample must then be cleaned, treated with a primer, coated with a TiO_2 film, and allowed to dry. Later, Green Millennium performs tests on the sample to ensure that the coating functions properly, such as a dye-fading test and a gas decomposition test [22]. Once the coated sample surface passes these tests, Green Millennium works to treat the entire commissioned building facade with their aqueous photocatalytic films.

General Benefits of Titanium Dioxide Coatings

The most prominent advantage of this new technology is its self-cleaning ability, which leads to other beneficial properties such as sterilization and deodorization. Viruses and bacteria populate all surfaces, thus the impact of these harmful microorganisms such as E coli or Salmonella are far reaching and are often the cause of widespread disease. The coatings, however, can react with these microorganisms as they do with VOCs, helping to eliminate not only pollutants but germs as well, effectively making areas more sterile [23].

Unpleasant odors can come from a variety of sources, formaldehyde being a notable one. It is a chemical which irritates the human body and is produced by countless indoor and outdoor appliances and activities including gas stoves, cigarette smoke, space heaters, and other household products. Fortunately, TiO_2 coatings are able to react with these chemicals as well, diffusing unpleasant smells and decreasing the health risks associated with living amidst them [24].

Yet another impressive quality of Green Millennium's TiO_2 coatings is their self-cleaning ability, which is very helpful in the maintenance of any structure such as a building or monument. The dirt and biological growth such as lichen or algae in itself is not immediately threatening, but grime on the exterior of a building is not visually pleasing, and over time it can cause permanent discoloration and erode the material. Often in cities where smog is an issue, unwanted dark spots will accumulate on most surfaces, especially apparent on lighter colored structures. If a city prioritizes cleanliness, it may expend energy and resources every so often to remove this displeasing discoloration. TiO_2 coatings would eliminate the need for this.

Self-Cleaning Properties of TiO_2

This type of coating has antistatic and hydrophilic properties as well as the ability to break down hydrocarbons and other organic growth [25]. During the initial application of the coating to the surface, the film reaches a hardness equivalent to that of glass and the two become bonded. This thin film is transparent and chemically resistant, and is responsible for preserving the cleanliness of a building. The mechanisms by which this is possible are displayed in Figure 5 below.

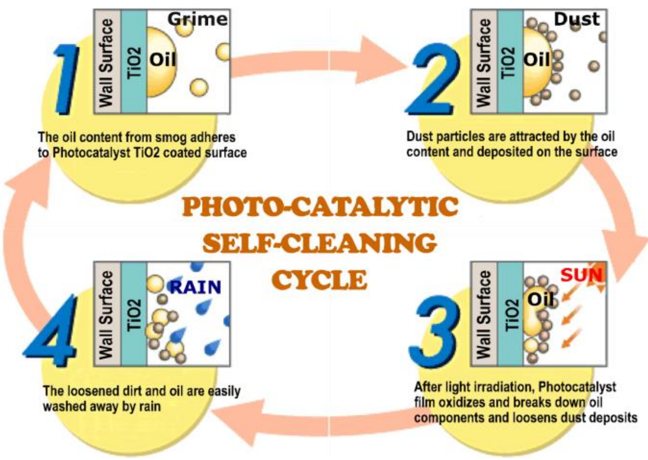

FIGURE 5 [24]
Diagram of the Photocatalytic Self-Cleaning Process

Its antistatic property prevents dust from clinging to the surface and prohibits biological material such as lichen or moss from growing on it. The hydrophilic aspect of the coating means it has the tendency to combine with water, which is a polar substance. Conveniently, smog has a slight oil content. This oil will collect on the surface of the coating but not react with the film of TiO_2 since it is hydrophilic and thus does not favor interactions with nonpolar substances such as oil [26]. Dust and other particles in the air are attracted to this oil, and this layer will harden until UV rays decompose the oil, weakening the adhesion of the oil to the TiO_2 coating. Then, rain can easily remove this layer of soot. Thus, the buildings will be cleaned along with the natural weather cycles. The benefits of TiO_2 coatings are quite extensive.

Maintaining Cleanliness in Cities

Based on an article published in the *New York Times* in 2017, New York City's Sanitation Department spent $58.2 million in 2016. This cost was directed towards trash removal, sidewalk and street cleaners, and building and window washing [27]. In addition, according to New York Curbed, a company dedicated to collecting various data on New York architecture, cleaning skyscraper windows is one of the most arduous and frequently performed tasks throughout the city. To alleviate some of this burden, a team of engineers spent three years and $3 million to build a cleaning rig [27]. Clearly, NYC has expended copious amounts of money on maintenance, as many cities around the world do.

Another such city is Los Angeles, which is notorious for its smog problem. The city's large population equates to an increase in exhaust emissions from automobiles, which greatly pollute the surrounding air. Additionally, the region's heat and humidity trap pollutants at ground level, creating a potent environment for smog to form and accumulate on building facades and windows. This past year, the California Air Resources Board approved a cleanup plan to mitigate the effects of smog in Los Angeles and the surrounding regions; however, this initiative would require about $1 billion a year in funding, which many officials have conceded as an unrealistic exhaustion of resources [28].

The application of TiO_2 coatings to buildings and windows in these urban communities would greatly contribute to their efforts to improve economic sustainability. Economic sustainability is defined by the nonprofit research organization Thwink as "the ability of an economy to support a defined level of economic production indefinitely" [29]. This broad definition encompasses the allocation of funds within a municipality and the subsequent raising of the standard of living. The implementation of self-cleaning TiO_2 films to building facades would undoubtedly decrease the rate at which these surfaces require manual maintenance, thus potentially saving cities millions of dollars annually. This recovered money could then be used to remedy other problems facing the community, such as deteriorating infrastructure and waste management. In the case of Los Angeles, the widespread application of titanium dioxide photocatalytic coatings would greatly reduce atmospheric smog concentrations over time, effectively eliminating the need for huge amounts of funding to combat the issue. The city would then have more resources to apply to more pressing matters. Communities that take advantage of TiO_2 coatings would not only achieve higher levels of economic sustainability, but also greatly improve the quality of life of their residents, who would obviously benefit from cleaner buildings and purified air. Clearly, the benefits of this new technology are far reaching.

REAL WORLD APPLICATIONS: TITANIUM DIOXIDE COATINGS IN ACTION

The properties of Green Millennium's TiO_2 coatings mean they are nonhazardous and appropriate for use in a wide variety of scenarios, not excluding indoor settings. Indoor air quality is not really considered by most people, but in fact quite a few factors decrease air quality in people's homes. In areas such as the basement or bathroom, humidity can lead to the growth of mold, while cleaning supplies such as aerosols release lingering chemicals. Kitchens can contain odors from cooking or trash, and gas from the stove, while garages often contain some level of carbon monoxide as well as other chemicals contained pesticides and other lawn care products. Bedrooms and living rooms can contain dust mites, and bacteria thrives virtually everywhere.

In environments such as casinos, photocatalytic coatings are useful in preventing smoke from staining surfaces as well as reducing the high levels of smoke in the air and removing as much odor as possible. Other locations such as nursing homes and hospitals also benefit from the application of TiO_2 coatings. Many patients' immune systems are very weak, and they are less able to fend off sickness caused by bacteria and viruses. Therefore it is beneficial to cover interior surfaces with TiO_2 coatings to reduce the accumulation of germs, which will in turn reduce the likelihood of patients contracting an illness (or in a hospital, reduce the chance of further infection). Finally, since this technology possesses self-cleaning abilities, it can be installed on a wide variety of outdoor surfaces such as the facades of buildings (including windows), automobiles, aircrafts, road structures such as traffic signs, historical landmarks, and even solar panels to increase the durability of these surfaces [30]. Below is an image in which Green Millennium demonstrates the effectiveness of their coatings on a sample of concrete, which is a common material used in the facades of buildings.

FIGURE 6 [24]
The surface on the left has been treated with TiO_2 film, while the right sample is untreated

The variety of applications and abilities of TiO_2 coatings, especially its self sufficiency, means they will gradually decrease the overall concentration of pollution in the atmosphere, which is fundamental in overcoming the air pollution epidemic.

ETHICAL CONCERNS PRESENTED BY THE USE OF TITANIUM DIOXIDE NANOPARTICLES

Since TiO_2 photocatalysis is a relatively new technological achievement, not many extensive investigations on associated health risks have been carried out. One article published in the U.S. National Library of Medicine has found mild concern associated with the compound, while other research conducted at the Quaid-i-Azam University in Pakistan claims TiO_2 nanoparticles are promising in terms of safety. The majority of research indicates that these nanoparticles are non-toxic, inert, and environmentally friendly [31].

In fact, TiO_2 was approved by the Food and Drug Administration as a food additive 21 years ago, and the European Food Safety Authority has approved daily ingestion of the nanoparticles in food [31]. Since the compound does not react with the human body neurologically or physically in any way, it poses little to no risks to humans. To test this claim, an experiment was conducted on 344 rats and mice using TiO_2 ,with three different concentrations. Some rodents' diets contained no TiO_2 at all; some had a concentration of 25000 mg/kg, and others were fed a concentration of 50000 mg/kg. All three groups remained unaffected over the course of two and a half years, which showed that TiO_2 has no toxicological or carcinogenic effects [31].

Finally, the World Health Organization (WHO) confirmed that the gastrointestinal tract does not readily absorb titanium compounds. Typically, this is the main form of exposure to other hazardous materials which causes issues for the general population, it is clear TiO_2 is not a huge threat to society. Furthermore, the WHO confirmed the compound has little to no impact on land or aquatic species, indicating the very low threat posed to public health and the biological environment by TiO_2 [31].

There is scant data which contradicts these findings. One test conducted in 2009, while ironically acknowledging the poor quality of their own study, still tentatively concluded that TiO_2 may cause respiratory tract cancer in rats [32]. Currently, there is still no substantial evidence that this compound poses a serious threat to human health. For now, it seems TiO_2 nanoparticles are something of an "environmental white knight" [31] thanks to the extremely low risks associated with them. The main ethical concern lies in the *lack* of intensive research done on the effects of this chemical compound. More information about titanium dioxide's potential side effects will be made known as scientists and engineers continue researching and developing its industrial applications.

TITANIUM DIOXIDE PHOTOCATALYSIS IS A STEP TOWARDS A GREENER FUTURE

While this paper has hardly scratched the surface on the nature of titanium dioxide and its many unique properties, it is clear that this compound represents a viable remedy to the air pollution crisis. The complex mechanism of the TiO_2 photocatalytic process is extremely efficient in removing harmful pollutants from the surrounding atmosphere, and it can be implemented into films and coatings that provide numerous benefits. These coatings possess the power to reduce both outdoor and indoor air pollution while remaining entirely self-sufficient, capable of being applied to virtually any surface. TiO_2 photocatalytic films also provide various other benefits, from odor elimination to the removal of grime and bacteria.

Scientists and engineers have recognized titanium dioxide's immense potential to revolutionize the manner in which they approach the problem of air pollution. Researchers are currently investigating techniques that could increase the efficiency of the photocatalytic process, specifically a method to widen the range of energies that can successfully induce photocatalysis [33]. TiO_2 electrons can only be excited by UV rays or radiation of higher energies. Since the sun is the main energy provider for TiO_2 photocatalysis, this process is effectively useless outside at night or on overcast days. However, if photocatalysis in TiO_2 could be induced via visible light, the rate of pollutant removal would dramatically increase. Street lamps and flashlights would thus theoretically be capable of promoting electrons within surfaces coated with TiO_2. Scientists and engineers alike have now assumed this task of enhancing the photocatalytic process to improve air quality [33].

If Green Millennium continues to develop their TiO_2 solution's ability to withstand the elements, perhaps it could be used to coat sidewalks and roads in addition to buildings, statues, and other structures. This would likely be most applicable in locations without drastic weather patterns; nevertheless, the Municipal Sanitization Departments would not have to designate millions of dollars towards power washing sidewalks and roads. In this way, TiO_2 coatings will not only contribute to economic and environmental sustainability, but the social aspect as well. Social sustainability is achieved when people's needs are satisfied, and by allocating more resources towards projects that will benefit the public, the quality of life for many residents would be enhanced. Additionally, the implementation of TiO_2 coatings would greatly improve the health of the general population in heavy manufacturing areas, as the concentrations of toxic particles in the surrounding atmosphere would be significantly reduced.

If the air pollution epidemic is not addressed in a comprehensive manner, the entire planet will be put at an even greater risk than it already is. The environment will suffer and people will continue to die from something that is entirely within the power of humans to stop. Scientists and engineers have the responsibility to prioritize the health and wellbeing of the public above all else, which goes hand in hand with environmental protection. Expansive implementation of titanium dioxide photocatalysis will pave the way to a cleaner and greener tomorrow.

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