

# A Review on Photo catalysis for Air Treatment: From Catalyst Development to Reactor Design

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**ABSTRACT:** *The intriguing possibilities in environmental remediation, chemical synthesis, and energy innovation have prompted significant research into photo catalysis for many decades. However, photo catalysis' functional uses in the area of building materials have been limited. Solving the problems of poor quantum efficiency in solar energy conversion and low levels of contaminants in photo degradation is very challenging. Photocatalytic oxidation of different pollutants, such as volatile organic chemicals or inorganic gases at relatively low concentrations, seems to be more commercially viable for air cleaning. This study begins with an introduction to PCO's contaminant removal process, followed by a thorough examination and discussion of photo catalysts and reactor architecture. This article intends to provide basic and detailed data for paving the way for commercialized gas-phase photo degradation.*

**KEYWORDS:** Air Purification, NO<sub>x</sub>, Photo Reactor, Sox, VOCs.

## 1. INTRODUCTION

The discovery of photo catalysis in 1972 on hydrogen production by water splitting attracted. Now next two energy crises, the 1973 oil shock and the 1979 energy crisis, sparked urgent research interests. A semiconductor of TiO<sub>2</sub> electrode was employed in the research by Fujishima and Honda to promote hydrogen evolution under irradiation. Once semiconductor particles are used, a variety of photo electrochemical cells may be created if the various locations of one particle can act as anodes and cathodes. Photo catalysis, based on the semiconductor mechanism, was then greatly expanded, with a variety of practical implications, including photo oxidation/photo degradation, photocatalytic CO<sub>2</sub> reduction, photocatalytic synthesis, photocatalytic gas-phase oxidation, photocatalytic heavy metal removal, and photo induced self-cleaning. The significant practical and theoretical advances in photo catalysis have allowed a number of outstanding reviews that have established the basics of photo catalysis ranging from activated surfaces, charge generation, surface reactions, and applications. Most photocatalytic processes were previously carried out on wide-band semiconductors like TiO<sub>2</sub> and ZnO[1].

The limits of photo catalysis were thought to be a combination of thermodynamic and kinetic constraints. The absorption of photons and the subsequent charge generation, recombination, and migration are all determined by the type of a photo catalyst material. The first phase, light absorption, also affects solar energy usage efficiency, with ultraviolet light collected by TiO<sub>2</sub> or ZnO accounting for less than 4% of solar spectrum energy. Even if photoinduced charges successfully move to the surface, where photocatalytic processes occur, they may be trapped by undesired reactants or undergo surface recombination. As a result, photocatalysis efficiency has remained very low. Photo degradation of aqueous or gaseous contaminants, as well as the generation of solar fuels through photocatalytic water splitting or CO<sub>2</sub> conversion, have been the hottest issues in photo catalysis for more than four decades. Although research efforts have

followed the margins of the research gap, whether via material explorations or theoretical investigations, the gap between research and practical implementation has yet to be bridged. Commercial photo catalysis must be technically and economically competitive with alternatives such as hydrogen generation via hydrocarbon reforming, CO<sub>2</sub> conversion through dry reforming and chemical synthesis, water treatment by adsorption, biological treatment, or advanced oxidation processes.

Air purification, particularly indoor air purification, seems to be a promising area in which photo catalysis may possibly function as a commercialized technology, integrating with particle matter removal technologies, when compared to the aforementioned industrial processes. For a long time, the harmful health effects of air pollution have been recognized all across the globe. Particulate matter and gaseous pollutants have been recognized as the two major types of air pollutants to be concerned about. Source management and air cleansing have both been shown to be successful methods for reducing air pollution. Increased ventilation may also help with interior air pollution. Source control and physical treatments, including such electrostatic precipitation, wet scrubbing, and filtration, may be used to address particle issues. Because particle pollutants are unlikely to be successfully removed by photocatalysis, we will concentrate on the photocatalytic removal of gaseous pollutants such as NO<sub>x</sub>, SO<sub>x</sub>, ozone, CO, smells, and volatile organic compounds in this study[2]. The criteria also show that VOCs and odorous chemicals are not properly controlled. However, the presence of such chemicals in indoor air, as well as the health problems connected with them, such as sick building syndrome, have been well established. Traditional air cleaning technologies for eliminating these gaseous pollutants are confined to physical techniques such as ventilation, adsorption, or filtration, and there has yet to be established an efficient approach for destroying such toxins[3].

#### *1.1 Air purification using photocatalytic oxidation:*

Due to the energy/oil crisis in the 1970s, photocatalytic water splitting was widely studied, but the photo catalysis was redirected to the destruction of organic contaminants. PCO removal of gaseous pollutants was developed in the same way that comprehensive research on aqueous pollutants were done.

#### *1.2 VOCs degrade when exposed to light:*

Partial oxidation of paraffins using gas-phase heterogeneous photo catalysis. Stone et al. [3, 61] studied the photo adsorption of oxygen and PCO of isopropanol on rutile surfaces in a systematic manner. It was demonstrated that moisture and oxygen may be chemically deposited out on to the TiO<sub>2</sub> surface, resulting in reactive species. Surface OHs - and bulk OHL - would result from dissociative chemisorption of water at Ti<sup>4+</sup>+O<sup>2-</sup> pairs at first. On TiO<sub>2</sub>'s reactive surface, OH might trap a positive hole to create OH, whereas surface adsorbed oxygen, O<sub>2</sub>ads, would generate O<sub>2</sub>ads - with electrons[4].

- *PCO of formaldehyde*

As a representative carbonyl compound, formaldehyde has been identified as one of the most significant indoor air pollutants, and HCHO exposure has been linked to cancer and other serious illnesses. In polluted air, HCHO concentrations are typically in the ppbv to ppmv range, which is still far higher than the WHO limit. Their research focused on the heterogeneous photocatalytic

oxidation of formaldehyde, acetone, 1-butanol, butyraldehyde, and m-xylene, among several other gaseous contaminants. The degradation processes of anatase TiO<sub>2</sub> particles were well characterized by the Langmuir-Hinshelwood rate forms after UV exposure. Due to the competing adsorption of water and organic molecules, humidity has a substantial impact on formaldehyde PCO efficiency. PCO of formaldehyde products and intermediates were studied, and a degradation process was suggested.

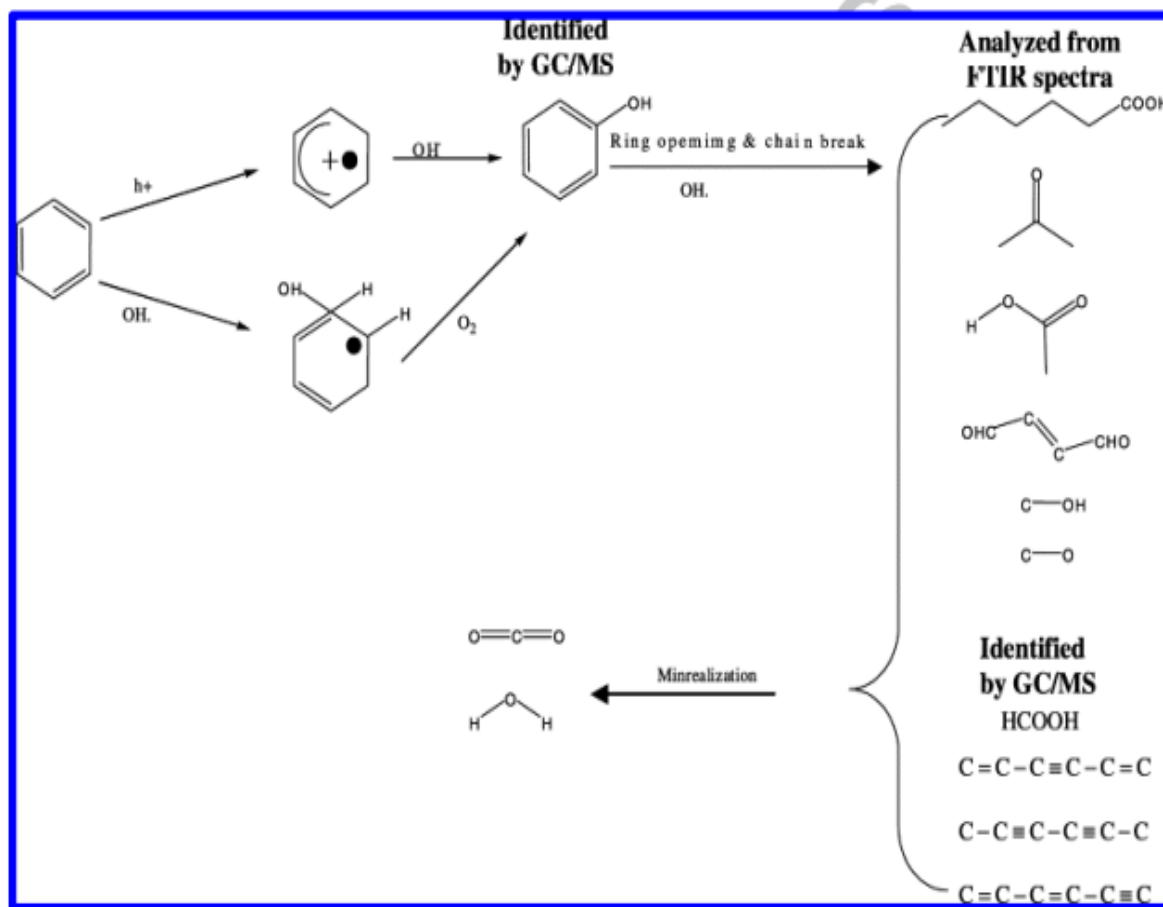
● *PCO of toluene*

Toluene is one of the most studied model pollutants in PCO research since it is commonly found in both indoor and outdoor contaminated air. In the AFNOR standard, XP-B44-013 developed by a French normalization group, toluene was suggested as the model pollutant for PCO assessment. The light source is critical in PCO because it regulates the first step in the generation of electron-hole pairs in photo catalysts. Jeong et al. compared the efficiencies of three different UV lights for PCO removal of toluene, including short-wavelength UV of 254 + 185 nm, 365 nm, and 254 nm, and found that UV of 254 + 185 nm provided the best results. Under UV irradiations of 254 + 185 nm, the impact of key factors on the PCO of toluene low concentration, which was emphasized to be more practical for interior air purification. The effect of catalyst film thickness was also optimized and discussed[5].

The intermediates generated by partial oxidation include benzaldehyde, benzoic acid, and tiny amounts of benzyl alcohol and phenol. The characterization of the species on TiO<sub>2</sub> following PCO of gaseous toluene, and detected a ring structure with a methyl groups. The generated intermediates will ultimately contaminate the surface of the photo catalyst. Prepared Pd/TiO<sub>2</sub> photo catalysts and used them to conduct toluene vapor PCO. They discovered that palladium may improve the resistance of TiO<sub>2</sub> to deactivation owing to the reduced production of benzaldehyde.

● *PCO on benzene*

Benzene is another characteristic aromatic chemical along with toluene, phenol, chlorobenzene, chlorophenols and benzoic acid. It originates from gasoline vapor, flue gas, chemical industries, paints, plastics, rubber, vehicle exhaust, and cigarette smoke, and it becomes a widespread pollutant. The health effects of even modest levels of benzene exposure, such as leukemia, have been documented. To carry out PCO of gaseous benzene, a batch-type photo reactor with a bundle of TiO<sub>2</sub>-coated quartz fiber is used. The main intermediate was supposed to be phenol, however the end products were CO<sub>2</sub>, CO, and H<sub>2</sub>O. Gas chromatography mass spectroscopy and Fourier transform infrared spectroscopy were used to demonstrate the degradation processes, as illustrated in Figure 1.



**Figure 1: Gas-phase PCO of benzene by UV/TiO<sub>2</sub> processes**

### 1.3 Development of a photocatalytic activity for PCO air purification:

Several parameters were considered when developing novel photo catalysts for PCO air purification, in addition to the general requirements for photo catalysts.

#### a. Proper band configurations for production of reactive species

The configuration of reactive radicals is critical for the oxidation processes in purification processes, including VOC degradation and oxidation of various inorganic gases. The photo catalyst materials must have the appropriate valence band position for the creation of  $\bullet\text{OH}$  and the proper conduction band position for the production of. Because the degradation of gaseous VOCs may be compared to the photo degradation of aqueous contaminants, the advancement of material development may be mutually advantageous[6].

#### b. The photo catalysts selectivity

CO<sub>2</sub>, H<sub>2</sub>O, and certain inorganic chemicals would be desired products in the breakdown of organic contaminants in water or VOCs. Coke, which can deposit on the surface of the photo catalysts, is an unwanted product of PCO removal of gaseous VOCs. Selectivity is also essential in PCO elimination of inorganic gas contaminants. The physiochemical properties of a photo catalyst, for

example, can lead to the formation of  $N_2$  or  $NO_3$  - in the removal of  $NO_x$ . When removing  $SO_x$  or  $H_2S$ , it's best to oxidize the compounds to  $SO_3/SO_4^{2-}$ , since sulfur on the surface will obstruct the photo catalysts' active sites.

*c. Stability of the photo catalysts:*

The selectivity may partly affect the stability of the photo catalysts. Long-term stability is critical in practical applications, since frequent filter replacement leads to significant expenses. The robust crystal structure, surface feature, and chemical states are all important in addition to selectivity. Advanced surface modification may be explored for adjusting the selectivity and extending the stability

*d. Visible light response:*

Visible light photo catalysis has gained global interest owing to the importance of efficient solar energy. It would be encouraging if an improved reactor could be developed to use solar energy for outdoor air cleaning. In reality, this is more practical than wastewater treatment, since in photo degradation of aqueous contaminants, the light diffusion by suspended particles is a key design parameter. In the case of indoor air purification, the materials' visible light response guarantees the avoidance of biohazardous UV exposure as well as the use of room illumination.

*e. Immobilization of the photo catalysts:*

Continuous reactors are commonly used in air purification, which differs from the photo degradation of organic pollutants in water. Continuous operation may also be used to real-world scenarios. Therefore, the immobilization of photo catalysts becomes a crucial method in this area. Fabrication of photo catalytic films including composition or surface structure change is one possibility. Additionally, porous supporting materials may be used to improve the photo catalysts' mechanics. Advanced material design should also address the simultaneous functionalization of the photo catalysts throughout the immobilization procedures.

*1.4 Design of gas-phase photocatalytic reactors:*

To breakdown organic contaminants in the air, gas phase photo catalysis employs the synergetic interaction of light, a semiconductor catalyst, and an oxidizing agent. Photo catalysis has a number of advantages over traditional methods like adsorption or filtration. Instead of being simply transported from one location to another, organic pollutants are fully oxidized to  $CO_2$  and  $H_2O$ , and therefore do not constitute a disposal problem. Because the process is run at room temperature, it may be easily integrated into current heating, ventilation, and air conditioning systems. Furthermore, photo catalysis is most effective at low concentrations, which is characteristic of contaminated air in workplaces and buildings[7]. The semiconductor catalyst produces electron-hole pairs upon irradiation, as described in the preceding sections. Adsorbed contaminants may be directly oxidized by the holes, or highly reactive hydroxyl radicals can be generated from adsorbed water, which are strong oxidants[8][9]. The charge transfer loop is subsequently completed by mixing the last electron with  $O_2$ .

*1.5 Photocatalytic reactors are being intensified:*

Photon transfer or mass transfer are generally two major constraints in photocatalytic reactors. One possibility that has previously been addressed in this article is the development of novel photo

catalysts for the absorption of light in the visible range. Other process intensification methods, such as new light source configurations, reactor designs, and the optimum utilization of environmental conditions, have been developed to overcome these constraints, and will be addressed below. Other light sources, such as optical fibers and LEDs, function as tiny lamps and therefore provide greater lighting in tight areas than traditional tube lights. In contrast to surface lighted monoliths, which suffer exponential light decay via the monolith channels, optical fibers may be successfully placed within monolith channels for gas-phase photocatalytic processes to offer enhanced lighting efficiency[10].

## 2. DISCUSSION

A range of specialist groups, such as band gap engineers, material scientists, chemical engineers, and chemists, will be required to contribute. As a result, doping well-known semiconductors like TiO<sub>2</sub> and ZnO with metals, metal oxides, or non-metals like carbon or carbon nitrides, as well as the usage of composites and perovskite-based materials, would be a good start. New ideas in reactor design will be needed to increase the surface area of the photo catalyst in contact with light while maintaining a minimal pressure drop of the flowing gas. Intrinsic kinetic models must be based on feasible degrading processes, depending on the pollutant, in order to be applicable to a variety of circumstances and reactor types. Computational models built from basic transport equations have shown to be effective tools for the experimental validation of different reactor designs. Nonetheless, understanding fluid fluxes is critical for the correct design of photocatalytic reactors, and CFD-based models are critical, especially when the reactor is large.

## 3. CONCLUSION

The enormous amount of effort put into the design of photo catalysts and photocatalytic reactors in recent years demonstrates the conviction that this process will become a future way of treating dirty air. Understanding the mechanisms of pollutant degradation, light absorption, and charge separation has advanced to the point where catalysts may now be tuned to produce even better results. Despite these advancements, photo catalysis will not be commercially feasible unless persistent problems such as poor quantum efficiency, visible light absorption capabilities, selectivity for CO<sub>2</sub> and H<sub>2</sub>O generation, and stability are solved. Furthermore, owing to the difficulties in producing and regulating such low concentrations, further research at the more realistic ppb levels are needed, as well as the impact of gas mixes, which will involve more complex degradation processes and reaction kinetics. Finally, a set of international standards for photocatalytic goods is needed so that simple tests may be used to compare products from various manufacturers. However, each test requires distinct, costly, and complex analytical equipment, and the preconditioning procedure varies per standard. In terms of experimental methods and data analysis, it has been recommended that comparable protocols be established for all contaminants, whereas published standards for other common pollutants such as formaldehyde and methyl mercaptan are needed and awaiting. As a result, several difficulties and issues in the promising area of photo catalysis must be solved before this method can be commercialized.

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