Current Approach to Develop TiO\textsubscript{2} Thin Film as Photocatalysts for Low-Density Plastic Degradation

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\textbf{INTRODUCTION}

Plastic waste is a worldwide issue; still, there is variability from region to region. Fumes released from plastic burning are one of the sources of environmental air pollution. Furthermore, dumping plastic into the ocean leads to releasing toxic chemicals contained in it because of which a large amount of water is polluted. Plastic waste accounts for approximately 10\% of all household waste disposed of in landfills (Barnes et al. 2009, Hopewell et al. 2009). However, 60 to 80 percent of waste is generated along coastlines, with the amount varying depending on the ocean (Barnes 2002, Derraik 2002). According to Central Pollution Control Board (CPCB) estimation, 8 million tons per annum of plastic is used in India, and annually about 5.7 million tons of plastic is transformed into waste (Rathi 2007). The rise in plastic consumption and production has resulted in increases in plastic waste (UNEP 2009). As a result, in 2007, higher than 250 million tons of plastic waste was generated. Plastic materials are not biodegradable and have a low density, making them unsuitable for landfill disposal. Since 1950, this figure has risen at an average annual pace of roughly 9\%, reaching 245 million tonnes in 2008. Plastic bags and other plastics have been a focus since they have been linked to several other problems in India, including animal deaths, contaminated soils, and clogged sewers (Gawande et al. 2012).

Large amounts of plastic will result in an increase in waste and have an adverse impact on the environment. Due to the lack of proper waste management practices, plastic waste will increase, adding to the already existing plastic waste. There is no evidence that specifies a definite time for plastic degradation, however, it could be thousands of years (Kershaw et al. 2011).

Waste disposal in landfills results in the irrevocable loss of major crude materials and energy. The incomplete ignition of Polyethylene (PE), Polystyrene (PS), and Polypropylene (PP) at the time of thermal usage can lead to a high amount of carbon monoxide (CO) and emanations, whereas PVC produces carbon black, dioxins, and aromatics compounds such as pyrene and chrysene. Bromide and different color pigments containing heavy metals such as copper, chromium, selenium, cobalt, cadmium, and lead, among others, can be detected in a noxious discharge. Plastic wastes are always accumulated at open grounds, drifts, railroad tracks, and drains (Islam et al. 2011). Despite many efforts to manage waste, over 91\% of MSW gathered is still landfilled or unloaded on open grounds (Verma et al. 2016).

Every year, around 140 million tonnes of plastic are produced, with the excess amount ending up in the environment as an industrial waste dump (Shimao 2001). Cosmetics, food packaging, synthetic compounds, pharmaceuticals,
and cleansers account for about 30% of all plastics used worldwide. Furthermore, this is still increasing at a rapid rate of 12 percent every year (Sangale et al. 2012). Plastics have supplanted paper and other cellulose-based items for packing as plastics have good elasticity, delicacy, protection from water, and microbial resistance. Usually applied plastics have mostly been used in polyethylene (Low Density, medium density, high density, and linear low density), polystyrene (PS), polyvinyl chloride (PVC), and polypropylene (PP) (Khanam & AlMaadeed 2015). Because of its hydrophobic backbone chain, low-density polyethylene is classified as a thermoplastic (Pramila & Ramesh 2015). It is considered non-degradable in nature (Misra et al. 2015). As a result, several countries have been forced to devise measures to counteract the threat.

The environmental impact of main and secondary sources of microplastics must be addressed immediately (Arthur et al. 2009). More research is needed to determine how many degrees of exposure are caused by plastic waste, as well as the components of plastic that may impact humans and animals. Those at the high degree of the food chain would be exposed to synthetic substances in larger quantities.

**TiO$_2$ as a Photocatalysts**

Since ancient times, TiO$_2$ powders have been widely used in paints to get white shades (Hashimoto et al. 2005). Later, its photocatalytic activity was explored and considered the most effective photocatalyst (Fujishima & Honda 1972). TiO$_2$ is known for its different properties, including strong photoactivity, high stability, low cost, and low toxicity (Pant et al. 2014a, Pant et al. 2020). Over the last few years, TiO$_2$-based nanomaterial has received a lot of attention in academia and has been used in a variety of applications, including the removal of natural toxins, sensors, photovoltaics, antimicrobials, and energy conservation (Bai & Zhou 2014, Hsu et al. 2019, Nakata & Fujishima 2012, Pant et al. 2014a, 2019b, 2020, 2016).

TiO$_2$ nanostructures with a bandgap of 3.0–3.2 eV can be activated in the presence of UV light irradiation. Because of this, the use of TiO$_2$ is limited because only 5% of the sunlight falls inside the UV spectrum (Daghri et al. 2013, Pant et al. 2014b, 2019a). TiO$_2$ is found in three types of crystal structures i.e. anatase, rutile, and brookite (Allen et al. 2018). Although brookite is known as the most unstable structure and is not favored for photocatalytic activity, rutile and anatase type crystal forms are examined for photocatalysis (Di Paola et al. 2013, Zhang et al. 2008). The bandgaps of mass anatase and rutile are 3.2 and 3.0 eV respectively, which relate to the absorbance at 388 nm and 414 nm, individually (Dette et al. 2014). In comparison to rutile, the anatase phase crystal structure is favored as the most photo catalytically active due to its ability to adsorb hydroxyl groups and water (Wang et al. 2018). Research has indicated that the synergistic impact among anatase and rutile is useful in upgrading the photocatalytic activity of the TiO$_2$ nano-structures (Zhang et al. 2008).

When a photon (with energy equal to or greater than the bandgap of TiO$_2$) stimulated the TiO$_2$ thin film or nanoparticles, the electrons moved from the valance bandwidth to the conduction bandwidth and generated electron-hole pairs. The created charge particles travel to the surface area and quickly react with the adsorbed organic compounds, resulting in the organic pollutant and solid waste being degraded. Fig. 1 depicts the technique for highly excited oxidant production and breakdown of organic waste.

**Correlation of Thin-film Structure and Photocatalytic Activity**

Titania (TiO$_2$) has been documented as an efficient photocatalyst along with high chemical stability and potent photocatalytic activity. As the outcome of various research, it was found that Titania has better photocatalytic activity than Zirconium oxide (ZrO$_2$), Tungsten trioxide (WO$_3$), Tin (IV) oxide (SnO$_2$), and Cadmium sulfide CdS. For instance, for the decomposition of phenol organic compound, TiO$_2$ was exhibited higher photocatalytic activity compared to CdS (Thiruvenkatachari et al. 2008). Titania is present in three different types of crystal structure; rutile, brookite, and anatase. Titania is primarily used in the anatase-type crystal structure as the photocatalyst since it has greater bandgap energy than rutile. Because of this, the anatase crystal structure can reduce electron-hole recombination, resulting in a higher degree of surface hydroxylation and the ability to create more hydroxyl radicals as the surface is illuminated. Certainly, this can lead to the efficiency of photocatalytic activity. On the other side, the crystal structure with a rutile type can absorb the beams that are somewhat nearer to the visible light range. It is accepted that the rutile type is more desirable as a photocatalyst for photocatalysis applications. Nonetheless, the rutile type energy structure is unable to provide the preferred photocatalytic execution since its conduction band is close to the redox potential of hydrogen, resulting in its reduced ability.

The oxygen ions present on the surface of the anatase crystal structure are displayed in a triangle shape, allowing better absorption of organic substances such as polyethylene (Thiruvenkatachari et al. 2008). Furthermore, the location of Ti ions provides a more favorable environment for reaction, as does the absorbed organic compound, which is not accessible in the rutile crystal structure (Thiruvenkatachari et
This remarkable property of anatase would result in strong photocatalytic activity. Nonetheless, a few studies revealed that pure anatase titania would not result in significantly improved photocatalytic activity (Thiruvenkatachari et al. 2008). The presence of a mesoporosity type structure and more extensive pore dissemination in a small percentage of the rutile phase crystal structure could explain the increased photocatalytic action. One of the instants is the commercially accessible Degussa P25 TiO$_2$, which consists of 70% anatase and 30% rutile type crystal structure.

The three-sided layout of oxygen particles on the uncovered precious stone surface of anatase allows for strong organic retention (Thiruvenkatachari et al. 2008). Furthermore, the presence of titanium particles provides a positive response state with assimilated organics that are inaccessible to the rutile structure (Thiruvenkatachari et al. 2008). This special character of anatase would prompt high photocatalytic movement. In any case, a few specialists expressed that unadulterated anatase TiO$_2$ would not lead to much better photocatalytic execution (Thiruvenkatachari et al. 2008). The inclusion of a few percent of the rutile stage results in a mesoporosity structure and more widespread pore dissemination, which could explain the increased photocatalytic activity. One of the models is the financially accessible Degussa P25 TiO$_2$, which contains 70% anatase and 30% rutile.

The surface area of photocatalytic agents is also a key factor that influences photocatalytic activity. A small size particle has a larger surface area and thus increases the availability of active sites per square meter, which boosts pollutant absorption on the photocatalytic agent’s surface. Photocatalytic activity is boosted as a result of this mechanism (Thiruvenkatachari et al. 2008).

Several investigations support that TiO$_2$ is a better photocatalytic agent for the degradation of organic compounds like polymer. Moreover, after degradation, no harmful by-products are released and this method has been confirmed as potent in eradicating trace concentrations of organic substance present in the liquid or gaseous phase. For instance; organic acid (Fallet et al. 2006, Sheng et al. 1999), alcohol (Choi et al. 2004, Xianyu et al. 2001), organic dyes (Bouras & Lianos 2005, Funakoshi & Nonami 2007, Ge et al. 2006, Gu et al. 2007, Jung & Imaishi 2001, Stoyanov et al. 2006, Yu et al. 2002b, Yuan et al. 2006, Zhou et al. 2006b), oxide gaseous (Takeuchi et al. 2000, Yu et al. 2006a, 2006b, Yusuf et al. 2002), and aldehyde gas (Chiba et al. 2005, Noguchi et al. 1998, Sopyan 2007, Sopyan et al. 1996, Watanabe et al. 2000) have been decomposed by TiO$_2$ photocatalytic activity. Various searches for biodegradation of organic...
substances such as various plastics using microflora such as bacteria, fungi, and algae have also been documented (Ditta et al. 2008, Sunada et al. 1998, Sunada et al. 2003). To date, only fine powders type photocatalysts are applied for decomposing pollutants as it has more oxidation ability to make photo-generated holes on the outer surface photocatalysts. Nevertheless, the application of fine powder photocatalysts may cause some serious problems such as [a] Complications to separate suspension and the photocatalyst (Begum & Ahmed 2008, Cho et al. 2007, Ge & Xu 2007, Zhou et al. 2006a), [b] High amount of fine powder of photocatalysts may be aggregated with suspended particles (Cho et al. 2007), and [c] Photocatalyst powder can be easily separated from weak adhesion supports if it is covered with particular support (Cho et al. 2007). As a result, advanced approaches such as a thin coated layer on solid wafer material, which makes it a more potent photocatalyst, should be used for critical environmental applications. Numerous materials like polymer, cement, clay, silica and mild steel have been applied as the adherence of TiO$_2$ photocatalytic agents. In the current review, TiO$_2$ film as a photocatalyst and various methods for the improvement of photocatalytic characteristics, TiO$_2$ deposition methods, and its environmental application for degradation of polyethylene will be also discussed.

**Photocatalyst Thin Films**

Nanocrystalline semiconductor thin films found a network in which electronic conduction can happen (Beydoun et al. 1999). A photocatalyst-coated thin film has unique efficiency properties that make it ideal for environmental purification. It is evidenced that titania thin films are extensively applied in various fields like adsorbent catalysts, as sensors (humidity and gas) functional materials, and mainly pollutant removal from wastewater and air (Machida et al. 1999, Mei et al. 2006). A photocatalyst-coated thin film can prevent inhaling particle problems caused by nano-photocatalyst powder, which can be hazardous to human health (Yu et al. 2006a). Furthermore, it is more dependable than the immobilization method, and as a result, photocatalyst-coated thin films may be applied to a number of substrates, such as thin film-coated stainless steel for a building, which has greater chemical corrosion resistance and mechanical strength. Besides this, the building material could be converted into an air-purifying and self-cleaning substance after being coated with a thin film of photocatalyst (Yu et al. 2006a). The penetration of UV or visible light is a key drawback for the photocatalysis process using slurry or powder of nanoparticles. However, these problems can be overcome by photocatalyst-coating on a solid substrate. Contrasting the nanoparticle, the photocatalyst-coated thin film has the ability to avoid light scattering and improve the light transmittance and ultimately increase the efficiency of photoreaction (Ge et al. 2006, Kitano et al. 2007, Otsuka et al. 2008, Sheng et al. 1999, Yu et al. 2002a, 2002b). Furthermore, the advantage of the photocatalyst-coated thin film is connected with an external layer only.

**Deposition Method for the Development of Photocatalyst Thin Film**

Various techniques have been applied for coating the photocatalyst thin film on different substrates such as reactive magnetron sputtering (Choi et al. 2004, Sheng et al. 1999), RF reactive ion plating (Chiba et al. 2005), solgel (Hu et al. 2008), liquid phase deposition (LPD) (Gu et al. 2007, Yu et al. 2006b, Zhou 2006b), vapor phase deposition (Chemical vapor deposition and metal-organic Chemical vapor deposition (Jung & Imaishi 2001), physical vapor deposition (PVD) (Aziz & Sopyan 2009), reactive evaporation (Kitano et al. 2007), atomic layer deposition (ALD) (Clouser et al. 2008), ionized cluster beam (ICB) (Zhou et al. 2006a), electrophotoreactive deposition (Chen et al. 2002), and pulsed laser deposition (PLD) (Kitano et al. 2007). Each technique has its specific pros and cons. For example, the solgel method required high-temperature calculations after treatment to achieve the required stabilities and mechanical strengths of thin coated films. (Zhou et al. 2006a). It could occur as a result of damage to porous substrates. The properties of TiO$_2$ thin films are largely dependent on the deposition process as well as the deposition parameter, according to several research findings (Hasan et al. 2008). All the above methods have been modified by researchers to obtain and develop nano-sized thin film along with required specific physical characteristics such as size, porosity, shape, crystalline structure, and surface area as per their application.

**Magnetron Sputtering Method**

Some deposition methods have limitations for developing photocatalytic active thin films, such as spray coating, which requires a high temperature to decompose metallorganics during the heating process and is limited to non-refractory substrates (Fig. 2). Sheng et al. (1999) made an effort to develop photocatalytically active Pt-titania thin films along with the anatase crystalline structure at 200°C temperature on a flexible substrate i.e. polyamide to broaden the application of film as a photocatalyst. Fleettaneously, they used the tripole magnetron sputtering system to develop thin films by applying two different methods of deposition. In the first method, interchangeably, sputtering co-axially placed titanium and platinum targets, and for platinum, the deposition time was 2 s, while for titanium it varied from 20 s to 140 s throughout each cycle to prepared different compositions. In the second method, the Pt-titania film was developed with
pure titania film depositing first on a polyamide substrate, afterward coating a thin layer of platinum on the surface then again coated with titania thin film. They revealed that coating using the second method is to provide bonding strength between film and polyamide along with anatase crystalline structure at 200°C deposition temperature. Tomaszewski et al. (2007) used DC magnetron sputtering on ceramic targets to create transparent nanostructured TiO\textsubscript{2} thin films. Mei et al. (2012) used DC reactive magnetron sputtering to create transparent titania thin films on silica substrates at varied deposition temperatures (300-600°C). They discovered that at 500°C, TiO\textsubscript{2} thin films had the maximum photocatalytic activity, owing to the crystalline structure of TiO\textsubscript{2} thin films (Mei et al. 2012). Kavaliunas et al. (2020) studied the effect of dopants Mg, Cu, and Ni on photocatalytic activity of amorphous titania thin film which was developed by reactive magnetron sputtering. The results showed that dopant concentrations in titania films between 0.1 and 0.9 percent gave the best photocatalytic activity. SantAna et al. (2020) investigated of optical transmittance of photocatalytic active titania films which were deposited using radiofrequency magnetron sputtering (SantAna et al. 2020). They revealed the optimum deposition parameter such as 0.2 electric currents (A), 437 voltage (V), 87 RF power (W), 3600 deposition time (s), 9.2 × 10\textsuperscript{-3} background pressure (mbar). Moreover, the experimental results show that the TiO\textsubscript{2} films deposited on glass were associated with the anatase phase with a [0 0 4] preferred orientation. Ultraviolet near-infrared spectroscopy revealed the high transmittance of the films in visible light and high absorption in the ultra-violet region under most deposition conditions.

CONCLUSION

This review emphasized the necessity of the elimination of plastic waste contaminants from landfills. Various types of plastic waste pollutants have been listed and the constraint of initial titania photocatalysis on plastic degradation was discussed. Some deposition parameters which have significant impacts on the titania-based photocatalytic degradation, and depositing parameters like dopant, particle size, catalyst concentration, temperature, crystalline structure, and selection substrate that aids in the use of titania as a photocatalyst for further commercialization were reviewed. Hence, photocatalytic process design and technical deposition method optimization are critical to investigate using a key emphasis on low-density plastic deterioration.

REFERENCES

Allen, N.S., Mahdjoub, N., Vishnyakov V., Kelly, P.J. and Kriek, R.J. 2018. The effect of crystalline phase (anatase, brookite, and rutile) and size on the photocatalytic activity of calcined polymorphic titanium dioxide (TiO\textsubscript{2}). Polym. Degrad. Stab., 150: 31-36.

Arthur, C., Baker, J.E. and Bamford, H.A. 2009. Proceedings of the International Research Workshop on the Occurrence, Effects, and Fate of Microplastic Marine Debris, September 9-11, 2008, University of Washington Tacoma, Tacoma, WA, USA.

Aziz, R.A. and Sopyan, I. 2009. Recent progress on the development of TiO\textsubscript{2} thin film photocatalysts for pollutant removal. Recent Pat. Mater. Sci., 2(2): 88-111.
Bai, J. and Zhou, B. 2014. Titanium dioxide nanomaterials for sensor applications. Chem. Rev., 114(19): 10131-10176.

Barnes, D.K. 2002. Invasions by marine life on plastic debris. Nature, 416(6883): 808-809.

Barnes, D.K, Galgani F, Thompson R.C. and Barlaz M. 2009. Accumulation and fragmentation of plastic debris in global environments. Philos. Trans. R. Soc. Lond., B, Biol. Sci., 364(1526): 1985-1998.

Begum, N.S. and Ahmed, H.F. 2008. Synthesis of nanocrystalline TiO$_2$ thin films by liquid phase deposition technique and its application for photocatalytic degradation studies. Bull. Mater. Sci., 31(1): 43-48.

Beydoun, D., Amal, R., Low, G. and McEvoy, S. 1999. Role of nanoparticles in photocatalysis. J. Nanopart. Res., 1(4): 439-458.

Bouras, P. and Lianos, P. 2005. Photodegradation of dyes in aqueous solutions catalyzed by highly efficient nanocrystalline titania films. J. Appl. Electrochem., 35(7-8): 831-836.

Chan, A.H., Porter, J.F., Barford, J.P. and Chan, C.K. 2002. Effect of thermal treatment on the photocatalytic activity of TiO$_2$ coatings for photocatalytic oxidation of benzoic acid. J. Mater. Res., 17(7): 1758-1765.

Chiba, Y., Kokai, H. and Kashiwagi, K. 2005. Effect of the plasma surface treatment on an anatase TiO$_2$ film. J. Mater. Sci.: Mater., 16(10): 645-648.

Cho, D.L., Min, H., Kim, J.H., Cha, G.S., Kim G.S., Kim, B.H. and Ohk, S.H. 2007. Photocatalytic characteristics of TiO$_2$ thin films deposited by PECVD. J. Indian Eng. Chem., 13(3): 434-437.

Choi, Y.L., Kim, S.H., Song, Y.S. and Lee, D.Y. 2004. Photodecomposition and bactericidal effects of TiO$_2$ thin films prepared by a magnetron sputtering. J. Mater. Res., 39(18): 5695-5699.

Clouser, S., Samia, A.C., Navok, E., Alred, J. and Burda C. 2008. Visible-light photodegradation of higher molecular weight organics on N-doped TiO$_2$ nanostructured thin films. Top Catal., 47(1-2): 42-48.

Daghiri, R., Drougi, P. and Robert, D. 2013. Modified TiO$_2$ for environmental photocatalytic applications: A review. Ind. Eng. Chem. Res., 52(10): 3581-3599.

Derraik, J.G. 2002. The pollution of the marine environment by plastic debris: A review. Mar. Pollut. Bull., 44(9): 842-842.

Dette, C., Pérez-Osorio, M.A., Kley, C.S., Punke, P., Patrick, C.E., Jacobson, P., Giustino, F., Jung, S.J. and Kern, K. 2014. TiO$_2$ anatase with a bandgap in the visible region. Nano Lett., 14(11): 6533-6538.

Di Paola, A., Bellardita, M. and Palmisano, L. 2013. Brookite, the least known TiO$_2$ photocatalyst. Catalysts, 3(1): 36-73.

Ditta, I.B., Steele, A., Liptrot, C., Tobin, J., Tyler, H., Yates, H.M., Sheel, D.W. and Foster, H.A. 2008. Photocatalytic antimicrobial activity of thin surface films of TiO$_2$, CuO, and TiO$_2$/CuO dual layers on Escherichia coli and bacteriophage T4. Appl. Microbiol. Biotechnol., 79(1): 127.

Fallet, M., Permpoon, S., Deschanvres, J.L. and Langlet, M. 2006. Influence of annealing temperature on structure and photocatalytic activity of TiO$_2$ films by chemical vapor deposition. J. Mater. Res., 34(11): 2569-2574.

Fang, T.H., Hsiao, Y.J. and Wu, P.C. 2019. Response and characteristics of TiO$_2$/perovskite heterojunctions for CO gas sensors. J. Alloys Compd., 794: 576-584.

Funakoshi, K. and Nonami, T. 2007. Photocatalytic treatments on dental surfaces of teeth. J. Photochem. Photobiol. C., 13(3): 169-189.

Gawande, A., Zamare, G., Renge, V. and Bharsakale, G. 2012. An overview on waste plastic utilization in asphalting of roads. J. Eng. Technol., 43(1): 1-7.

Ge, L. and Xu, M. 2007. Fabrication and characterization of TiO$_2$ photocatalytic thin film prepared from peroxo titanio acid sol. J. Solgel Sci. Technol., 43(1): 1-7.

Ge, L., Xu, M. and Fang, H. 2006. Preparation and characterization of silver and indium vanadate co-doped TiO$_2$ thin films as visible-light-activated photocatalyst. J. Solgel Sci. Technol., 40(1): 65-73.

Gu, D.E., Yang, B.C. and Hu, Y.D. 2007. A novel method for preparing V-doped titanium dioxide thin-film photocatalysts with high photocatalytic activity under visible light irradiation. Catal. Lett., 118(3-4): 254-259.
adsorption and simultaneous decomposition of organic dyes. J. Colloid Interface Sci., 434: 159-166.

Pant, B., Pant, HR., Park, M., Liu, Y., Choi, J.W., Barakat, N.A. and Kim, H.Y. 2014b. Electrosynopsis CsS–TiO₂ doped carbon nanofibers for visible-light-induced photocatalytic hydrolysis of ammonia borane. Catal. Commun., 50: 63-68.

Pant, B., Park, M. and Park, S.J. 2019a. MoS₂/CdS/TiO₂ ternary composite incorporated into carbon nanofibers for the removal of organic pollutants from water. Inorg. Chem. Commun., 102: 113-119.

Pant, B., Park, M. and Park, S.J. 2019b. TiO₂ NPs assembled into a carbon nanofiber composite electrode by a one-step electropinning process for supercapacitor applications. Polymers, 11(5): 899.

Pant, B., Park, M. and Park, S.J. 2020. Hydrothermal synthesis of Ag2CO3–TiO₂ loaded reduced graphene oxide nanocomposites with highly efficient photocatalytic activity. Chem. Eng. Commun., 207(5):688-695.

Pant, B., Saud, P.S., Park, M., Park, S.J. and Kim, H.Y. 2016. General one-pot strategy to prepare Ag–TiO₂ decorated reduced graphene oxide nanocomposites for chemical and biological disinfection. J. Alloys Compd., 671: 51-59.

Park, H. and Choi, W. 2004. Effects of TiO₂ surface fluorination on photocatalytic reactions and photoelectrochemical behaviors. J. Phys. Chem. B 108(13): 4086-4093.

Pramila, R. and Ramesh, K.V. 2015. Potential biodegradation of low-density polyethylene (LDPE) by Acinetobacter baumannii. J. Bacteriol. Res., 7(3): 24-28.

Rathi, S. 2007. The need for separation of plastics from municipal solid waste. Chem. Week. Bombay, 53(18): 177.

Sangale, M., Shahnavaz, M. and Ade, A. 2012. A review on biodegradation of polythene: the microbial approach. J. Bioremed. Biodegr., 3: 1-9.

SantAna, P.L., Bortoleto, J.R.R., da Cruz, N.C., Rangel, E.C., Durrant, S.F., Azevedo. S, Simões C.I.S. and Teixeira, V. 2020. Study of optical characterization, and photocatalytic activity of in situ Fe-doped TiO₂ thin films. J. Solgel Sci. Technol., 24(2): 95-103.

Shima, M. 2001. Biodegradation of plastics. Curr. Opin. Biotechnol., 12(3): 242-247.

Sopyan, I. 2007. Kinetic analysis on photocatalytic degradation of gaseous acetaldehyde, ammonia, and hydrogen sulfide on nanosized porous TiO₂ films. Sci. Technol. Adv., 8(1-2): 33-39.

Sopyan, I., Watanabe, M., Murasawa, S., Hashimoto, K. and Fujishima, A. 1996. An efficient TiO₂ thin-film photocatalyst: photocatalytic properties in gas-phase acetaldehyde degradation. J. Photochem. Photobiol. A., 98(1-2): 79-86.

Stoyanov, S., Mladenova, D. and Dushkin, C. 2006. Photocatalytic properties of mixed TiO₂/V₂O₅ thin films in water purification at varying ph. React. Kinet. Catal. Lett., 88(2): 277-283.

Sunada, K., Kikuchi, Y., Hashimoto, K. and Fujishima, A. 1998. Bactericidal and detoxification effects of TiO₂ thin film photocatalysts. Environ. Sci. Technol., 32(5):726-728.

Sunada, K., Watanabe, T. and Hashimoto, K. 2003. Bactericidal activity of copper-deposited TiO₂ thin film under weak UV light illumination. Environ. Sci. Technol., 37(20): 4785-4789.

Takeuchi, M., Yamashita, H., Matsuoka, M., Anpo, M., Hirao, T., Itoh, N. and Iwamoto, N. 2000. Photocatalytic decomposition of NO on titanium oxide thin film photocatalysts prepared by an ionized cluster beam technique. Catal Lett., 66(3): 185-187.

Thiruvennakatchari, R., Vigneswaran, S. and Moon, I.S. 2008. A review on UV/TiO₂ photocatalytic oxidation process (Journal Review). Korean J. Chem. Eng., 25(1): 64-72.

Tomaszewski, H., Eufinger, K., Poelman, H., Poelman, D., De Gryse, R., Smet, P.F. and Marin, G.B. 2007. Effect of substrate sodium content on crystallization and photocatalytic activity of TiO₂ films prepared by dc magnetron sputtering. Int. J. Photoenergy., 2007: 54-69.

Tung, W.S. and Daoud, W.A. 2011. Self-cleaning fibers via nanotechnology: A virtual reality. J. Mater. Chem., 21: 7858-7869.

UNEP 2009. Marine Litter: A Global Challenge. Nairobi: UNEP.

Verma, R., Vinoda, K., Papireddy, M. and Gowda, A. 2016. Toxic pollutants from plastic waste-a review. Procedia Environ. Sci., 35: 701-708.

Wang, H., Huang, X., Li, W., Gao, J., Xue, H., Li, R.K. and Mai, Y.W. 2018. TiO₂ nanoparticle decorated carbon nanofibers for removal of organic dyes. Colloids Surf. A Physicochem. Eng. Asp., 549: 205-211.

Watanabe, T., Fukayama, S., Miyauchi, M., Fujishima, A. and Hashimoto, K. 2000. Photocatalytic activity and photo-induced wettability conversion of TiO₂ thin film prepared by sol-gel process on soda-lime glass. J. Solgel Sci. Technol., 19(1-3): 71-76.

Xianyu, W.X., Park, M.K. and Lee, W.I. 2001. Thickness effect in the photocatalytic activity of TiO₂ thin films derived from solgel process. Korean J. Chem. Eng., 18(6): 903-907.

Yu, H., Lee, S., Yu, J. and Ao, C. 2006a. Photocatalytic activity of dispersed TiO₂ particles deposited on glass fibers. J. Mol. Catal. A Chem., 246(1-2): 206-211.

Yu, J., Jimmy, C.Y., Cheng, B. and Zhao, X. 2002a. Photocatalytic activity and characterization of the sol–gel derived Pb-doped TiO₂ thin films. J. Solgel Sci. Technol., 24(1): 39-48.

Yu, J., Jimmy, C.Y. and Zhao, X. 2002b. The effect of SiO₂ addition on the grain size and photocatalytic activity of TiO₂ thin films. J Solgel Sci Technol., 24(2): 95-103.

Yu, J., Yu, H., Ao, C., Lee, S., Jimmy, C.Y. and Ho, W. 2006b. Preparation, characterization, and photocatalytic activity of in situ Fe-doped TiO₂ thin films. Thin Solid Films, 496(2): 273-280.

Yuan, Z., Li, B., Zhang, J., Xu, C. and Ke, J. 2006. Synthesis of TiO₂ thin film by a modified sol-gel method and properties of the prepared films for photocatalyst. J. Solgel Sci. Technol., 39(3): 249-253.

Yusuf, M.M., Imai, H., Hirashima and H. 2002. Preparation of porous titania film by modified sol-gel method and its application to photocatalyst. J. Solgel Sci. Technol., 25(1): 65-74.

Zhang, J., Xu, Q., Feng, Z., Li, M. and Li, C. 2008. Importance of the relationship between surface phases and photocatalytic activity of TiO₂. Angew. Chem. Int., 120(9): 1790-1793.

Zhou, J., Takeuchi, M., Zhao, X., Ray, A.K. and Anpo, M. 2006a. Photocatalytic decomposition of formic acid under visible light irradiation over V-ion-implanted TiO₂ thin film photocatalysts prepared on quartz substrate by ionized cluster beam (ICB) deposition method. Catal. Letters., 106(1-2):67-70.

Zhou, L., Yan, S., Tian, B., Zhang, J. and Anpo, M. 2006b. Preparation of TiO₂–SiO₂ film with high photocatalytic activity on PET substrate. Mater. Lett., 60(3): 396-399.