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Recent Developments in Nanophotocatalysis for Everyday Applications and Consumer Products

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ABSTRACT

Nano-photocatalysis is one of the greatest beneficial technologies where both photo-energy even solar-energy and nano-sized catalyst materials have been used to solve two major problems facing world, day-to-day demand for energy sources and increasing pollution with advancement of human activities/civilisation. Nowadays, this interesting technology has been incorporated into different industrial sectors and everyday consumer products to revolutionise and improve product efficiencies and performances across various domains. In the field of agriculture, food safety, water purification, pharmacy, cosmetics, personal care, etc., nano-sized man-made engineered materials have been utilised which exhibit unique properties that differ from natural bulk materials. Several suitable photocatalyst nanomaterials, such as TiO_2, ZnO, Ag_2O, CuO, Fe_3O_4, ZnS, CdS, plasmonic Au, Ag, Cu, metal nanoparticles, some metal-free carbon-based Graphene, Graphene Oxide (GO), Carbon Nanotubes (CNTs), and Carbon Quantum Dots (CQDs), Nanoparticles (NPs) etc., and their composites have been successfully explored and exhibit outstanding performance towards some catalysis-chemical reactions for multifunctional photocatalysis applications. Integration of such a nano-photocatalysis mechanism into different consumer products such as UV-protective textiles, personal care products, self-cleaning building construction materials, roof tiles, glazed ceramic tiles, concrete, paint, and transports; anti-bacterial medical textiles, clothing, food packaging; anti-fogging and anti-reflective glasses, mirrors, solar panels, etc., has ushered in a new era of innovation and enhanced product efficiencies and performances. Another important problem regarding the gradual waning stage of natural fuel sources has been solved through the production of alternative renewable and non-fossil hydrogen fuel using this nanophotocatalysis technology. Even some semiconducting nanomaterials have been developed in such a way that it can absorb unlimited and free solar-light energy, and the performance for photo-catalytic reactions has been increased much more. In this chapter, it has been expounded how light energy, even solar energy, can be used to drive intriguing technologies to be utilised in daily life.

Keywords: *Air Purification; Hydrogen-Fuel; Light-Driven Chemical Reactions; Photo-Catalysis; Self-Cleaning; Semiconducting Nano-Materials; Waste-Water Treatment*

Introduction

Photocatalysis is one of the greatest beneficial technologies where photoenergy has been utilised to conduct a chemical reaction. Very recent nano-photocatalysis technology, i.e., nanotechnology-based photocatalysis, has been developed where small semiconductor materials having a few nanometre sizes have been utilised as catalyst materials and have been integrated into many industrial sectors and everyday consumer products to revolutionise and improve product efficiencies and performances across various domains. Several research works have demonstrated that nanophotocatalyst materials have some unique properties different from those of bulk material (Long, Evans & Halliwell, 1999). As the dimension of a nanomaterial is so small, some new fascinating properties have been generated inside the material, such as interesting chemical and physical properties, a large specific surface-to- volume ratio and high catalyst-loading capacity (Dutta *et al.*, 2012; Maji *et al.*, 2012). In the presence of both photoenergy and nanosized semiconductor materials, chemical reaction speed is generally increased much more. Here, the light energy is the driving force for conducting a chemical reaction (Ge *et al.*, 2018). Light is an outstanding source of energy; it can give life to plants as well as power to human bodies. When solar energy is utilised in a photochemical reaction, it will be most useful alternative sustainable energy source, as the abundance is virtually unlimited and free. So, focus needs to be done on improving environmentally friendly, low-energy and cost-effective technologies for fully utilising this powerful unlimited resource for the sake of society. Nowadays, with tremendous development of science and technology, so many photo-catalysis research works have been devoted to the innovation and development of interesting technologies to be utilised in daily life. In the field of environmental wastewater treatment and air purification, the photocatalysis process has already been utilised worldwide for complete degradation of organic pollutants in the presence of nanocatalyst materials under light illumination (Dutta, Maji & Adhikary, 2014). Very recently, photocatalysis has been widely applied for hydrogen fuel production as an alternative non-carbon energy source (Banerjee *et al.*, 2021). In the field of environmental pollution, the nanophotocatalysis technology provides excellent support towards decomposition of numerous organic pollutants under solar and visible light illumination and has been successfully utilised in wastewater treatment, agricultural pesticide residue treatment, and air purification. Photocatalytic nanofiber membrane-based filtration processes have been successfully employed in commercial water purification systems to provide safe drinking water.

Integration of such a mechanism of nanophotocatalysis technology into different consumer products such as agriculture, food safety, medicine, pharmacy, cosmetics, personal care products, etc., has a new era of innovation and enhancing product efficiencies and performances (Festus-Ikhuoria *et al.*, 2024). The use of Titanium dioxide (TiO_2) and Zinc oxide (ZnO) semiconducting nanomaterials in Sunscreen, offer superior UV and Sun-protection through the creation of an efficient barrier that blocks harmful UV rays, ensuring better skin protection (Rajasekar *et al.*, 2024). Nano-titanium pigments have been integrated into paints, plastics, surface coatings, papers, personal-care products, and food additives to mediate excellent photoactive properties. Nano-photocatalytic self-cleaning surface coatings have widely been used in exterior building construction materials, tent materials, transport cars, trains, planes, etc. in which solar light or indoor light has been used to decompose pollutants that can be washed away with rain/water (Padmanabhan & John, 2020). Some commercial painting materials, when mixed with photo-catalytic materials, have been widely utilised for improving the air quality and eliminating bad odours through degradation of carbon monoxide (CO) and nitrogen and sulphur-containing organic compounds (NO_x), and even Volatile Organic Compounds (VOCs) and Inorganic Pollutant and converted to harmless substances under solar or indoor light irradiation that come into contact with the surface of them (Zhao & Yang, 2003). Again, in the case of indoor air pollution caused by different sources like the adhesives and building material's discharge and the ignition (fire) processes in addition to the use of household products, furniture, and electric and electronic devices, VOCs can encourage damages to organs and metabolic systems or asthma and cardiovascular diseases. Nowadays, some wall paints, mixed with photocatalytic materials, have been widely applied for improving the indoor air quality. Nano-catalyst thin-film coatings on roof tiles, glazed ceramic tiles, concrete, glass windows, anti-fogging and anti-reflecting glasses, and mirrors can prevent the accumulation of deposited dust, dirt or contaminant particles on their surfaces, keeping them clean.

For medical applications, nano-photocatalytic coatings and solutions are widely commercialised to improve anti-bacterial, anti-viral, anti-microbial, and anti-fungal action to protect against infections from different viruses, bacteria, and even the COVID-19 and SARS-CoV-2 viruses. Face masks, surgical cloths, and wound dressing material with nano-catalysis coating can protect against bacterial growth, spread of contagious disease, and wound infections and can sterilise rooms, instruments, etc. through degradation of the cell wall and cytoplasmic membrane of micro-organisms and viruses that survive on surfaces for a long time (Prakash, Cho & Mishra, 2022). This type of photocatalytic disinfection has broadly been applied to protect against healthcare-associated infections in hospitals, public areas like bathrooms and train stations, and cleaning areas in the food industry. In the textile industry, nanophotocatalysis technology provides us UV-protective, heat-resistant fire-fighter's suits, coffee-red wine stains-resistant garments, etc. TiO_2 and ZnO-type semiconducting materials can absorb ultraviolet radiation and can protect the textile fabric from the harmful effect of UV rays and also act as a self-cleaning agent by photo-catalytic degradation of various colour stains (Shah *et al*., 2022). In the year of 1972, Prof. Fujishima and Honda of Tokyo University of Science, Japan, first exposed that in photo-catalysis technology, similar types of photo-chemical reactions that occur during the natural photo-synthesis process in plant leaves have been carried out under light illuminations. Since their successful research, so many nanotechnology-based photocatalysis research works have widely been devoted to the development of interesting technologies such as hydrogen fuel generation as an alternative energy source from water splitting, carbon dioxide reduction to hydrocarbon fuels, environmental pollution remediation through degradation of pollutants, air purification, UV protection and self-cleaning on textile clothing, etc., in the presence of a catalyst material under light illumination for the sake of society (Hoffmann *et al*., 1995).

General mechanism of Photo–catalysis

In the nano-photocatalysis process, metal oxides and metal sulphide-based NPs are so chosen as heterogeneous nano-photocatalyst materials because they are semiconductor materials and possess appropriate band-gap energy and flat band-potential levels with filled valance-band (VB) and vacant conduction-band (CB) (Figure 1). TiO_2 NPs has been chosen as a reference material to validate general photocatalytic reactions on semiconductor nanomaterial's surface. It is generally accepted that the main reaction responsible for nano-photocatalysis is the interfacial redox reaction of carriers generated when a certain amount of energy is absorbed by the semiconductor catalyst. If The band gap energy of the catalyst is equivalent to or less than the energy of the incident light, the electrons residing in VB will absorb the photon and be promoted to the CB, thus leaving behind a hole in VB of the semiconducting nanomaterials (Figure 3). As a result, electron/hole pairs (e-/h+) are generated. Many of them have a possibility for recombination, but some could be separated at the surface of the semiconductor, and that electrons are able to react with electron acceptors (O_2) and holes can accept electrons from water bodies to generate hydroxyl radicals (OH•) and other reactive oxygen species (ROS) (Al–Ekabi *et al*., 1989). These radicals actually convey the photochemical reactions.

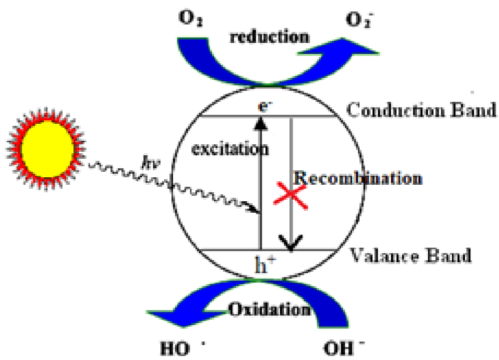

Figure 1: Illustration of Photo-Catalytic Mechanism

The complete photo-chemical reactions are represented as follows

$$TiO_2 + h\nu \longrightarrow TiO_2\ (e^-_{CB} + h^+_{VB})$$

$$H_2O \longrightarrow H^+ + OH^-$$

$$OH^- + h^+_{VB} \longrightarrow OH^\cdot$$

$$\text{Pollutants} + OH^\cdot \longrightarrow \text{Products}$$

The organic pollutants have been further degraded by O_2^- active species and superoxide radicals (O_2^-), which were produced on the proposed nanomaterial's surface according to following mechanisms.

$$O_2 + e \longrightarrow O_2^-$$
$$O_2^- + 2H^+ + 2e \longrightarrow H_2O_2$$
$$H_2O_2 + e \longrightarrow OH^- + {}^{\cdot}OH$$
$$\text{Pollutants} + OH^{\cdot} \longrightarrow \text{Products}$$

As a whole, both O_2^- and $OH^{\cdot}$ are responsible for photochemical reactions.

If that band-gap energy between VB and CB becomes tremendously low, the lifetime of the produced electron/hole pairs (e-/h+) also becomes short, and there is a possibility of the recombination of electron–hole pairs, and hence the photocatalytic performance of the material is decreased. In that case, different modifications on that nano-catalyst's surface have been carried out, such as amalgamation of semiconductors with other components by ion-doping, hetero-structure fabrication, noble-metal loading, morphology or size modulation, defect engineering, tuning of active crystal facets, etc., for enhancing the catalytic performances.

Defect engineering and surface modification generally have been used to modify a semiconductor's band structure for better light absorption and electron-hole pair separation, which can boost photo-chemical reactions. Also, in a hetero-nanostructure (Figure 2), lattice mismatch arises in the junction area due to the presence of different lattice spacing between two semiconductors and causes lattice defects as a whole. Actually, vacancy defects can enhance the catalytic efficiency of the semiconductors through changing its electronic structure and generate defective energy levels near the conduction-band (CB) or near the valence-band (VB) in case of *n*-type or *p*-type semiconductors, respectively. The newly formed energy level (Fermi level) in semiconductors can effectively prohibit the electron–hole pair recombination, can effectively promote light absorption or improve visible light harvesting, promote charge carrier separation (photo-induced carrier separation) and photo-electron transfer, which really extends the carrier lifetime, increases conductivity, and reduces the energy barriers for efficient multiple nanophotocatalytic applications.

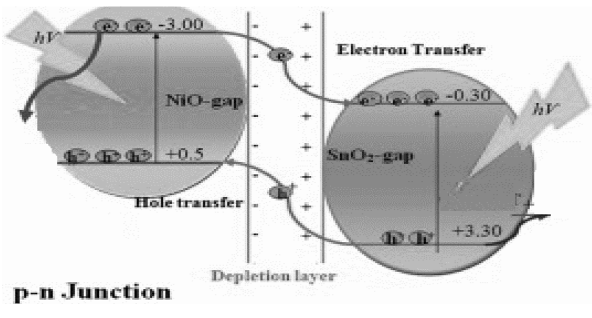

Figure 2: Synergistic-Effect Diagram on Charge Transference Towards Photo-Catalytic Reaction (Dutta, Maji & Adhikary, 2014)

Very recent combinations of carbon-based materials, such as graphene, graphene oxide (GO), rGO nano-sheet, CNT, Carbon QDs, polymeric graphite carbon nitride (g-

C_3N_4) with semiconductor nano-catalysts, become more promising strategies to enhance catalytic performance and the solar or visible-light-driven response because carbon acts as a photosensitiser and can tune photocatalytic activity in the visible region (Wang *et al.*, 2009). Owing to possessing a wide band-gap energy, the TiO_2 or ZnS NPs are inactive under visible light; then graphene helps as a photosensitiser to absorb visible light and generate charge carriers, which get transferred to the CB of TiO_2 or ZnS NPs, making that wide band-gap semiconductor visible-light active (Zhang *et al.*, 2012).

Nano-Photocatalytic hydrogen-fuel production

Recently, nanophotocatalysis has been widely applied for hydrogen fuel production as an alternative non-carbon energy source. This is the low-cost method and does not evaluate harmful CO_2 gas, like natural fossil fuels (coal, oil, natural gas, etc.), which makes a serious impact on the environment with global warming. Inspirational from the first research work of Fujishima and Honda (1972) on water-splitting technology in a photoelectrochemical (PEC) setup using a TiO_2 electrode under light irradiation, nowadays, so many research groups have paid substantial attention to increasing hydrogen manufacturing efficiency in a large-scale way using efficient catalyst material even under natural solar light illumination.

Similar to the general mechanism of photocatalysis discussed above, photocatalytic hydrogen production occurs through water splitting into H_2 and O_2 over a heterogeneous semiconductor nanophotocatalyst under light illumination and mild conditions according to equation.

$$2\,H_2O + 4\,h^+ \rightarrow 4\,H^+ + O_2\ (E^0 = 1.23\ \text{V vs. RHE})$$

$$2\,H^+ + 2\,e^- \rightarrow H_2\ (E^0 = 0\ \text{V vs. RHE})$$

The photochemical reactions basically start from incident light energy activating semiconducting nanocatalysts, followed by free electron-hole pair (e-/h+) formation. That (e-/h+) have been transferred to the active sites of the semiconductor nano-catalyst's surface; after that, they will act as reducing/oxidising agents to drive reduction/oxidation reactions. In water splitting process, water molecules are reduced by the photo-induced electrons to form H_2 and are oxidised by the photo-induced holes to form O_2, i.e., the hydrogen evolution reaction (HER) and oxygen evolution reaction (OER). The hydrogen gas produced was collected using a gas-tight syringe and analysed by gas chromatography.

Several research groups have proved that to pursue the complete water splitting process, nano-catalyst material must possess bottom level of the conduction band (CB) position more negative than the redox potential of H^+/H_2 (0 V vs. NHE) and the top level of the valences band (VB) position more positive than the standard reduction potential of O_2/H_2O (1.23 V vs. NHE). Figure 3 represents the band potential positions of several metal chalcogenide semiconductors, which can proficiently split water to produce hydrogen. For TiO_2, its band gap is large enough to split water (3.0 eV vs. 1.23 eV for the formation of H_2 and O_2), and also its band structure matches well with redox potentials of water splitting (Qiao *et al*., 2018).

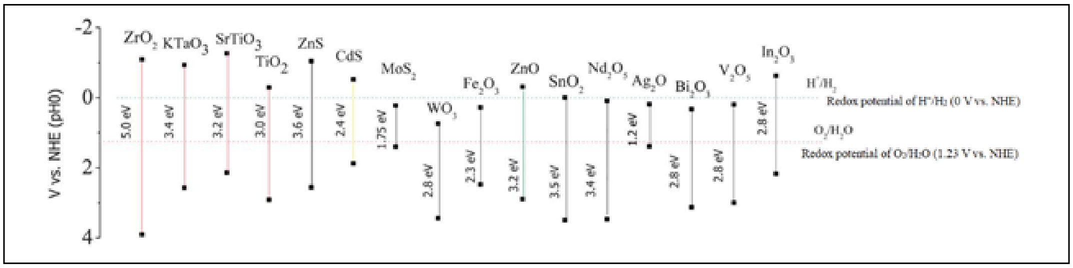

Figure 3: Band Potential Situation of Numerous Metal Chalcogenides NPs (Qiao et al., 2018).

Some research groups have noticed another problem that after formation of hydrogen, some backward reaction of H_2 and O_2 to H_2O occurs and numerous effective strategies have been explored to increase hydrogen production efficiency using different efficient nanocatalysts, such as metal oxides, carbon nitrides, polymers, and heterostructures. When some semiconductors (TiO_2) are coupled with highly conductive supports such as metallic Silver, Gold, Pd, Pt or bimetallic PdPt NPs, they can strongly prevent the recombination of photogenerated electrons of the semiconductor, enhance the electron-transport behaviour and improve their photoelectrocatalysis performances towards water-splitting (da Silva *et al*., 2020). ZnS nanostructure has excellent potential in solar-energy-driven hydrogen formation because of its ability to quickly generate photo-induced carriers. Again, zinc vacancies can modulate the electronic energy level of ZnS and affect the CB and VB position in such a way that it can decrease the oxidation capacity of the holes, protecting the Zn-deficient ZnS from photo-corrosion, leading to long-term photo-catalytic stability and exhibiting an outstanding light-energy-driven hydrogen productivity of ~338 μmol/h/g. Very recently, to effectively utilise sunlight, various near-infrared (NIR) and long-wavelength light (highest 49% contribution in the entire solar spectrum) harvesting systems have been developed which can efficiently harvest solar light, optimise the redox process and exhibit high solar-to-hydrogen (STH) conversion efficiency (Kim *et al.*, 2015).

Nano-Photocatalysis in Agriculture

Organic Pesticides are widely used in agriculture, but their unnecessary usage may generate hazards to both humans and the environment. DDT has been used extensively as a pesticide for agricultural purposes, but it does not degrade under natural conditions since it is lipophilic. Its poisonous effect has been persisting for long time in water bodies, making severe adversative influences on life and the environment of the planet, and it tends to bioaccumulate in fatty tissues and is biomagnified up the food chain. Considering their high solubility in water and low biodegradability, complete removal from wastewater is vital, and treatment of that wastewater is often being made difficult by conventional methods. So, pesticide residues require effective treatment like wastewater due to their toxicity, high chemical Stability and low biodegradability.

Similar to wastewater treatment, nanophotocatalysis technology is a promising approach to solve the pesticide residue problem. Using the most effective and useful TiO_2 photocatalyst, pesticide particles have been easily degraded into H_2O, CO_2 and other less harmful compounds through a photocatalytic oxidation process under light illumination. Sarkar *et al*. (2016) had reported that, using Bi_2S_2 NPs as nano-photocatalyst, the rate of degradation of highly toxic dichlorodiphenyltrichloroethane (DDT) has been found to be much better compared to that exhibited by commercial WO_3, and through aromatic ring cleavage, after degradation, it produces less harmful para-chlorotoluene and, at last, chloro-benzene (Figure 4).

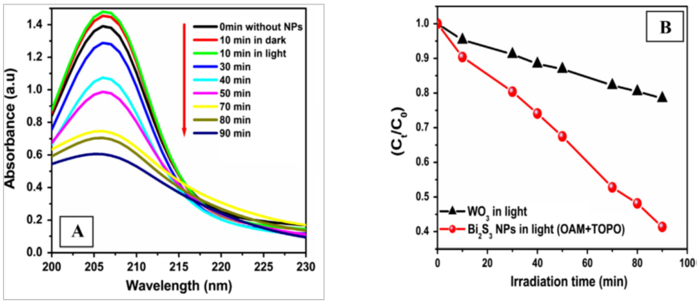

Figure 4: (A) Time Dependent UV–vis Spectral Change of DDT Solution (2×10^{-5} M) Using 20 mg Nano-Photocatalyst, Bi_2S_3 NPs, Under Visible Light Illumination (B) C_t/C_0 vs Time (t) Plot of DDT Decomposition Process (Sarkar et al., 2016).

Another Common pesticide, 2,4-dichlorophenoxyacetic acid, has been reported to be decomposed in the presence of highly effective photocatalyst Ag-TiO_2 NPs under visible light illumination.

Nano-photocatalytic air purification

Nowadays, several air-purifier devices have been developed to be utilised in daily life based on nanophotocatalysis technology, where air pollutants are converted to harmless substances in the presence of a nanocatalyst under solar or indoor light irradiation. In these devices, photocatalytic oxidation (PCO) has been incorporated to purify air where nanocatalyst material can oxidise the gaseous compounds such as carbon monoxide, nitrogen oxides, volatile organic compounds (VOCs), other inorganic gases, etc., that come into contact with the surface of them (Zhao & Yang, 2003). In case of indoor air pollution caused by different sources like the adhesives and building materials' emissions and the combustion processes as well as the use of household products, furniture, electric and electronic devices, VOCs can encourage damages to organs and metabolic systems or asthma and cardiovascular diseases. Very recently, numerous carbon-based materials such as 2D graphene, graphene oxide (GO), rGO nano-sheets, CNT, Carbon QDs, polymeric graphite carbon nitride (g-C_3N_4) supported semiconductor composites have been fabricated to enhance PCO technology and used in air purification technology that utilises light energy to break down pollutants and bacteria, remove VOCs (VOCs mineralization) and improve air quality. Again, some wall paints mixed with photocatalytic materials have been widely applied for improving the air quality through degradation of volatile organic and inorganic pollutants present in air or deposited on paint surfaces. Some TiO_2 (Titania)-based nanomaterials as a thin film coating on a piece of glass or ceramic or aluminium metal substrate have been used as photocatalysts. Similar to radical mechanism of photocatalysis, electrons that are released on the TiO_2 surface upon UV light irradiation interact with water molecules in the air to generate reactive oxygen species (ROS) such as hydroxyl radicals (OH.), superoxide radicals (O_2^-), and hydrogen peroxide radicals (OOH), which can actually occur in the oxidation process to reduce contaminants. In the case of VOCs, a photocatalytic degradation process has been carried out similar to organic dye degradation in wastewater treatment, and the bigger carbon-based organic pollutant molecules break down into the harmless Substances CO_2 and H_2O. In comparison to air cleaner technology through simple filtration or trapping pollutants, photocatalytic air treatment shows a big advantage, where all harmful molecules (exhaust fumes) have been completely decomposed and effectively destroyed. Even in case of indoor air pollutants such as volatile organic compounds (formaldehyde, acetaldehyde) evaporating from paints, hairsprays, etc., photocatalytic chemical decomposition is the best route instead of removing them completely by sucking air-polluted particles and blowing clean out.

Nano-Photocatalytic UV-protection

With the help of superior photocatalytic and UV-light absorption properties of some semiconducting nanomaterials, protection of the wearer against the weather and the sun's harmful rays has been developed. Nano-titania or ZnO embedded sunscreen, textiles and clothing offer superior UV and Sun-protection through the creation of an efficient barrier that blocks harmful UV rays, ensuring better skin protection (Rajasekar *et al*., 2024). Compared to traditional organic UV-blocking agents, ZnO NPs are more stable and have intense absorption in the UV region. UV-blocking characteristics of the textile's fabric have been improved by the incorporation of nano-ZnO and provide cost-effective UV-protective suits to the society in which transmission of the ultraviolet radiation to the skin through the fabric is blocked.

Very recently, some cosmetic products containing inorganic nano-sized UV filters have been developed in the form of creams, lotions, gels, sprays, and sticks and exhibit different protection mechanisms, sometimes absorbing or scattering and/or reflecting UV radiation. Nano-titania or ZnO are the most commonly used and have been included in cosmetic product formulations and exhibit a high sun protection factor (SPF). Occasionally, silver-based nanomaterials such as Ag_2O, Ag_2S, etc., have been incorporated into cosmetic product formulations due to the presence of well-known anti-microbial properties and also serve as photo-sensitisers in the photo-catalysis process.

Unlike traditional organic UV filters, the nanomaterials are more photostable and can enhance the durability of skin protection, prevent penetration of UV radiation into the deeper skin layers, decrease the release of ROS, which can start different photochemical reactions on skin. The nanomaterials are environmentally friendly, non-toxic and have a lower potential to produce skin irritation. Nano-sized particles make the products lightweight and transparent (Rajasekar *et al.*, 2024).

Nano-Photocatalytic self-cleaning

Following radical mechanism of photocatalysis, the photocatalytic self-cleaning process of deposited dirt or contaminant particles from any surface has become very popularised and commercialised through the decomposition of that dirt particles under solar-light or indoor-light irradiation. The photoexcited electron and valence band hole (h^+_{VB}) on the nanocatalyst surface can generate reactive oxygen species (ROS) that can convert dirt organic matter into CO_2 and water, resulting in the cleaning of the surface. This type of self-cleaning infused with nanophotocatalysis technology has been incorporated in different sections, including biomedical, healthcare, electronics, tissue engineering, packaging, clothing, first aid, surface disinfectants, dietary supplements, etc.

Especially in the textile industry, self-cleaning, stain-resistant, dirt-repellent clothing has been introduced through the incorporation of nanophotocatalysis technology. Traditional cotton-silk fabrics, rayon yarn, etc., finished with photocatalytic and antibacterial nanomaterials, provide effective protection against various colour stains and bacteria. Nano-titania or ZnO embedded textile clothing, when exposed to ultraviolet or visible light, the photocatalytic characteristic of the semiconducting nanoparticle allows it to act as a self-cleaning agent by photocatalytic degradation of various colour stains. Even the photocatalytic self-cleaning ability has been retained after several cycles of home washing. Silver-based nanomaterials, which have well-known anti-microbial and photo-sensitiser properties, have been immobilised to develop sun-light-driven cleaning and anti-bacterial characteristics, and fabrics of socks, inner wear, etc. embedded with silver nanoparticles can protect against odour and infection. Nowadays, with tremendous development of science and technology, so many research works have been devoted to the innovation and development of textile material with more features like more comfort, durable, hygienic, anti-odour, anti-microbial, anti-static, breathability, improved softness, better tear strength, water/spill repellence and wrinkle resistance but without altering the inherent properties of the textiles, including flexibility and washability (Tania, Ali & Akter, 2022).

Another nano-textile research work develops nano-fibres with diameters in the few nm range, which have been directly used to weave a cloth. Nano-fibres have been generated from different nano-sized polymeric materials. They are lightweight, low-density and have a controllable pore structure with a high surface-to-volume ratio. Textile-garments using nano-fibre yarn can enhance comfort, breathability, moisture management, and anti-bacterial properties. Like the surface of a lotus leaf, nanofibre-made cloths show excellent water-repellent activity, i.e., they are resistant to water or liquids, and droplets bead up into spheres and easily roll off due to the presence of superhydrophobic surface morphologies with contact angles >150°. Nano-photocatalytic self-cleaning nano-fibre-based surfaces also utilise sunlight or indoor light to break down deposited dirt or contaminant particles and easily be washed away with rain/water. Sporting goods, swimming suits, even PPE kits, face masks, surgical goods, etc., using nano-fibre yarn have benefitted from photocatalytic self-cleaning. The self-cleaning efficiency with super-hydrophilic (WCA less than 5°) nanomaterials-based surface coating can spread water droplets to form a film throughout itself and utilise solar light or indoor light to decompose any adsorbed organic contaminants such as oil and dirt. After that, the contaminants are washed away with the help of water flow.

Nano-photocatalytic Anti-microbial and Self-sterilising

Using these self-cleaning surface coating phenomena, photocatalytic disinfection has broadly been applied to protect against healthcare-associated infections in hospitals, public areas like washrooms, transport stations, cleaning areas in the food industry, etc. Similar to well-known anti-microbial Silver-based medicines, photocatalyst nano-materials can degrade the cell-wall and cytoplasmic membrane of micro-organisms and viruses, that survive on surfaces for a long time, through the production of reactive oxygen species (ROS) such as hydroxyl radicals and hydrogen peroxide (Manke, Wang & Rojanasakul, 2013).

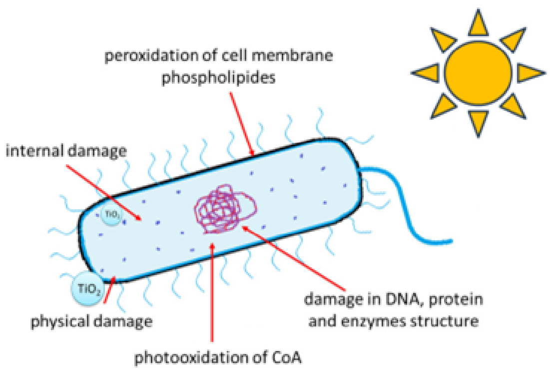

Figure 5: Mechanisms of Photocatalytic Bacterial Inactivation (Chae, Watanabe & Wiesner, 2011)

The unique photochemical and electrical properties of engineered nanomaterials induce oxidative stress response through the generation of ROS in bacterial cells and cause inflammation, genetic damage, inhibition of cell division, and cell death. Photocatalytic bacterial mineralisation has been carried out through reduction or complete termination of bacterial growth, photo-oxidation of Coenzyme A (CoA), leading to bacterial cell death. During interactions between the photocatalyst and bacterial cells, the ROS, which is generated on the photocatalyst's surface, can induce the oxidative interference of proteins, metabolic activities, or damage in bacterial DNA and enzyme structures (Figure 5) (Chae, Watanabe & Wiesner, 2011).

That is why face masks, surgical cloths, and wound-dressing material with nano-catalysis coating have been widely commercialised, which can protect against bacterial growth, the spread of contagious disease, and wound infections and can sterilise rooms, instruments, etc. Silver (Ag), gold (Au) nanoparticles and even metal oxides nanoparticles (ZnO, TiO_2, CuO, Ag_2O, etc.) generally possess outstanding antibacterial and antimicrobial activity. Imparting these nanomaterials on cotton fabric can protect against bacterial growth and be effective against a wide range of micro-organisms.

Nano-photocatalysis in Cancer Treatment

During the development of Cancer treatment, heterogeneous nano-photocatalysis has been employed to provide advantage of catalysis chemical reaction on growing tumour cells and to accelerate depletion of metabolism of cancer cells. Owing to being extremely small in size, nanomaterials can be easily absorbed by the cells in a biological system and easily travel into blood vessels and organs within the body. Following the nano-photocatalytic mechanism, nanomaterials can encourage photodynamic therapy (PDT), where they act as photosensitisers and can generate reactive oxygen species (ROS) upon exposure to light. That ROS causes apoptotic and necrotic cell death and triggers oxidative damage of the amino acids of proteins, fatty acids in lipids and the nucleobases in DNA of tumour cells. Again, a photosensitiser can transfer the light energy to the surrounding oxygen molecules and generate Singlet oxygen that interacts with adjacent cancer tissues to induce apoptosis, necrosis-related cell death.

Mesoporous-structured nanomaterials with functionalised surfaces can act as carriers to transport anti-cancer drugs to tumour tissues. Unlike very common carriers like liposomes, dendrimers, micelles, etc., nanocarriers have high drug-loading capacity, improved stability, bio-compatibility, enhanced permeability-retention effect, precise targeting, and good pharmacokinetics, which can induce an anti-cancer drug's accumulation into tumour tissues. Nowadays, red-light-emitting carbon nanoparticles with high fluorescence quantum yield, NIR-light-harvesting N-doped carbon dots, plasmonic gold nanoparticles (AuNPs), etc., have been used in cancer treatment. In this case, bio-nanomedicine and photo-catalysis have been merged to provide the advantages of both bio-imaging markers and photo-dynamic agents.

Upon exposure to NIR radiation, the carbon-based nanoparticles can enhance photo-catalytic response towards ROS generation and destroy the cancerous cell's structure. Simultaneously, the deep penetration power and photothermal effect of NIR light raises the temperature of tumours and accelerates photothermal therapy (PTT), where light-to-heat conversion efficiency kills cancer cells. It has been noted that the cancer cells are more heat sensitive than normal cells and the cancer cells die at the temperature above about 45°C. Again, the NIR region is regarded as a biologically transparent window as the normal biological molecules, cells, etc. do not absorb in the NIR region, and NIR light possesses the optimum wavelength for penetration into deep tissues for cancer treatment.

Similarly, upon exposure to light, plasmonic gold nanoparticles (AuNPs) exhibit interesting Surface Plasmon Resonance from free surface electron oscillation and dipole oscillation along the direction of the electric vector of the light and can rapidly convert the absorbed light energy into the localised heat energy, and the temperature may rise to 330 K. When those AuNPs have been properly biofunctionalised at their surfaces so that they can be received preferentially by the target cancer cell receptors and preferentially accumulated into the cancer cells, then produce the localised heat energy upon irradiation with an NIR beam, which can easily destroy the heat-sensitive cancer cells.

Nano-photocatalytic Waste-water Treatment

Nowadays, photocatalytic nanofibre-based membranes are often used in the removal of micro-pollutants and finer contaminants from water bodies. Analogous to 'Safe Drinking Water Foundation, Canada', the Department of Science and Technology, Govt of India, has implemented 'Nano Mission' to convey collaborative research and development projects for nanotechnology-based water purification process. When nano-photocatalysis technology is incorporated into membrane-based filtration process, i.e., the filtration-photocatalysis integrated method both separation and decomposition of unwanted pollutants are carried out simultaneously and provide high-quality drinking water to millions of people in developing countries. Very similar to reverse osmosis (RO) purification, the nanofiber membrane-based filtration process has been successfully employed in commercial water purification system and has been extensively used for the softening of water and the removal of both physical, chemical and biological contaminants, leading to the formation of safe drinking water. When contaminated wastewater has been passed across the nanofiltration membrane under pressure, the membranes are capable of separating larger multivalent ions such as calcium sulphate while allowing smaller monovalent ions such as sodium chloride to pass through it. Also, some dissolved solids, even smaller molecules such as dissolved organics, pesticides, herbicides, agricultural chemicals phenols, polyaromatic hydrocarbons, etc., have easily been separated. Moreover, the Photo-generated ROS on the nano-fibre membrane's surface can effectively do the photo-degradation process of the unwanted pollutants, organic chemicals, and microbial species in water, as well as the self-cleaning properties (photocatalytic and anti-microbial) of membrane surfaces, which can significantly reduce blockage of its surface pores due to continuous deposition or adsorption of macro-molecules and make the membrane cost-effective, re-cyclable and reusable. Incorporation of photocatalytic Ag, Cu, Zn, activated carbon granules or Graphene into these nanofibre membranes can enhance photocatalytic disinfection through effective killing of a wide range of micro-organisms such as viruses, bacteria, parasites, algae, and pathogens and provide improved water filtration (Singha & Mishrab, 2020). In this way, these photocatalytic nanofiltration membranes can retain healthy minerals, maintain healthy total dissolved solids (TDS) as per WHO, and provide long-lasting water purification of up to 14,000+ litres.

Too much research work has been focused on the development of hybrid water-treatment process involving photocatalysis and membrane technology through the fabrication of photocatalytic and antimicrobial nanomaterials onto traditional polymeric membranes such as polystyrene (PS), polyethersulfone (PES), Polyester, polyacrylonitrile (PAN), etc. Electrospinning of PES nanofiber membranes infused with TiO_2 nanomaterials has been reported for simultaneous separation and photodegradation of water pollutants. Electrospun PAN layers coated with ZnO NPs can easily achieve both photocatalytic and antibacterial properties for water treatment. Some research groups have paid great attention to developing activated carbon-based nanofibre membranes because activated carbon granules have been widely used in water filtration process over the past three decades. Carbon-based nanomaterials are highly porous materials, and due to the presence of different functional groups on a single sheet surface, these nanomaterials act as versatile absorbents used for the removal of heavy metals, lead, fluoride, chlorine and inorganic contaminants. Simultaneously, its good reducing properties can do bacterial reduction, chlorine-toxic chemical reduction and improve the taste and odour of drinking water, providing point-of-use (POU) water purification for domestic use.

Conclusion

This chapter aims to outline the diverse nanophotocatalysis applications in daily life. Nowadays, in the presence of light energy, some catalysis-chemical reactions provide outstanding support that can be utilised in everyday consumer products. Several innovative catalyst materials, especially nano-sized inorganic materials, have been developed worldwide for multi-functional photocatalysis applications. Some environmentally friendly, cost-effective nanomaterials, such as TiO_2, ZnO, CuO, Fe_3O_4, FeS, ZnS, CdS NPs, etc., and their composites, have been successfully industrialised and established as effective heterogeneous recyclable catalysts for conducting several photochemical reactions. More cost-effective metal-free carbon-based Π-conjugated semiconductor nanomaterials have been successfully developed as organic photocatalysts. Recently, to achieve more complete utilisation of solar light, full-spectrum photocatalytic activity, i.e., full spectral-range (320-800 nm) light-driven photocatalysis, has been achieved with the help of carbon-based quantum dots (CQDs) and carbon dots (CDs), which can effectively accelerate the electron transfer, facilitating the effective utilisation of those photo-induced charge carriers in the nano-photocatalysis process. The catalytic capabilities of the NPs have also been effectively enhanced using nano-engineering technology, i.e., different modifications on the nanocatalyst's surface, electronic energy structure through tuning shape, size, morphology and band-gap energy during the synthesis process. The nanomaterials have been widely explored as an efficient photocatalyst for the degradation of various organic pollutants under solar and visible light illumination. The possible photocatalytic decomposition mechanism has also been deliberated through the detection of reactive oxygen species (ROS) such as hydroxyl radical (OH), superoxide radicals (O_2^-), and hydrogen peroxide radical (OOH). These photocatalytic self-cleaning materials can also be used in many applications, including anti-bacterial, anti-fogging, and anti-reflective coatings and can provide a solution to the growing problem of environmental pollution. By improving interaction between nanomaterials and biological systems, the nanotechnology-based therapy has now broadly been applied in the biomedical and biotechnology fields. The proposed nanomaterials have been successfully commercialised in other different fields, such as hydrogen fuel generation as an alternative energy source from water splitting, self-cleaning air purification, etc. Finally, environmentally friendly, cost-effective technologies have been developed for solar-light-driven photocatalysis so that most of the solar spectrum and light energies can be utilised in the society for large-scale application.

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