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Medical Waste Management by The Photocatalysis Approach -A Comprehensive Review

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ABSTRACT

Biomedical waste handling and disposal can be challenging due to its nature and the potential presence of harmful organic compounds. This paper talks about the comprehensive review of the medical waste, types of medical waste, and their management strategies. Degradation of medical waste by using the advanced photocatalysis gained a lot of prominence during the last few years. Several nano structured semiconductor materials such as Titanium Dioxide, Zinc Oxide, Cadmium sulphide, Bismuth Vanadate and Tungsten Oxide are showing the photosensitive properties. These materials can be explored for the photo degradation of medical waste with the mechanism of photocatalysis.

Keywords: Biomedical waste management, photocatalytic degradation, pharmaceutical waste management.

INTRODUCTION

Biomedical waste management is very important concern faced by healthcare facilities, wet lab research institutions and other biological related research centres, therefore it is imperative that the biomedical waste generated by such places is treated effectively and efficiently. Biomedical waste, if not treated it may cause an array of negative environmental impacts coupled with health risks as well. Currently there are many ways of treating such waste such as autoclaving, incineration and chemical disinfection. However, these traditional methods are either often ineffective or not sustainable. These methods often lead to harmful effects on environment, health, and the overall bio ecosystem. One effective way of overcoming these challenges is using photocatalysis. Photocatalysis employs the use of photocatalytic materials and light irradiation. These materials often are semiconductors such as Titanium Dioxide, Zinc oxide and others. Biomedical waste such as wastewater from labs or research facilities can be treated through photocatalysis. Some other applications of photocatalysis are also used for air purification, antifogging, antifouling, conservation, and storage of energy and sterilization[1].

In this study, review if focussed on biomedical waste classification, characteristics of biomedical waste along with photocatalysis, its principle, mechanisms & applications. To implement effective strategies for managing and degrading biomedical waste generated by healthcare facilities, research laboratories, or through medical procedures requires knowledge about its critical characteristics. Biomedical waste covers a broad spectrum of materials that needs proper categorization for appropriate treatment methods. This section will outline the common classification system in use while reflecting on essential traits unique to biomedical wastage.

1. Definition and Categories of Biomedical Waste:

Any type of refuse generated during procedures such as diagnosis, treatment, immunization among humans or animals; in addition to experimental research activities involving biological substances constitutes biomedical waste. The World Health Organization (WHO), through its classification systems have made it easier for healthcare practitioners and researchers alike adopt optimal standards for proper handling and disposal procedures[2].
The following are commonly recognized categories:

1.1. Infectious Waste: The categorization we're discussing pertains to materials that bear contamination from potentially infectious agents. To elaborate, the said agents may include blood, body fluids, tissues, laboratory cultures and waste emanating from isolation wards· A few instances of such waste comprise used bandages, discarded surgical gloves and cultures of infectious microorganisms[3,4,5].

1.2. Sharps Waste: The management of sharps waste calls for heightened awareness as it includes various items that pose a threat of injury or piercing wounds. This may consist of needles, syringes, scalpels, and splintered glass amongst others sharp instruments which require proper disposal methods. Furthermore, discarded medical equipment including lancets, shattered ampoules or discarded surgical blades must be accounted for within this classification too[4,5].

1.3. **Pathological Waste:** Managing pathological waste requires special attention because it involves potentially hazardous biological materials alongside culturally and ethically sensitive issues. This type of medical debris encompasses various human tissues such as organs or foetuses from surgical procedures and medical examinations[4,5].
1.4. **Pharmaceutical Waste:** Expired or unutilized medicinal products including drugs, vaccines and related items fall into the category of pharmaceutical waste. This section also comprises discarded medication such as empty vials along with their relevant packaging material. Proper disposal techniques are crucial in order to prevent any negative impact on our environment alongside attempting to curb any drug mis-4usage amongst individuals who may come across it accidentally or otherwise[4,5].
1.5. **Chemical Waste:** Healthcare establishments must handle hazardous wastes with extreme caution since they contain dangerous chemicals such as disinfectants, heavy metals, or solvents. Chemical wastage includes but is not limited to discarded cleaning agents and empty containers with no purpose. Laboratory reagents and expired or useless chemicals fall under this classification too[4,5].
1.6. **Radioactive Waste:** Radioactive waste is defined as materials tainted with radioactive substances originating from diagnostic and remedial practices, studies, or nuclear medicine. This grouping includes previously employed radioactive isotopes, polluted protective gear or gloves and belongings exposed to radiation[4,5].
1.7. **Non-Hazardous General Waste:** this classification falls under non-hazardous general waste and typically involves banal articles such as disposable office paraphernalia, leftover nourishment substances alongside different unsoiled pieces. Nonetheless within healthcare facilities there belongs a particular group of wastage objects which do not present any immediate danger to either our welfare or the integrity of our ecosystem[4,5].

Figure 1 Categories of biomedical waste

2. Characteristics and Composition of Biomedical Waste:
Biomedical waste exhibits specific characteristics that necessitate special handling and disposal methods. The composition of biomedical waste can vary depending on the source and nature of the healthcare activities.
The following are key characteristics of biomedical waste:
2.1. **Infectivity:** Biomedical wastes have inherent potentials for infectivity resulting from its likely contamination by microbial agents such as bacteria species (e.g., E. coli), viruses (e.g., HIV), parasites (e.g., Plasmodium falciparum), or prions (associated with 'Mad Cow Disease')[6,7]. Hence effective management is critical in averting their transmission between agents involved in medical care services or disposal sites as well as to households within surrounding communities through domestic collection activities undertaken by routine garbage collectors/waste handlers. A strict adherence regime governing its controlled handling from generation points through segregation/disposal up until its final treatment is pertinent[7].
2.2. **Hazardous Chemicals:** The presence of hazardous chemicals like disinfectants, solvents, heavy metals, cytotoxic drugs, and radiopharmaceuticals in biomedical waste emphasizes the need for safe handling and disposal methods[7,8]. These substances are known for their toxic or carcinogenic properties that can cause significant harm to human health and also affect the surrounding environment[6].
2.3. **Physical Properties:** The diverse physical features within biomedical waste could range from liquid to solid forms that vary with semisolid consistency. Additionally, within this category poses an added danger with sharp components such as needles or shattered glass shards which greatly increase the potential risk for injury. Therefore, it is strongly recommended that proper handling methods such as effective packaging protocols ensure safe removal upon disposal[6,7].
2.4. **Volume and Quantity:** Biomedical waste production differs depending on multiple factors including the characteristics or magnitude of healthcare operations, patient volumes treated, and procedure complexity level. Given

that larger healthcare facilities may be responsible for a noticeable amount of this kind of waste stream, it's important to have sound infrastructure that facilitates effective handling[7,8].

2.5. Decomposition Rate: It's important that we address various aspects of biomedical waste when putting together an effective disposal strategy - one element being organic compounds' rapid biodegradability[6]. When mishandled or mismanaged, the outcome results in an unpleasant smell permeating the surroundings and an invitation for vermin infestation - causing even more damage than it already has done[7]. It is thus essential that sufficient control measures are put in place through reliable degradation methods that protect the environment from harmful outcomes at every stage of handling these dangerous wastes[8].

PHOTOCATALYSIS

An innovative technique known as "photocatalysis" promises unique advantages for degrading organic compounds within biomedical waste. Harnessing light energy with specialized catalysts allows hazardous substances from these sources to be broken down more efficiently into milder components thereby better protecting our environment against harm from such chemicals. Touted not only for its ability to degrade complex constituents but also due to its remarkable efficacy towards selective elimination; researchers now look at this method considered highly sustainable while offering opportunity towards ecological medical industry evolution[1].

A. Principles of Photocatalysis:

Photocatalysis functions by linking the principles of semiconductor physics and heterogeneous catalysis allowing you to initiate chemical reactions through an absorbing process with photons emitted from various light sources that beget a series of chemical reactions carried out specifically by photocatalyst material. Essential changes occur with energy having enough power capable of generating electron-hole pairs seen when photons become absorbed generating electron-exciting processes located in valence band transitions uprooting positively charged valanced holes within this same state becoming prevalent. The generated electron-hole pairs turn highly reactive causing various redox reactions necessary with adsorbed molecules located on catalysts surfaces, ultimately leading to breaking down organic compounds found in biomedical waste[1,9].

Photocatalytic behaviour essentially transfers electrons from the conduction band towards organic compounds absorbing light thereby resulting in oxidation whereas holes lying within valence bands undertake reduction processes or undergo reactions with adsorbed water molecules causing highly reactive oxygen species (ROS), such as hydroxyl radicals (•OH) or superoxide radicals (•O2^-)[9,10].

Photocatalytic behaviour gets influenced by several factors such as the band structure of photocatalyst material, as well as light intensity and optimal wavelength necessary to achieve maximum efficiency. Different kinds of catalyst materials display distinct absorbed photon patterns based on specific levels of absorption spectra making them suitable for particular light sources or wavelengths[10].

To improve the efficiency of Photocatalytic processes, various approaches have undergone exploration. This involves doping materials used in photocatalysis with metal ions, modifying surface area morphology, and engaging efforts involving multiple semiconductor materials enabling efficacy. Furthermore, this promotes better charge separation capabilities allowing increased exposure surfaces suited for adsorption and reaction requirements increasing surface area optimization potential[1,10]. Effective optimization of photocatalyst design for maximum degradation efficiency and selectivity towards target compounds in biomedical waste demands a thorough understanding of photocatalysis principles in this regard, selecting appropriate light sources and controlling reaction parameters can finesse the critical factors involved in the process[9,10].

B. Photocatalytic Mechanisms

Intricate mechanisms underlie efficient and selective photodegradation processes used for dealing with biomedically-sourced organic compounds involving photo catalysts. It is necessary to familiarize oneself with these intricate processes as they help optimize photodegradation reactions based on functional responses by employing variables like temperature, surface area and catalyst concentration or activity levels etc[11].

This section investigates such elaborate sequential processes along with common applications as demonstrated through various types of often used photo catalysts available for practical implementation practice purposes[11].

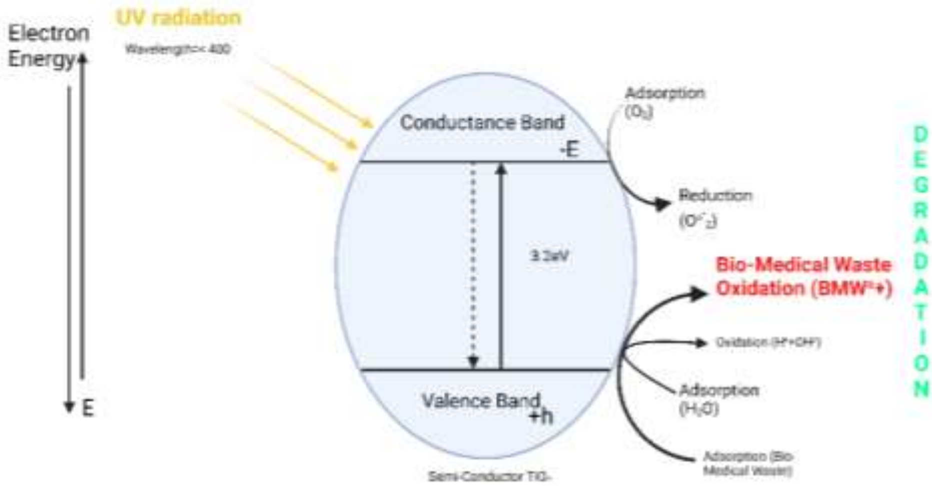

Figure 2 Photocatalysis mechanism

1. **Excitation of Electrons:** To achieve successful biomedical waste degradation photocatalysts with high performance like titanium dioxide (TiO2) zinc oxide (ZnO) along with metal sulphides including cadmium sulphide (CdS) and Zinc Sulphide (ZsS) are commonly utilized. Essentially[12]. These catalytic agents work by absorbing photons whose energies match or exceed their corresponding electron excitation levels known as "bandgap." As a result. Electrons in the valence band get activated to move to higher energy conduction canals. Leaving behind holes[12].
2. **Charge Separation:** Due to built-in potential within the photo catalyst material, excited electrons and holes remain apart spatially preventing their recombination[12]. This also allows better participation from these charged particles in subsequent redox reactions. For an enhanced photocatalytic efficiency, using metal ions like silver or copper for doping and depositing platinum or palladium for co-catalyst deposition is quite helpful[12].
3. **Adsorption of Target Molecules:** Organic molecules found in biomedical waste tend to cling onto photocatalyst materials. Amongst the many such molecules include pharmaceuticals, dyes, and a range of other organic pollutants. The surfaces of TiO2 assume these attachments creating a flawless scenario for immediate photocatalytic deterioration[11,12].
4. **Redox Reactions:** The excited electrons in the conduction band can transfer to the adsorbed organic compounds, leading to their oxidation. For instance, TiO2 photocatalysis can oxidize organic compounds by donating electrons to them, resulting in the degradation of complex organic molecules into simpler, less harmful substances[11,12].
5. **Reactive Oxygen Species (ROS) Generation:** The holes in the valence band can react with adsorbed water molecules or directly with the organic compounds, generating highly reactive oxygen species (ROS) such as hydroxyl radicals (•OH) or superoxide radicals (•O2^-). These ROS play a crucial role in the degradation of organic compounds through non-selective oxidation reactions. For example, the generation of hydroxyl radicals by TiO2 photocatalysis contributes to the efficient degradation of various organic pollutants[12,11].
6. **Migration and Reaction of Species:** The generated electrons, holes, and ROS migrate on the surface of the photocatalyst material and react with adsorbed organic compounds. This migration and reaction process occur within the photocatalyst material and at the interface with the adsorbed molecules[35]. Control of the surface properties and morphology of photocatalysts can enhance species migration and reaction kinetics, leading to improved photocatalytic performance[11.12].
7. **Byproduct Formation:** The photocatalytic degradation of organic compounds ultimately leads to the formation of simpler and less harmful byproducts, such as carbon dioxide (CO2), water (H2O), and inorganic salts. The complete mineralization of organic pollutants into harmless end products is one of the key advantages of photocatalysis[11,12].

Examples of photocatalysts, such as TiO2, ZnO, and metal sulphides have been extensively studied for biomedical waste degradation. These photocatalysts exhibit excellent stability, high photocatalytic activity, and low toxicity. Additionally, efforts are being made to develop novel photocatalyst materials and modify their properties to enhance their performance for specific biomedical waste degradation applications[11,12].

C. Photocatalytic Materials

When it comes to photocatalysis's efficacy and efficiency in degrading biological waste, photocatalytic materials are essential. Selecting appropriate photocatalytic materials is crucial for achieving maximum efficiency and concentrating on certain pollutants.

Table 1 Photocatalytic Materials for Biomedical Waste Degradation

Photocatalytic Material	Bandgap (eV)	Excitation Wavelength (nm)	Applications
Titanium Dioxide (TiO2)	3.0-3.2	380-400	Pharmaceutical waste degradation, pathogen inactivation, water treatment
Zinc Oxide (ZnO)	3.3-3.4	365-385	Hospital and laboratory waste treatment, sterilization of medical equipment
Cadmium Sulfide (CdS)	2.4-2.6	480-520	Pathogen inactivation, pharmaceutical waste degradation
Bismuth Vanadate (BiVO4)	2.4-2.5	490-520	water treatment, pharmaceutical waste degradation
Tungsten Oxide (WO3)	2.6-2.9	420-480	Pathogen inactivation, hospital, and laboratory waste treatment

1. **Titanium Dioxide (TiO2):** TiO2 is one of the primary compounds used as photocatalytic materials. It exhibits excellent photocatalytic activity, chemical stability, and low toxicity. TiO2 is capable of being synthesized in several forms, such as anatase, rutile, and mixed-phase configurations. It is particularly effective in degrading organic compounds and has been extensively employed in the degradation of pharmaceuticals, dyes, and other contaminants found in biomedical waste[12,13].
2. **Zinc Oxide (ZnO):** ZnO is a high efficiency degrader of organic compounds(pollutants). It possesses a wide bandgap, allowing it to absorb both UV and visible light, thus enabling photocatalytic reactions under solar irradiation. ZnO exhibits good photocatalytic activity and stability, making it suitable for biomedical waste treatment applications[12,13,14].
3. **Metal Sulfides (e.g., CdS, ZnS):** Metal sulfides have gained attention as photocatalytic materials due to their unique properties. They possess suitable energy band structures and bandgap values that enable light absorption in the visible range. Metal sulfides offer great potential for photocatalytic degradation of organic contaminants found in biomedical waste, including pharmaceuticals and dyes[12,13,14].
4. **Other Semiconductor Materials:** Besides TiO2, ZnO, and metal sulfides, other semiconductor materials such as tungsten oxide (WO3), bismuth vanadate (BiVO4), and g-C3N4 have also been explored for photocatalysis. These materials exhibit specific properties that can enhance photocatalytic performance, such as narrow bandgaps and efficient charge carrier separation[12,13,14].
5. **Nanomaterials:** Nanoscale photocatalytic materials, such as nanoparticles, nanorods, and nanotubes, offer unique advantages in terms of increased surface area, enhanced light absorption, and improved photocatalytic activity. Nanomaterials can be produced (synthesized) using different methods, including sol-gel, hydrothermal, and chemical vapor deposition methods, to achieve desired morphology and properties[14,15].

Various criteria, including the target pollutants, reaction circumstances, and desired degradation efficiency, must be taken into consideration when choosing appropriate photocatalytic materials. In order to improve their efficiency and broaden their uses in the degradation of biomedical waste, researchers are continually investigating and creating new photocatalytic materials and techniques.

D. Applications of Photocatalysis in Biomedical Waste Degradation

Photocatalysis has emerged as a promising technology for the degradation of biomedical waste due to its ability to efficiently break down a wide range of organic compounds. This subsection focuses on the applications of photocatalysis in biomedical waste degradation, highlighting its potential benefits and key areas of application[1,16].

Table 2 Applications of Photocatalysis in Biomedical Waste Management

Application	Description
Pharmaceutical waste degradation	Photocatalysis can effectively degrade various pharmaceutical compounds present in biomedical waste, minimizing their environmental impact.
Pathogen inactivation	Photocatalysis can help inactivate bacteria, viruses, and fungi present in biomedical waste, reducing the risk of infections and contamination.
Sterilization of medical equipment	Photocatalysis offers an environmentally friendly alternative for the sterilization of medical instruments and equipment, eliminating microbial contaminants.

Water treatment	Photocatalysis can be used to degrade organic pollutants in water contaminated by biomedical waste, ensuring the safety of water resources and protecting ecosystems.

1. **Pharmaceutical Waste Degradation:** The pharmaceutical industry generates a significant amount of waste containing various active pharmaceutical ingredients (APIs) and other organic compounds. Photocatalysis is an effective solution for the degradation of pharmaceutical waste because it can break down complex organic molecules and eliminate their environmental and health risks[1,16].
2. **Pathogen Inactivation:** Infectious pathogens such bacteria, viruses, and fungi are frequently found in biomedical waste and provide a serious danger to human health. By producing reactive oxygen species (ROS) that may degrade microbial structures and DNA, photocatalysis has shown to be capable of inactivating these pathogens and counteracting their detrimental effects[17].
3. **Sterilization of Medical Equipment:** Photocatalysis can also be utilized for the sterilization of medical equipment, such as surgical instruments, by effectively eliminating microbial contaminants. Harnessing and utilising the antimicrobial properties of photocatalytic materials can provide a reliable and environmentally friendly alternative to traditional disinfection methods[17,18].
4. **Water Treatment**: If biomedical waste is not handled correctly, it may include different organic substances that affect water sources. In order to ensure the security of water supplies and safeguard aquatic ecosystems, photocatalysis has been used in water treatment systems to destroy organic pollutants[1,17,18].

CONCLUSIONS

As a novel and long-term approach to biomedical waste degradation, photocatalysis is recommended for use in this review. Conventional disposal techniques frequently fall short, posing hazards to the environment and human health. With light-activated catalysts like zinc oxide and titanium dioxide, photocatalysis has remarkable transformational potential. Examining the basic ideas and classification of biological waste, This review emphasises the need for accurate and environmentally responsible disposal techniques. Photocatalysis breaks down complicated organic molecules into harmless byproducts with the help of electron excitation, charge separation, and the formation of reactive oxygen species. Important components such as zinc oxide and titanium dioxide demonstrate minimal toxicity and stability throughout the breakdown of biological waste. Photocatalysis has a wide range of uses, such as water treatment, medical equipment sterilisation, pathogen inactivation, and pharmaceutical waste degradation. The versatility of this technique in biological waste treatment is attributed to its selectivity and environmental friendliness. Continuous research and development might lead to cost-effective technologies for large-scale deployment and efficiency optimisation. In conclusion, photocatalysis shows promise as a flexible, sustainable, and adaptable solution to the problems associated with biomedical waste management. Its relevance in promoting an ethical and environmentally conscious healthcare sector is highlighted by its possible influence on the handling of medical waste.

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