CHAPTER I
INTRODUCTION

1. 1 Background

Environmental damage and pollution, along with the importance of preserving clean soil and water ecosystems, have become urgent global issues. Environmental pollution caused by pharmaceutical waste has been a global concern in recent decades (Ahmed et al. 2022; Oyekunle et al. 2025). Pollution by pharmaceutical waste resulting from the pharmaceutical sector, hospitals, and also the disposal of unused medications can lead to contamination of water and soil resources, which may then cause ecosystems and human health to be affected (Pandey et al. 2025). Pharmaceutical waste constitutes expired drugs and items that are no longer needed and/or are contaminated and/or contain contaminated molecules. Pharmaceutical waste carries the same characteristics that make it hazardous and chemical substances. However, they are the very substances that, when released into the environment, cause pollution (Sapkota and Pariatamby 2023).

The problem of pollution with pharmaceutical waste is directly related to some Sustainable Development Goals (SDGs). SDGs 3 (Good Health and Well-being) is a goal laid out in the SDGs which highlights the significance of climate change mitigation that is antibiotic resistance due to pharmaceutical pollution. SDGs 6 (Clean Water and Sanitation) is pertinent to the undertakings directed at preserving water quality by averting pharmaceutical waste from polluting it. Besides, SDGs 12 (Responsible Consumption and Production) also puts the focus more on sustainable pharmaceutical waste management, a major player whose influence revitalizes the environmental and human health.

Over the past few years, water pollution due to antibiotic residues in water bodies has been increasingly a cause for concern. Incompletely degraded antibiotics during wastewater treatment may infiltrate into aquatic environments, where they can induce antimicrobial resistance (AMR) that is detrimental to the environmental and human health (Kulik et al. 2023). As per the World Health Organization (WHO) report, AMR is now a worldwide menace to be tackled in earnest and could led to an even worse health emergency in the coming years. These antibiotic-resistant pathogens can spread within communities and healthcare facilities, undermining the effectiveness of modern medicine and increasing the risk of treatment failure, prolonged illness, and mortality. Vulnerable populations, such as children, the elderly, and immunocompromised individuals, are particularly at risk of suffering severe consequences from exposure to antibiotic-resistant bacteria. Furthermore, contaminated water sources used for irrigation can introduce antibiotic residues into crops, extending the pathway of human exposure beyond direct water consumption (De Oliveira et al. 2020).

Antibiotic residues in water affect the structure and function of microbial ecosystems. Solution antibiotics have an effect on microbial ecology in terms of increased mutation frequencies, the spread of antibiotic resistance genes, and the development of antibiotic-resistant bacteria (Kulik et al. 2023). Water pollution by antibiotic waste is not only harmful to aquatic ecosystem security but also results in water resource loss (Wei et al. 2020). There will be leftover antibiotics in the environment for an extended period since antibiotics have a non-biodegradable nature (Zeng et al. 2025).

Antibiotic contamination can enter the human body through various pathways. One major route is via the food chain, where antibiotics present in contaminated water or soil are taken up by plants or accumulate in aquatic organisms such as fish and shellfish. Humans consuming these food products may ingest residual antibiotics or antibiotic-resistant bacteria (Kim et al. 2022). Crops irrigated with polluted water or fertilized with animal manure that contains antibiotic residues can carry trace amounts of antibiotics into the human diet. In livestock farming, the overuse of antibiotics can lead to drug residues in meat, milk, and eggs, which further contributes to indirect human exposure through food consumption. These subtle and cumulative exposures can promote antimicrobial resistance, even in the absence of direct antibiotic use (He 2025).

The sources of antibiotic contamination are diverse. Major contributors include effluents from pharmaceutical manufacturing industries, discharges from hospitals and healthcare facilities, and the improper disposal of unused or expired medications by households (Cheng et al. 2024). Agricultural activities are also a significant source, particularly due to the widespread use of antibiotics in animal husbandry. Wastewater treatment plants, which often lack the capability to fully remove pharmaceutical compounds, play a crucial role in allowing these contaminants to persist and accumulate in surface and groundwater. This multifaceted and pervasive pollution requires an integrated and sustainable approach to mitigate its long-term impacts on both ecosystems and human health (B. Q. Wang et al. 2024).

The government of Indonesia reacted to environmental antibiotic pollution by issuing Presidential Regulation No. 7 of 2021 on the National Action Plan for Antimicrobial Resistance Control (RAN-PRA) 2025-2029. The regulation aims to strengthen the control of antibiotic use, minimize the discharge of antibiotic residues into the environment, and encourage research on wastewater treatment with antibiotics. In addition, there are regulations enacted by the Ministry of Health regarding the disposal of expired medicine, such as antibiotics, to prevent negative impacts on the environment and public health. The persistence of antibiotics and their resistance to degradation will result in some severe environmental issues, including severe water contamination and the emergence of drug resistance. Moreover, the occurrence of antibiotics in water induces the development of antibiotic-resistant bacteria, compromising human health and the efficiency of antibiotics (Wei et al. 2020). The risks posed by antibiotics have been identified by the European Directives 2015/495/EU and 2018/840/EU, in which it is advised to monitor the occurrence, distribution, and frequency of active substances and incorporate them into environmental risk assessments. They seek to enhance environmental monitoring of pharmaceutical wastewater and minimize its adverse effects on human health and the ecosystem (Brillas 2023).

Researchers are currently working on pharmaceutical wastewater treatment technologies based on the Advanced Oxidation Processes (AOPs) method (Hunge et al. 2022; Li et al. 2019; Shang et al. 2018; Yang et al. 2020). AOPs is an approach that is based on employing processes of oxidation reactions. One of the technologies that can be employed under the approach is photocatalysis. Photocatalysis is the selected technology as it is a green, inexpensive, proficient, and eco-friendly technology that has drawn significant attention from researchers. Solar energy conversion and utilization have also ranked photocatalysis among the most demanded subjects in the recent past (Bouarroudj et al. 2021; Kefeni and Mamba 2020; Malakootian et al. 2020; L. Wu et al. 2022; Zhu et al. 2020).

Bismuth-based materials, such as bismuth oxide (Bi_2O_3) is strong candidates due to their excellent photocatalytic activity in the degradation of organic compounds, water splitting, and nitric oxide (NO) reduction. (Zhou et al. 2019). Several previous research have also shown that bismuth oxide is capable of degrading pharmaceutical waste such as sulfamethoxazole, amoxicillin, paracetamol, tetracycline, and ciprofloxacin (Wei et al. 2020). Bi_2O_3 was shown to work optimally under visible light at a band gap of 2.58–2.85 eV (Y. Liu et al. 2022). Bi_2O_3 can be utilized in two useful forms: powder and thin films. Bi_2O_3 powder has been used extensively in photocatalysis because of its large specific surface area. The high surface area is the most significant parameter that establishes the effectiveness of the photocatalytic reaction. However, because of the highly fine nature of the powder, it becomes very challenging to reclaim and recycle the powder, and hence it becomes a contributor to pollution (Falsetti et al. 2021).

To address this issue, one of the solutions is immobilization as thin films. Thin films facilitate the recovery of the catalyst and reusable character of the material, making the material cost-effective and environmentally friendly (Camacho-López et al. 2022). The Bi_2O_3 performance is largely determined on the crystalline and phase structure. Bi_2O_3 photocatalytic activity has a strong dependence on the crystal structure and morphology of Bi_2O_3. Thus, the controlled synthesis of Bi_2O_3 through certain methods in photocatalysis is important. To utilize

Bi_2O_3 in photocatalytic reaction, one must choose the appropriate synthesis method. Metal atom doping of photocatalysis is a trendy way of achieving improved photocatalytic activity in recent times (Tolan et al. 2023). Metal doping is a means of modifying the electronic structure of photocatalyst materials. The incorporation of metals such as copper (Cu), iron (Fe), cobalt (Co), and zinc (Zn) can narrow reduce the band gap of semiconductor photocatalyst, resulting in wide light response and high photocatalytic activity (Zhou et al. 2019). The metal ions serve as trapping centre from the charge carriers produced in the photocatalytic process and thus suppress the recombination process. Hence, metal incorporation is yet another strategy for increasing photocatalytic activity (El-Kalliny et al. 2023).

In this study, Bi_2O_3 thin films are prepared by sol-gel method via spray coating technique. The sol-gel method is chosen because it is simple, requires minimal equipment, and is more cost-effective (Sahoo and Panigrahi 2022). Although a simple method, the sol-gel technique is capable of producing homogeneous thin films with a larger surface area (Ilsatoham et al. 2023).

Spray coating technique is a process where coating particles, as individual particles, are transported by the pressure of a pressurized gas onto a surface. These particles interact with the substrate, stick to it, and create a thin even coating. This spray coating method is a single-step process with the potential to deposit thin films with strong adhesion. There has been extensive research in the synthesize of thin films using the sol-gel spray coating method. Research has shown that temperature has a key influence on the determination of the thickness of the thin films. With the rising temperature, the rate of absorption of the thin film also rises, and the films becomes thicker. This affects the band gap value of the thin films produced (Indriyani et al. 2017). In order to find optimum condition of the thin film synthesis process, optimization was performed using Response Surface Methodology (RSM). RSM is also deemed a robust mathematical methodology in design modelling and optimization (El-Kalliny et al. 2023). Central Composite Design (CCD) is widely applied during the optimization process. CCD is used to find out the number of experiments to be performed in the study through the determination of the main points, star points, and centre points. This method is used since it is effective in establishing the effect of variables and their interaction on the response and is capable of plotting multidimensional and nonlinear graphs (Afshari et al. 2025)

This study will examine the efficiency of applying Bi_2O_3 -based photocatalyst technology that is modified with metals in order to degrade antibiotics. Optimization will be conducted to achieve the optimum material, such as temperature, metal concentration, and antibiotic concentration. The response chosen is the degradation efficiency of antibiotics and total organic carbon (TOC) removal efficiency. Apart from being used as a photocatalytic agent for antibiotic degradation, the metal-modified Bi_2O_3 photocatalyst will also be used as a degradation agent for pharmaceutical wastewater. Pharmaceutical industries have wastewater treatment plants (WWTPs) that are specially constructed to treat and handle the liquid waste of drug manufacturing. Pharmaceutical industry WWTPs has various treatments processes, and each one of them employs various treatment methods such as coagulation, anaerobic treatment, chemical treatment, aeration, and sedimentation.

Research into antibiotic treatment in Indonesia has become crucial at this point due to the fact that not only does it assist in the attainment of the National Action Plan, but also plays a significant role in attaining the SDGs target. The development of efficient wastewater treatment technology using bismuth oxide photocatalysts can offer a solution for reducing the adverse effect of antibiotic residues on the environment. Hence, this research is a strategic move toward a more sustainable pharmaceutical waste handling system, ecosystem protection, and Indonesia's compliance with safeguarding both environmental and public health.

1. 2 Problem Formulation

The increasing presence of antibiotic residues in the environment, particularly from pharmaceutical wastewater, has become a major global concern. Regular treatment plants struggle to pull out these stubborn drugs, so the pollution keeps building up and hurting fish, plants, and even the people who rely on them. The problem hits hardest in places like Indonesia, where checks on factory waste and clean-up gear are still pretty weak.

Researchers over the last ten years have zeroed in on Bi_2O_3 thin films as an answer; the material works well under visible light and its band gap seems spot-on for breaking down medicines. However, Bi_2O_3 still suffers from limited photocatalytic efficiency and fast recombination rates of charge carriers. To overcome these limitations, recent studies have explored the modification of Bi_2O_3using various metal dopants such as Cu, Zn, Co, and Fe to enhance photocatalytic activity. These metal-doped Bi_2O_3 thin films have shown improved performance in degrading a variety of antibiotics—such as amoxicillin, ciprofloxacin, tetracycline, doxycycline, and levofloxacin—under both UV and visible light. Additionally, researchers have begun to assess the toxicity of the resulting degradation products, which is essential for validating the environmental safety of the photocatalytic process.

To achieve optimal photocatalytic performance, it is important to carefully control synthesis parameters such as dopant concentration, annealing temperature, and antibiotic concentration. Response Surface Methodology (RSM) and Central Composite Design (CCD) have been successfully used for this purpose, allowing for efficient experimental design and performance optimization. Despite these advancements, there is still a lack of integration between laboratory-scale innovations and real-world applications, particularly for treating complex pharmaceutical wastewater matrices. Moreover, comprehensive studies that combine material synthesis, photocatalytic performance, optimization, and environmental safety assessment are still limited.

Therefore, the main problem formulation of this thesis is: How can metal-doped Bi_2O_3 thin films be optimized, characterized, and applied for efficient, safe, and sustainable degradation of antibiotics in real pharmaceutical wastewater systems, particularly within the context of environmental challenges and treatment practices in Indonesia?

1. 3 Originality

This research, entitled "Pharmaceutical Wastewater Treatment Using Bismuth Oxide-Based Photocatalytic Method," represents a novel investigation that has not been previously explored. It is distinct from existing studies in terms of its title, objectives, and methodology. This research aims to fill significant gaps by considering.

1. Real-world application: The inclusion of a case study from an Indonesian pharmaceutical WWTP provides valuable, context-specific insights into the problem about antibiotic pollution
2. Multi-metal doping strategies: The study explores the impact of various metal dopants (Co, Cu, Fe, Zn) on the photocatalytic properties of Bi_2O_3, extending the knowledge of how metal doping affects degradation efficiency and material stability. This is essential for tailoring photocatalysts for different antibiotics and real-world conditions.
3. Comprehensive approach to antibiotic removal: Through the use of advanced optimization techniques, such as RSM-CCD the research aims to not only optimize the material performance but also to fine-tune the photocatalytic degradation of specific antibiotics (amoxicillin, ciprofloxacin, doxycycline, etc.) under both UV and visible light. This makes it a comprehensive study, bridging laboratory experiments and real-world applications.
4. Long-term environmental and health implications: The research also emphasizes the long-term environmental impact of pharmaceutical wastewater and antibiotic resistance, which are critical issues in both environmental science and public health. The ability to address these concerns with an effective, sustainable photocatalytic process makes the research highly relevant to both scientific communities and industries.

The review of the research results is used to assess the originality of this study and serves as a reference for conducting research, as shown in Table 1.

Table 1.1. Originality of research based on previous research

No.	References	Material/Photocatalyst	Target Pollutant	Optimization Method	Limitations/Gaps	Novelty of Current Research
1.	Kutuzova et al. 2021	TiO_2 thin films	Sulfamethoxazole, trimethoprim, and ciprofloxacin.	Various parameter studies	Different material (TiO_2); No doping	Focus on Bi_2O_3 thin films with metal modification
2.	Lalliansanga et al. 2022	Ce^{3+}-doped TiO_2 thin films	Amoxicillin, and Tetracycline	Template method	TiO_2 material, limited antibiotics	Applies dopant strategy to Bi_2O_3; and broader antibiotic testing
3.	Liu et al. 2022	Bi_2WO_6/nano-ZnO composite	Amoxicillin	Not specified	Composite not Bi_2O_3-based	Focused on doped single-phase Bi_2O_3 thin films
4.	Liu et al. 2021	α- Bi_2O_3/g-C_3N_4 + H_2O_2	Doxycycline	External additive (H_2O_2)	Requires external agents	Enhances intrinsic photocatalytic properties through doping
5.	Zhang et al. 2023	$BiVO_4$/CO_3^{2-} Bi_2O_3 CO_3	Levofloxacin	Hydrothermal	Other bismuth-based material, and composite-based material	Bi_2O_3 thin films; no composites

No.	References	Material/Photocatalyst	Target Pollutant	Optimization Method	Limitations/Gaps	Novelty of Current Research
6.	Singh and Sharma 2023	Co-Mn-Gd-doped $BiFeO_3$	None (no degradation test)	Spin coating	No photocatalytic test	Direct antibiotic degradation test on real pollutants
7.	Falsetti et al. 2021	Bi_2O_3 thin films	Rhodamine B dye	Spin coating method for thin films deposition	Not antibiotics; No doping	Application to antibiotics; dopant modification
8.	Utami et al. 2022	Fe-doped Bi_2O_3 powder	Amoxicillin	Variation of Fe concentration	Focus only Fe and powder form	Uses thin films with various metal modified (Co, Cu, Fe, and Zn); Various antibiotics
9.	El-Kalliny et al. 2023	Co-doped Bi_2O_3 thin film	Ofloxacin	RSM (Box-Behnken)	Single dopant, limited method (BBD)	Uses CCD with full modelling; multiple dopants; more antibiotics
10.	Sa'adah et al. 2022	Cu-doped Bi_2O_3 powder	Tetracycline	CCD-RSM optimization; synthesize using precipitation-assisted microwave	Only Cu doping; Limited synthesis method	Broader dopants; thin films form; and extended antibiotic range

1. 4 Research Purpose

This research aims to explore the potential of Bi_2O_3 thin films as an effective photocatalysts for antibiotic degradation, with a particular focus on their application in real-world pharmaceutical wastewater treatment. The research purpose is driven by six key topics:

1. Evaluate the effluent quality of a pharmaceutical company's wastewater treatment plant (WWTP) in Semarang, Central Java
2. Provides a bibliometric analysis of the research trends on the application of Bi_2O_3 thin films for antibiotic degradation from 2013 to 2023
3. Analyzing the efficiency of Co-doped Bi_2O_3 for the removal of antibiotics (amoxicillin, ciprofloxacin, and tetracycline)
4. Analyzing the efficiency of Immobilization of Copper-Doped Bi_2O_3 thin films for Levofloxacin Degradation
5. Evaluating the effect of various metal modifications (Co, Cu, Fe, and Zn) on the photocatalytic performance and toxicity of Bi_2O_3 thin films in the degradation of doxycycline.
6. Optimize the operating parameter of Zn-incorporated α- Bi_2O_3 thin films for amoxicillin degradation and real pharmaceutical wastewater application

By addressing these topics, the research aims to optimize the photocatalytic properties of Bi_2O_3-based materials for efficient antibiotic degradation, providing sustainable and eco-friendly solutions for wastewater treatment in the pharmaceutical industry.

1. 5 Benefit

The benefits of this research are as follows:

1. Scientific Benefit:

This study will advance the understanding of Bi_2O_3 thin films in photocatalytic degradation, providing crucial insights into their potential applications for antibiotic removal. It will also contribute to the identification of knowledge gaps, fostering future innovations in photocatalytic materials and wastewater treatment technologies.

2. Benefit to Institutions

Research institutions and universities will benefit by gaining valuable data on the optimization of Bi_2O_3-based materials for antibiotic degradation. This research may also open new avenues for further studies, strengthening academic knowledge in materials science, environmental engineering, and waste management.

3. Benefit to Government

The findings will support governmental efforts to regulate pharmaceutical wastewater management and antibiotic resistance by providing sustainable and effective technologies for addressing environmental pollution. It will also assist in achieving sustainable development goals (SDGs) related to clean water, sanitation, and public health.

4. Benefit to Practitioners

For industries, particularly in the pharmaceutical sector, this research offers practical solutions for improving wastewater treatment systems. It will provide evidence-based recommendations on the use of Bi_2O_3 thin films as an efficient, eco-friendly method for reducing pharmaceutical waste and mitigating environmental harm, helping industries comply with environmental regulations while improving their sustainability practices.

1. 6 Synthesis

Synthesis explains the relationship of the chapter. This study examines the use of Bi_2O_3 thin films for degrading antibiotics, linking bibliometric trends with materials science and practical applications. The first chapter of this study explains the background of the research. This chapter contains the research background, problem formulation and the basis for this thesis research. Chapter II explains the literature review related in this research. In this chapter focuses on the understanding of antibiotic contamination in the environment, including its sources, pathways of exposure, and impacts on both ecosystems and human health. It explains how antibiotics can enter the environment through various routes such as pharmaceutical industry effluents, which related with the study conducted in chapter III.

Chapter III presents a case study on antibiotic pollution from pharmaceutical WWTPs in Semarang, Central Java. This chapter aims to assess the presence and persistence of antibiotics in wastewater effluents and identifies current limitations in existing treatment technologies. The findings establish the necessity for developing advanced treatment methods that are both effective and environmentally sustainable, thus providing the practical context and justification for the subsequent studies. Based on bibliometric study from 2013 to 2023, treatment technology for antibiotic degradation. It can be overcome by using Bi_2O_3 photocatalyst material, more fully presented in chapter IV. This chapter evaluates the global research landscape concerning the use of Bi_2O_3 thin films for antibiotic degradation, which was tested in chapter V.

Chapter V focuses on the efficiency of antibiotic removal using copper-doped Bi_2O_3 synthesized via a precipitation-assisted microwave method. This study investigates the degradation performance against three common antibiotics (AMX, CIP, and TC) in aqueous media. The aim is to determine the photocatalytic efficiency of the developed material under controlled conditions. However, the weakness of the research in this chapter is the use of Bi_2O_3 material that cannot be used repeatedly, so it is necessary to modify it in the form of a thin layer, as tested in Chapter VI. This modification could enhance its durability and efficiency, potentially making it more suitable for various applications. Future studies should focus on optimizing the thin films properties to improve performance and longevity, by modification of thin film using various metal (Co, Cu, Fe, and Zn).

Chapter VII expands the scope by evaluating metal-modified Bi_2O_3 thin films through the incorporation of Co, Cu, Fe, and Zn. This chapter addresses how various dopants influence both the degradation performance and the environmental toxicity of the photocatalyst, providing insights into the design of more effective and safer photocatalytic materials. To optimize the operating parameters of antibiotic degradation treatment, chapter VIII uses CCD-RSM. The aim is to maximize photocatalytic degradation of amoxicillin under visible light conditions, with experimental validation using actual pharmaceutical wastewater samples. Chapter IX complete this research by explain conclusion and future perspective of this research. Overall, the research components presented across these chapters are systematically interlinked, as see in figure 1.1.

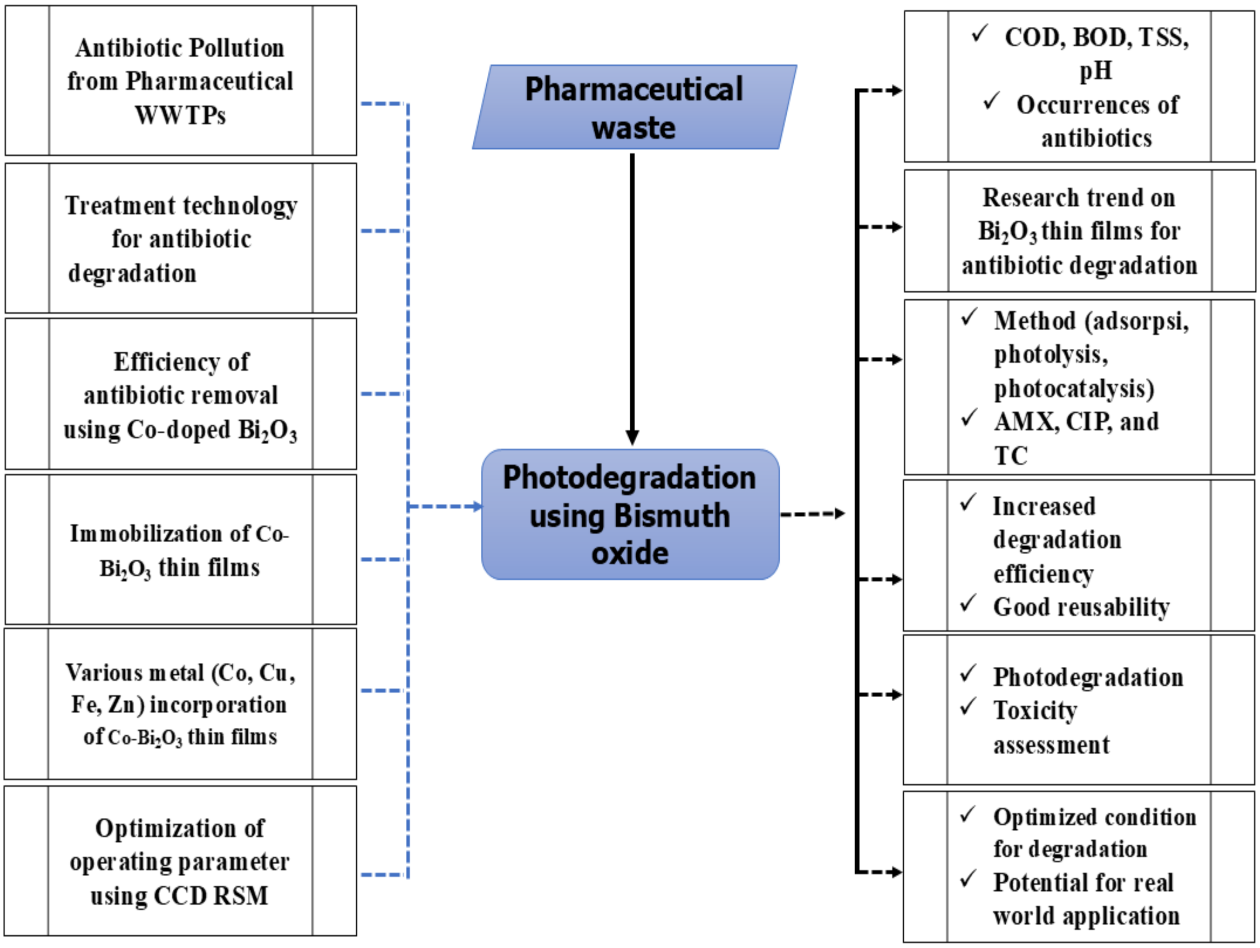

Figure 1.1 The research diagram illustrates study variables and outputs.

The thesis progresses from identifying real-world problems and reviewing global research trends to experimentally developing, characterizing, and optimizing novel photocatalytic materials. This integrated approach not only addresses a significant environmental issue but also contributes to the advancement of material science and sustainable wastewater management practices. A key sustainability aspect of this research lies in its ability to remove toxic pharmaceutical pollutants, particularly antibiotics from wastewater, which are often inadequately treated by conventional methods and pose significant risks to the environment and public health. This aligns with environmental management principles by minimizing pollutant loads before discharge, thus reducing ecological contamination and supporting better water quality management practices.

Bi_2O_3 thin films offer a visible-light photocatalytic treatment that is both energy-efficient and easy to reuse, producing only small amounts of secondary waste. When metal ions are added, the same films work faster and become more selective toward different pollutants. Tests with actual pharmaceutical wastewater show that the system performs well outside the lab. Meanwhile, response-surface methodology in a CCD streamlined the synthesis, cutting down on chemicals and time. These combined advances strengthen the case for greener technology while supporting several United Nations Sustainable Development Goals.

In supporting the United Nations Sustainable Development Goals (SDGs), this research contributes to Goal 6 (Clean Water and Sanitation) by enhancing wastewater treatment technologies, Goal 3 (Good Health and Well-being) by reducing antibiotic pollution and its impact on antimicrobial resistance, and Goal 12 (Responsible Consumption and Production) through the development of low-waste, energy-efficient materials. Furthermore, the environmentally friendly synthesis approach aligns with Goal 13 (Climate Action) by minimizing chemical usage and energy demand.

1. 7 Research Framework

The research adopts a comprehensive and structured framework to address the issue of pharmaceutical wastewater pollution, specifically focusing on antibiotic residues and the development of Bi_2O_3-based photocatalysts. The methodology integrates field observations, materials synthesis, characterization, laboratory experiments, optimization modelling, and real-wastewater application, as illustrated in the flowchart below (figure 1.2).

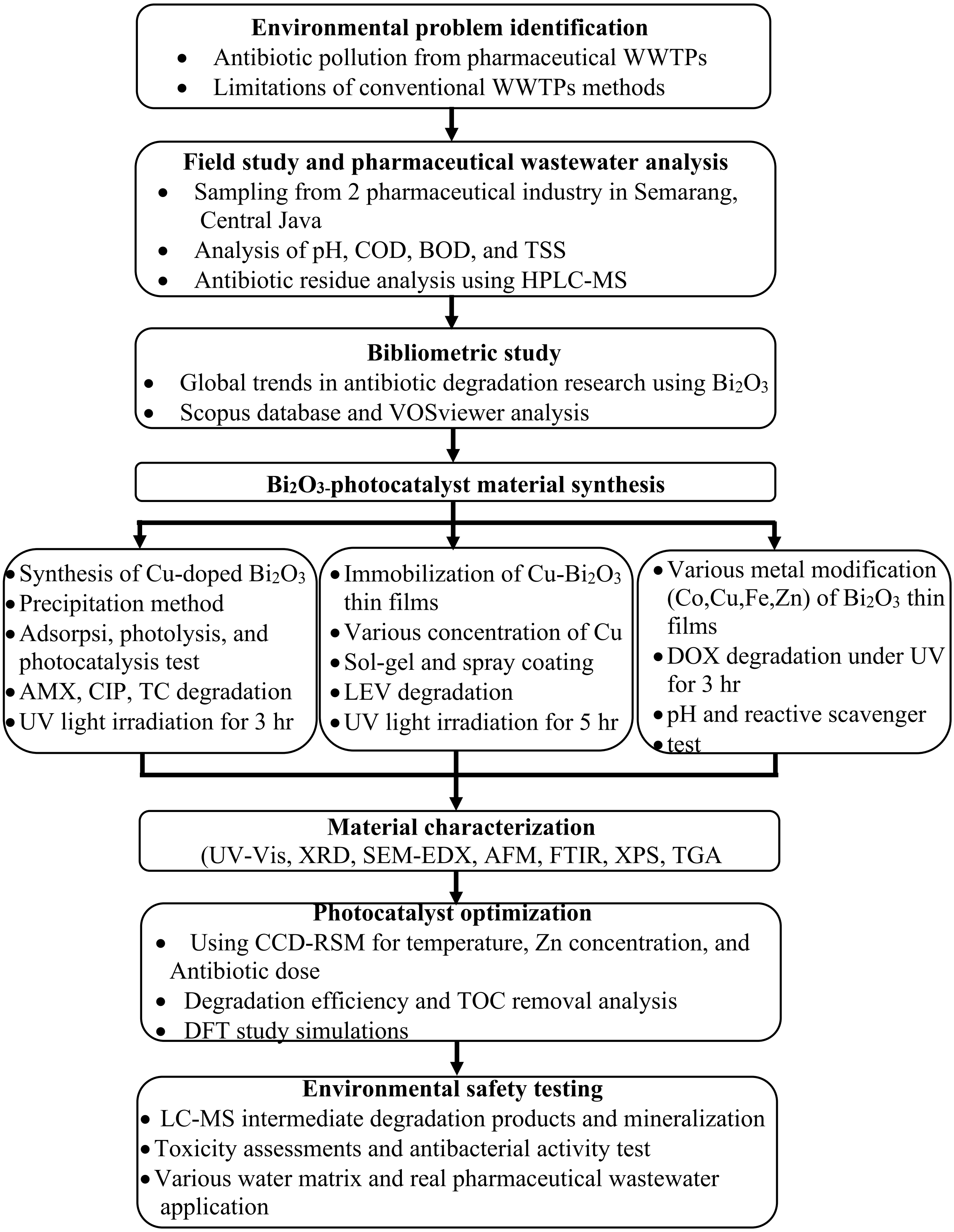

Figure 1.2 Research framework of this study

The research begins with the identification of environmental problems, specifically the persistence of antibiotic residues that are not effectively removed by conventional WWTPs. This limitation poses serious risks to ecosystems and public health. To ground the research in actual environmental conditions, field studies were conducted in two pharmaceutical industries located in Semarang, Central Java. Wastewater samples were collected and analyzed for physicochemical parameters such as pH, COD, BOD, and TSS. Also, the number of antibiotic leftovers, like AMX, CIP, OTC, DOX, and CEF, was measured using HPLC. These results confirmed the presence of significant antibiotic contamination and demonstrated the inadequacy of current treatment systems.

A study was then done using articles from Scopus published between 2013 and 2023 to look at global research trends in using Bi_2O_3 thin films to break down antibiotics. The bibliometric results validated the relevance and growing interest in Bi_2O_3-based photocatalytic materials within the scientific community. Following this, the research moved to the synthesis phase, where two types of photocatalyst materials were developed. First, Cu-doped Bi_2O_3 powder was synthesized using a precipitation-assisted microwave method. Second, a set of immobilizations using thin films made of Cu- Bi_2O_3 by sol-gel and spray coating method. Immobilization with thin films make material have good durability. To explore the effect of metal modification on Bi_2O_3 structure, various metal incorporation (Co, Cu, Fe, and Zn) was synthesized with the same metal concentration. The best materials were selected based on their potential to improve visible-light photocatalytic activity and enhance degradation performance.

The synthesized materials were then characterized using a combination of analytical techniques. X-ray diffraction (XRD) helped us understand the crystal structure and quality, while scanning electron microscopy (SEM)-energy dispersive X-ray spectroscopy (EDX), and atomic force microscopy (AFM) were used to look at the surface details and the elements present. Other tests included UV-Vis to measure band gaps, Fourier transform infrared spectroscopy (FTIR), X-ray photoelectron spectroscopy (XPS), and thermogravimetric analysis (TGA).

The ability of the prepared materials to break down different antibiotics was tested using UV and visible light. Degradation kinetics were evaluated using both pseudo-first-order and pseudo-second-order models. To identify the optimum photocatalytic conditions, CCD-RSM was employed. This approach allowed the investigation of the effects of different variables, such as synthesis temperature, metal dopant concentration, and antibiotic dosage, on the degradation and total organic carbon (TOC) removal efficiency. Once optimized, the best-performing Zn–Bi_2O_3 thin film was applied to actual pharmaceutical wastewater samples. The photocatalytic process was tested for its ability to reduce BOD, COD, and TSS levels. The application demonstrated that the material could function effectively under real environmental conditions.

To ensure environmental safety, toxicity assessments were conducted. LCMS was used to find byproducts created during the breakdown process, and possible breakdown routes were suggested. Environmental safety was also checked with the T.E.S.T. software, which estimated harmful effects like LC_{50} values, mutagenicity, and developmental toxicity. Additional antibacterial tests using *Escherichia coli* and *Staphylococcus aureus* were performed to confirm whether the treated wastewater retained any residual antibacterial activity. The research presents a practical and scientific advancement for pharmaceutical wastewater treatment, bridging the gap between laboratory innovation and industrial application in Indonesia.