NANOCOMPOSITE OF BISMUTH FERRITE AND ACTIVATED CARBON FOR PHOTOCATALYTIC DISINFECTION OF MICROBE

NUR ATIQAH BINTI DAUB

A thesis submitted in fulfilment of the
requirements for the award of the degree of
Master of Philosophy

School of Chemical and Energy Engineering
Faculty of Engineering
Universiti Teknologi Malaysia

AUGUST 2022

DEDICATION

This thesis is dedicated to my beloved mom and dad, Zaiton binti Suhut and Daub bin Hashim who taught me that the best kind of knowledge to have is that which is learned for its own sake. I also dedicated this thesis to my siblings who always give me an endless encouragement. Last but not least, this thesis is dedicated to my supportive friends, Eiza Fareeza and Nurul Syazwani for always offering me an emotional support and genuine reassurance. May this thesis be an inspiration and guidance in future.

ACKNOWLEDGEMENT

First and foremost, all glory and praise is to ALLAH, The Almighty, whose Mercy and countless blessings enabled me to complete my research successfully. In preparing this thesis, I was in contact with many people, researchers, academicians, and practitioners. They have contributed towards my understanding and thoughts in this research. I am eternally grateful and wish to express my sincere appreciation to my main supervisor, Dr Farhana Aziz, for providing me invaluable advice, encouragement, guidance, critics, and friendship throughout this process. I am also very thankful to my co-supervisor, Dr Nor Azimah Mohd Zain for her guidance, advices and motivation. Without her continued support and interest, this thesis would not have been the same as presented here.

My sincere appreciation also extends to all my fellow colleagues in AMTEC and Environmental Engineering Lab III who have aided at various occasions. Their views and tips are very useful indeed. In addition to that, I would also like to extend my gratitude to AMTEC and School of Chemical and Energy Engineering staffs for all their helps and guidance throughout my master study. Unfortunately, it is not possible to list all of them in this limited space. I am also grateful to all my family members especially my parents who has pushed me towards my decision in getting into postgraduate study and my siblings who has supported me in every decision I made.

ABSTRACT

Microbial pathogenic contaminants such as bacteria, viruses and protozoa pose a major threat to environment human health that can cause deadly infectious diseases. One promising way of disinfection activity is by photocatalysis. Bismuth ferrite (BFO) has been regarded as an efficient visible-light driven material for photocatalyst due to its narrow band gap value. However, rapid recombination of photogenerated electron (e^-) – hole (h^+) pairs has limits its application as photocatalyst. To overcome this, BFO-activated carbon nanocomposites (BFO-AC) was synthesized by ultrasonication method with various ratio of activated carbon. Characterization using X-Ray diffraction analysis showed no change in crystallinity of BFO nanoparticles when activated carbon was incorporated into nanoparticles. By using the UV-Vis diffuse reflactance spectroscopy (UVDRS), the emission band of all BFO and BFO-AC nanocomposites were found within visible light range (400-700 nm) and BA (1:1.5) was having the lowest band gap value of 1.86 eV. Interestingly, after the addition of AC, the Brunauer–Emmett–Teller (BET) surface area of BA (1:0.5), BA (1:1) and BA (1:1.5) dramatically increased ie., 267.51 m^2/g, 351.82 m^2/g and 862.99 m^2/g, respectively. BET results indicate BA (1:1.5) has the highest surface area due to its porous property. The field emission scanning electron micrograph has shown that BA (1:1.5) possess a better distribution and less agglomeration. The photoluminescence analysis demonstrated the intensity of all BFO-AC nanocomposites decreases compared to pristine BFO. The decrease of photoluminescence indicate the lower rate of electron (e^-) – hole (h^+) pairs recombination. Photocatalytic disinfection of *S.aureus* by AC, BFO, BA (1:0.5) and BA (1:1) were obtained within 150 min, 120 min, 120 min and 90 min, respectively. BA (1:1.5) exhibited the strongest bactericidal activity as a complete inactivation of *S.aureus* was achieved within 60 min. The surface and morphology of *S.aureus* were characterized by transmission electron microscopy analysis. Bacterial cell had a smooth and spherical shape before being irradiated under visible light. However, the bacterial cell were severely damaged and ruptured as the irradiation time increased, implying that *S.aureus* was killed. It is herein worth noting that the incorporation of AC onto BFO significantly improved the performance of photocatalytic disinfection of *S.aureus* under visible-light irradiation.

ABSTRAK

Bahan cemar patogen mikrob seperti bakteria, virus dan protozoa menimbulkan ancaman besar terhadap isu alam sekitar serta mengancam kesihatan manusia kerana ianya boleh menyebabkan penyakit yang membawa maut. Salah satu cara yang boleh menjanjikan pembasmian kuman adalah dengan fotomangkin. Bismuth ferrite (BFO) telah dianggap sebagai bahan fotomangkin di pacu cahaya tampak yang berkesan kerana mempunyai nilai jalurnya yang kecil. Walaubagaimanapun, penggabungan semula pasangan lubang elektron yang pantas menghadkan penggunaannya sebagai fotomangkin. Untuk menangani permasalahan ini, nanokomposit BFO-karbon teraktif (BFO-AC) telah disintesis melalui kaedah ultrasonik dengan nilai nisbah karbon teraktif yang berbeza. Pencirian menggunakan analisis pembelauan sinar-X menunjukkan tiada perubahan dalam kehabluran nanopartikel BFO apabila karbon teraktif dimasukkan ke dalam nanopartikel. Dengan menggunakan spektroskopi pemantulan resap UV-Vis (UVDRS) jalur pancaran semua nanokomposit BFO-AC dan BFO berada dalam julat cahaya nampak (400-700 nm) dan BA (1:1.5) mempunyai nilai jurang jalur paling rendah iaitu 1.86 eV. Menariknya, selepas penambahan AC, luas permukaan Branauer-Emmett-Teller (BET) BA (1:0.5), BA (1:1) dan BA (1:1.5) masing-masing meningkat setiap satunya adalah 267.51 m^2/g, 351.82 m^2/g dan 862.99 m^2/g. Analisis BET menunjukkan BA (1:1.5) mempunyai luas permukaan paling tinggi disebabkan oleh sifat berliang. Analisis mikroskopik elektron pengimbasan pelepasan medan menunjukkan bahawa BA (1:1.5) mempunyai taburan yang lebih baik dan kurang penggumpalan. Analisis foto pendarcahaya menunjukkan keamatan bagi semua BFO-AC nanokomposit berkurangan berbanding dengan BFO. Pengurangan foto pendarcahaya menunjukkan penggabungan pasangan lubang elektron dengan kadar yang lebih rendah. Pembasmian kuman fotopemangkin *S.aureus* oleh AC, BFO, BA (1:0.5) dan BA (1:1) masing-masing diperoleh dalam masa 150 min, 120 min, 120 min dan 90 min. BA (1:1.5) menunjukkan penyahaktifan bakteria yang paling tinggi dalam masa 60 min. Permukaan dan morfologi *S.aureus* dicirikan melalui analisis mikroskopi elektron transmisi. Sel bakteria berbentuk sfera dan mempunyai permukaan yang licin sebelum disinari dibawah cahaya tampak. Walaubagaimanapun, sel bakteria pecah dan rosak apabila masa sinaran meningkat dan ini membuktikan bahawa *S.aurues* telah dimatikan. Secara ringkas, penggabungan AC kepada BFO telah menunjukkan peningkatan prestasi pembasmian fotopemangkin kuman *S.aureus* di bawah penyinaran cahaya tampak.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

AOPs	-	Advanced Oxidation Process
BET	-	Brunauer–Emmett–Teller
BFO	-	Bismuth Ferrite
BFO-AC	-	Bismuth Ferrite-Activated Carbon
BJH	-	Barrett–Joyner–Halenda
DI	-	Deionized Water
FESEM	-	Fourier Electron-Scanning Electron Microscope
FTIR	-	Fourier Transform Infrared
IUPAC	-	International Union of Pure and Applied Chemistry
PL	-	Photoluminescence
ROS	-	Reactive Oxygen Species
TiO_2	-	Titanium Dioxide
TEM	-	Transmission Electron Microscopy
TOC	-	Total Organic Carbon
UV	-	Ultraviolet
UVDRS	-	Ultraviolet-Diffuse Reflection Spectra
WHO	-	World Health Organization
XRD	-	X-ray powder diffraction

LIST OF SYMBOLS

CFUL/mL	-	Colony Forming Unit/ mililitre
h	-	Hour
Mg	-	Miligram
L	-	Litre
°C	-	Degree Celcius
µm	-	Nanometre
g	-	Gram
%	-	Percentage
M	-	Molarity
Min	-	Minutes

CHAPTER 1

INTRODUCTION

1.1 Research Background

Water is the most essential and fundamental to human population across the world. Human beings need water for drinking, cooking, washing, irrigated agricultural and other socioeconomic activities. Only about 1% of water is consumable for human consumption (Anjum *et al.,* 2019). With the increasing population growth rate, the world's population is expected to reach over 9 billion people by the year 2050. Microbial contamination includes bacteria, viruses, and parasites in water has become significantly cause a great threat to human and other lives in developed and developing countries. According to the World Health Organization (WHO), severe lack of cleanliness and inadequate knowledge of sanitation cause 80% of disease in humans across the world (Punia *et al.,* 2021). Concerns related to water safety plays an important role in sustaining life. Contaminated water sources contain pathogenic microorganisms which lead to various of serious diseases such as diarrhea, cholera, typhoid, polio and dysentery (Pandey *et al.,* 2014). More than 3.5 million people die each year due to waterborne diseases. The treatment of contaminated water can reduce these concerns to provide safe and readily available water (Pinki *et al.,* 2021).

Different methods have subsequently been investigated to improve the efficiency of treating microbially contaminated water. Despite many conventional water disinfection techniques such as cholorination, ozonation, UV irradiation, these application are still limited to the removal of microorganisms. In a way to efficiently remove microbial, this research has been focus on photocatalysis, a green solution technology that possess a vital role for antimicrobial disinfection application by generating reactive oxygen species (ROS) which are responsible for damaging the cell components of bacteria in the presence of light (Ganguly *et al.,* 2018).

The discovery of water splitting experiment was reported by Fujishima and Honda, (1972) by using titanium dioxide (TiO_2) photocatalyst in the presence of solar light. This pioneered research led to developing numerous photocatalyst for degradation of various contaminants. Further, Matsunaga *et al.* (1985) studied the photocatalytic disinfection of *Escherichia coli* (*E.coli*), *Saccharomyces Cerevisiae* and *Lactobacillus Acidophilus* using TiO_2 under UV light. Following this, a lot of studied have investigated photocatalytic disinfection by various photocatalyst including graphitic carbon nitride- silver bromide (g-C_3N_4-AgBr), iron-dope bismuth vanadate (Fe-doped $BiVO_4$), molybdenum disulfide (MoS_2) and tungsten disulfide (WS_2) nanoparticles, carbon supported vanadium tetrasulfide (VS_4/CP), cadmium sulfide (Cds), copper-titanium dioxide (Cu-TiO_2) nanofibers and lead-bismuth ferrite/reduced graphene oxide (Pb-$BiFeO_3$/rGO). However, according to Kumar *et al*. (2021), there are still very few study on bismuth based photocatalytic disinfection activity. To harness solar light, bismuth ferrite (BFO) has been regarded as one of the promising photocatalyst due to their low band gap value (~2.2eV) and possessed magnetic properties. Howbeit, the application of BFO alone was practically restricted by rapid recombination of photo-generated electron – hole ($e^- - h^+$) pairs (Li *et al.,* 2019). An attempt needs to be made in order to circumvent this limitation. Thereupon, the modification of BFO needs to be emphasized to enhance photocatalytic performance of visible light-responsive photocatalysts.

Photocatalyst combine with carbonaceous material have been attempted to surmount these shortfalls in photocatalytic performance (Yahya *et al.*, 2018). The application of carbonaceous material such as activated carbons (AC) to support photocatalyst has been widely applied by researchers to improve photocatalytic efficiencies. According to Saravanan *et al.* (2021) nanocomposite photocatalyst which comprise of metals or metal oxides have been showing excellent photocatalytic performance. Activated carbon has a remarkable properties including high adsorption capacity, large surface area, microporous structure, high thermal stability and environmental applications (Alhan *et al.,* 2019). AC greatly promote the separation of photo-induced $e^- - h^+$ pairs and improve the activity of photocatalysis (Chen *et al.,* 2017). Various studies have shown interesting characteristics upon integration of adsorbent with photocatalyst thus, improving the overall photocatalytic efficiency (Yahya *et al.,* 2019).

1.2 Problem Statement

The most widely studied photocatalyst, TiO_2 are facing crucial problems, wide band gap (3.2-3.35 eV) that limits the utilization of visible-light and resulted in low quantum efficiency (Gamage and Zhang, 2010). Thus, BFO is the potential candidate as the photocatalyst due to their intrinsic properties such as low band gap (~2.5 eV) compared to commercial TiO_2. Moreover, it also has an outstanding properties as a photocatalyst due to its non-toxic nature, excellent chemical stability, low cost, magnetic properties, efficient response to visible light irradiation and have been proved to have a good antimicrobial properties. This photocatalyst shows a comprehensive properties compare to other materials. Despite these promissory findings, there are some limitation of BFO that needs an improvement in which designing of more efficient nanostructures including fast recombination of photogenarated $(e^- - h^+)$ pairs. Separation of photogenerated $(e^- - h^+)$ pairs subsequently influence the performance of photocatalytic activity (Wei *et al.,* 2017). In order to further improve the practical applications of BFO photocatalyst in photocatalytic activity, the modification on BFO needs to be emphasized to enhance the properties of BFO.

The synergistic effects between AC and semiconductor significantly influence the photocatalytic activity (Li *et al.*, 2019). Incorporation of AC remarkably prevent the $(e^- - h^+)$ pairs recombination in photocatalytic activity (Ramya *et al.,* 2018). AC have an outstanding potential as adsorbent due to its fascinating properties such as microporous structure, large surface area and high adsorption capacity (Yahya *et al.,* 2018). Moreover, due to its good biocompatibility, AC can remove microorganisms which can play a part in water treatment (Devi, Mohanta and Ahmaruzzaman, 2019). Yamamoto, Sawai and Sasamoto (2002) also reported AC has an excellent affinity to microorganisms and adsorbed large amount of bacteria. These intriguing properties of AC increase its use as a stable supporting material for the synthesis of BFO.

An efficient bacterial inactivation often entails the interruption or complete destruction of their physiological functions including cell membrane (Zhang *et al.*, 2018). The cell membrane appears to be an important first target by ROS species in disinfection activity leading to the loss of membrane permeability. The destruction of bacterial cell membrane during photocatalytic disinfection subsequently result in the releasing of intracellular components (Zhang *et al.*, 2019). Hence, the changes of microbial morphology to further validate the efficiency of bacterial inactivation.

1.3 Research Objectives

The aim of this study is to synthesis BFO: AC nanocomposites for adsorption and photocatalytic microbial disinfection present in water under visible-light irradiation. In order to achieve that, there are three specific objectives in this study, which are:

i. To assess the effects of activated carbon (AC) ratio incorporated onto BFO via ultrasonication method on physicochemical properties of the synthesized BFO-AC nanocomposites.

ii. To identify the effects of irradiation time and BFO-AC ratio on antimicrobial activity of BFO-AC nanocomposites on Gram-positive bacteria (*Staphylococcus aureus*).

iii. To establish the disinfection mechanism on a subcellular level via systematic analysis focusing on cell morphology.

1.4 Scope of Study

i. Synthesizing pure BFO using sol-gel auto combustion method with calcination temperature at 500°C for 3 h.

ii. Synthesizing BFO-activated carbon (BFO-AC) with different activated carbon ratio using ultrasonication method for 3 h.

iii. Characterization of physicochemical properties of the synthesized pure BFO and BFO: AC nanocomposites by using several characterizations such as X-ray diffractometer (XRD), UV-Vis diffuse reflectance spectroscopy (UVDRS) analysis, Brunauer-Emmet-Teller (BET), Fourier Transform Infrared Spectroscopy (FTIR), field emission scanning electron microscopy (FESEM) and photoluminescence analysis (PL).

iv. Performing photocatalytic disinfection study of *S.aureus* with 1 mg catalyst loadings at pH 7 under visible light irradiation. Initial bacterial concentration is 3 $\times 10^6$ CFU/ml.

v. Evaluation of bacterial cell death by Transmission Electron Microscopy (TEM) analysis.

1.5 Significance of Study

Photocatalysis, is an effective method to oxidize many organic contaminants at ambient conditions. Thus, researches on synthesizing visible-light driven photocatalyst that are easy to be produced and large scalable nanoparticles with desired properties are the main priorities. In this study, the synthesized BFO photocatalyst was prepared via sol-gel auto combustion and activated carbon was incorporated onto BFO via ultrasonication method. Activated carbon was considered as better adsorbents due to its large surface area, microporous structure as well as reduce the recombination rate of charge carriers ($e^- - h^+$) pairs. Additionally, varying different weight ratios of activated carbon onto BFO was proved to significantly enhance the efficiency of photocatalytic activity. In fact, this study shows the bacterial cell wall was severely damaged upon irradiation of visible light at different time intervals. The synthesized BFO-AC nanocomposites led to significant improvement in photocatalytic disinfection of *S.aureus* under visible light irradiation. The utilization of activated carbon supported semiconductor provides as an effective alternative in photocatalytic disinfection activity.

REFERENCES

A, M., J, M., Ashokkumar, M., & Arunachalam, P. (2018). A review on BiVO 4 photocatalyst: Activity enhancement methods for solar photocatalytic applications. *Applied Catalysis A: General, 555*, 47-74. doi:10.1016/j.apcata.2018.02.010

Albero, J., Mateo, D., & Garcia, H. (2019). Graphene-Based Materials as Efficient Photocatalysts for Water Splitting. *Molecules, 24*(5). doi:10.3390/molecules24050906

Alhan, S., Nehra, M., Dilbaghi, N., Singhal, N. K., Kim, K. H., & Kumar, S. (2019). Potential use of ZnO@activated carbon nanocomposites for the adsorptive removal of Cd(2+) ions in aqueous solutions. *Environ Res, 173*, 411-418. doi:10.1016/j.envres.2019.03.061

Anjum, M., Miandad, R., Waqas, M., Gehany, F., & Barakat, M. A. (2019). Remediation of wastewater using various nano-materials. *Arabian Journal of Chemistry, 12*(8), 4897-4919. doi:10.1016/j.arabjc.2016.10.004

Bajpai, O. P., Mandal, S., Ananthakrishnan, R., Mandal, P., Khastgir, D., & Chattopadhyay, S. (2018). Structural features, magnetic properties and photocatalytic activity of bismuth ferrite nanoparticles grafted on graphene nanosheets. *New Journal of Chemistry, 42*(13), 10712-10723. doi:10.1039/c8nj02030b

Basith, M. A., Yesmin, N., & Hossain, R. (2018). Low temperature synthesis of BiFeO3 nanoparticles with enhanced magnetization and promising photocatalytic performance in dye degradation and hydrogen evolution. *RSC Advances, 8*(52), 29613-29627. doi:10.1039/c8ra04599b

Begum, S., & Ahmaruzzaman, M. (2018). Biogenic synthesis of SnO2/activated carbon nanocomposite and its application as photocatalyst in the degradation of naproxen. *Applied Surface Science, 449*, 780-789. doi:10.1016/j.apsusc.2018.02.069

Benton, O., Apollo, S., Naidoo, B., & Ochieng, A. (2016). Photodegradation of Molasses Wastewater Using TiO2–ZnO Nanohybrid Photocatalyst Supported on Activated Carbon. *Chemical Engineering Communications, 203*(11), 1443-1454. doi:10.1080/00986445.2016.1201659

Bharathkumar, S., Sakar, M., Archana, J., Navaneethan, M., & Balakumar, S. (2021). Interfacial engineering in 3D/2D and 1D/2D bismuth ferrite (BiFeO3)/Graphene oxide nanocomposites for the enhanced photocatalytic activities under sunlight. *Chemosphere, 284*. doi:10.1016/j.chemosphere.2021.131280

Burchacka, E., Pstrowska, K., Beran, E., Faltynowicz, H., Chojnacka, K., & Kulazynski, M. (2021). Antibacterial Agents Adsorbed on Active Carbon: A New Approach for S. aureus and E. coli Pathogen Elimination. *Pathogens, 10*(8). doi:10.3390/pathogens10081066

Casbeer, E., Sharma, V. K., & Li, X.-Z. (2012). Synthesis and photocatalytic activity of ferrites under visible light: A review. *Separation and Purification Technology, 87*, 1-14. doi:10.1016/j.seppur.2011.11.034

Chen, X., Wu, Z., Gao, Z., & Ye, B. C. (2017). Effect of Different Activated Carbon as Carrier on the Photocatalytic Activity of Ag-N-ZnO Photocatalyst for Methyl Orange Degradation under Visible Light Irradiation. *Nanomaterials (Basel), 7*(9). doi:10.3390/nano7090258

Cruz, J. F., Valdiviezo, G., Carrión, L., Rimaycuna, J., Ainassaari, K., Gómez, M. M., . . . Cruz, G. J. F. (2019). Production and characterization of activated carbon based on coffee husk residue for phosphate removal in aqueous solutions. *Journal of Physics: Conference Series, 1173*. doi:10.1088/1742-6596/1173/1/012007

Dalrymple, O. K., Stefanakos, E., Trotz, M. A., & Goswami, D. Y. (2010). A review of the mechanisms and modeling of photocatalytic disinfection. *Applied Catalysis B: Environmental, 98*(1-2), 27-38. doi:10.1016/j.apcatb.2010.05.001

Datta, A., Chakraborty, S., Mukherjee, S., & Mukherjee, S. (2017). Synthesis of carbon nanotube (CNT)-BiFeO3and (CNT)-Bi2Fe4O9nanocomposites and its enhanced photocatalytic properties. *International Journal of Applied Ceramic Technology, 14*(4), 521-531. doi:10.1111/ijac.12670

Devi, T. B., Mohanta, D., & Ahmaruzzaman, M. (2019). Biomass derived activated carbon loaded silver nanoparticles: An effective nanocomposites for enhanced solar photocatalysis and antimicrobial activities. *Journal of Industrial and Engineering Chemistry, 76*, 160-172. doi:10.1016/j.jiec.2019.03.032

Erdem, A., Metzler, D., Cha, D., & Huang, C. P. (2014). Inhibition of bacteria by photocatalytic nano-TiO2 particles in the absence of light. *International Journal of Environmental Science and Technology, 12*(9), 2987-2996. doi:10.1007/s13762-014-0729-2

Fujishima, A., & Honda, K. (1972). Electrochemical Photolysis of Water at a Semiconductor Electrode. *Nature, 238*.

Gamage, J., & Zhang, Z. (2010). Applications of Photocatalytic Disinfection. *International Journal of Photoenergy, 2010*, 1-11. doi:10.1155/2010/764870

Gamage McEvoy, J., & Zhang, Z. (2016). Synthesis and characterization of Ag/AgBr–activated carbon composites for visible light induced photocatalytic detoxification and disinfection. *Journal of Photochemistry and Photobiology A: Chemistry, 321*, 161-170. doi:10.1016/j.jphotochem.2016.02.004

Ganguly, P., Byrne, C., Breen, A., & Pillai, S. C. (2018). Antimicrobial activity of photocatalysts: Fundamentals, mechanisms, kinetics and recent advances. *Applied Catalysis B: Environmental, 225*, 51-75. doi:10.1016/j.apcatb.2017.11.018

Gao, W., Lu, J., Zhang, S., Zhang, X., Wang, Z., Qin, W., . . . Sang, Y. (2019). Suppressing Photoinduced Charge Recombination via the Lorentz Force in a Photocatalytic System. *Adv Sci (Weinh), 6*(18), 1901244. doi:10.1002/advs.201901244

Ge, J., Zhang, Y., & Park, S. J. (2019). Recent Advances in Carbonaceous Photocatalysts with Enhanced Photocatalytic Performances: A Mini Review. *Materials (Basel), 12*(12). doi:10.3390/ma12121916

Ghaedi, M., Nasab, A. G., Khodadoust, S., Rajabi, M., & Azizian, S. (2014). Application of activated carbon as adsorbents for efficient removal of methylene blue: Kinetics and equilibrium study. *Journal of Industrial and Engineering Chemistry, 20*(4), 2317-2324. doi:10.1016/j.jiec.2013.10.007

Grabowska, E. (2016). Selected perovskite oxides: Characterization, preparation and photocatalytic properties—A review. *Applied Catalysis B: Environmental, 186*, 97-126. doi:10.1016/j.apcatb.2015.12.035

He, J., Zheng, Z., & Lo, I. M. C. (2021). Different responses of gram-negative and gram-positive bacteria to photocatalytic disinfection using solar-light-driven magnetic TiO2-based material, and disinfection of real sewage. *Water Res, 207*, 117816. doi:10.1016/j.watres.2021.117816

Hoseinzadeh Hesas, R., Arami-Niya, A., Wan Daud, W. M. A., & Sahu, J. N. (2013). Preparation of granular activated carbon from oil palm shell by microwave-induced chemical activation: Optimisation using surface response methodology. *Chemical Engineering Research and Design, 91*(12), 2447-2456. doi:10.1016/j.cherd.2013.06.004

Hossain, F., Perales-Perez, O. J., Hwang, S., & Roman, F. (2014). Antimicrobial nanomaterials as water disinfectant: applications, limitations and future perspectives. *Sci Total Environ, 466-467*, 1047-1059. doi:10.1016/j.scitotenv.2013.08.009

Irfan, S., Li, L., Saleemi, A. S., & Nan, C.-W. (2017). Enhanced photocatalytic activity of La3+ and Se4+ co-doped bismuth ferrite nanostructures. *Journal of Materials Chemistry A, 5*(22), 11143-11151. doi:10.1039/c7ta01847a

Irfan, S., Zhuanghao, Z., Li, F., Chen, Y.-X., Liang, G.-X., Luo, J.-T., & Ping, F. (2019). Critical review: Bismuth ferrite as an emerging visible light active nanostructured photocatalyst. *Journal of Materials Research and Technology, 8*(6), 6375-6389. doi:10.1016/j.jmrt.2019.10.004

Jain, S., Krishna, R. H., Shivakumara, C., Motappa, M. G., & Nagabhushana, B. M. (2015). Eco-friendly synthesis of biologically important BiFeO3 and Ti4+:BiFeO3 for photocatalytic applications. *International Journal of Current Biotechnology, 3*(11).

Juang, R.-S., Yei, Y.-C., Liao, C.-S., Lin, K.-S., Lu, H.-C., Wang, S.-F., & Sun, A.-C. (2018). Synthesis of magnetic Fe 3 O 4 /activated carbon nanocomposites with high surface area as recoverable adsorbents. *Journal of the Taiwan Institute of Chemical Engineers, 90*, 51-60. doi:10.1016/j.jtice.2017.12.005

Kong, J., Yang, T., Rui, Z., & Ji, H. (2019). Perovskite-based photocatalysts for organic contaminants removal: Current status and future perspectives. *Catalysis Today*, *327*, 47-63. doi:10.1016/j.cattod.2018.06.045

Kumar, R., Raizada, P., Verma, N., Hosseini-Bandegharaei, A., Thakur, V. K., Le, Q. V., & Singh, P. (2021). Recent advances on water disinfection using bismuth based modified photocatalysts: Strategies and challenges. *Journal of Cleaner Production, 297*. doi:10.1016/j.jclepro.2021.126617

Lam, S.-M., Sin, J.-C., & Mohamed, A. R. (2017). A newly emerging visible light-responsive BiFeO 3 perovskite for photocatalytic applications: A mini review.

Materials Research Bulletin, 90, 15-30. doi:10.1016/j.materresbull.2016.12.052

Laxma Reddy, P. V., Kavitha, B., Kumar Reddy, P. A., & Kim, K. H. (2017). TiO2-based photocatalytic disinfection of microbes in aqueous media: A review. *Environ Res, 154*, 296-303. doi:10.1016/j.envres.2017.01.018

Li, J., Wang, Y., Ling, H., Qiu, Y., Lou, J., Hou, X., . . . Chai, G. (2019). Significant Enhancement of the Visible Light Photocatalytic Properties in 3D BiFeO(3)/Graphene Composites. *Nanomaterials (Basel), 9*(1). doi:10.3390/nano9010065

Li, Y., Liu, F., Li, M., Li, W., Qi, X., Xue, M., & Han, F. (2019). Study on adsorption coupling photodegradation on hierarchical nanostructured g-C3N4/TiO2/activated carbon fiber composites for toluene removal. *Journal of Sol-Gel Science and Technology, 93*(2), 402-418. doi:10.1007/s10971-019-05198-7

Li, Y., Zhao, J., Zhang, G., Zhang, L., Ding, S., Shang, E., & Xia, X. (2019). Visible-light-driven photocatalytic disinfection mechanism of Pb-BiFeO3/rGO photocatalyst. *Water Res, 161*, 251-261. doi:10.1016/j.watres.2019.06.011

Mahlambi, M. M., Ngila, C. J., & Mamba, B. B. (2015). Recent Developments in Environmental Photocatalytic Degradation of Organic Pollutants: The Case of Titanium Dioxide Nanoparticles—A Review. *Journal of Nanomaterials, 2015*, 1-29. doi:10.1155/2015/790173

Martins, A. C., Cazetta, A. L., Pezoti, O., Souza, J. R. B., Zhang, T., Pilau, E. J., . . . Almeida, V. C. (2017). Sol-gel synthesis of new TiO 2 /activated carbon photocatalyst and its application for degradation of tetracycline. *Ceramics International, 43*(5), 4411-4418. doi:10.1016/j.ceramint.2016.12.088

Matsunaga, T., Tomoda, R., Nakajima, T., & Wake, H. (1985). Photoelectrochemical sterilization of microbial cells by

semiconductor powders. *FEMS Microbiology Letters*.

Mohd Azmy, H. A., Razuki, N. A., Aziz, A. W., Abdul Satar, N. S., & Mohd Kaus, N. H. (2017). Visible Light Photocatalytic Activity of BiFeO3 Nanoparticles for Degradation of Methylene Blue. *Journal of Physical Science, 28*(2), 85-103. doi:10.21315/jps2017.28.2.6

Nodeh, M., Bidhendi, G., Gabris, M., Akbari-adergani, B., Nodeh, H., Masoudi, A., & Shahabuddin, S. (2020). Strontium Oxide Decorated Iron Oxide Activated

Carbon Nanocomposite: A New Adsorbent for Removal of Nitrate from Well Water. *Journal of the Brazilian Chemical Society*. doi:10.21577/0103-5053.20190138

Pandey, P. K., Kass, P. H., Soupir, M. L., Biswas, S., & Singh, V. P. (2014). Contamination of water resources by pathogenic bacteria. *AMB Express, 4*(51).

Phin, H.-Y., Ong, Y.-T., & Sin, J.-C. (2020). Effect of carbon nanotubes loading on the photocatalytic activity of zinc oxide/carbon nanotubes photocatalyst synthesized via a modified sol-gel method. *Journal of Environmental Chemical Engineering, 8*(3). doi:10.1016/j.jece.2019.103222

Plakas, K. V., Taxintari, A., & Karabelas, A. J. (2019). Enhanced Photo-Catalytic Performance of Activated Carbon Fibers for Water Treatment. *Water, 11*(9). doi:10.3390/w11091794

Punia, P., Bharti, M. K., Chalia, S., Dhar, R., Ravelo, B., Thakur, P., & Thakur, A. (2021). Recent advances in synthesis, characterization, and applications of nanoparticles for contaminated water treatment- A review. *Ceramics International, 47*(2), 1526-1550. doi:10.1016/j.ceramint.2020.09.050

Ravichandran, A. T., Srinivas, J., Manikandan, A., & Baykal, A. (2018). Enhanced Magneto-optical and Antibacterial Studies of Bi1−xMgxFeO3 ($0.0 \leq x \leq 0.15$)) Nanoparticles. *Journal of Superconductivity and Novel Magnetism, 32*(6), 1663-1670. doi:10.1007/s10948-018-4842-1

Regmi, C., Joshi, B., Ray, S. K., Gyawali, G., & Pandey, R. P. (2018). Understanding Mechanism of Photocatalytic Microbial Decontamination of Environmental Wastewater. *Front Chem, 6*, 33. doi:10.3389/fchem.2018.00033

Rivera-Utrilla, J., Bautista-Toledo, I., Ferro-García, M. A., & Moreno-Castilla, C. (2001). Activated carbon surface modifications by adsorption of bacteria and their effect on aqueous lead adsorption. *Journal of Chemical Technology & Biotechnology, 76*(12), 1209-1215. doi:10.1002/jctb.506

Rojas-Cervantes, M., & Castillejos, E. (2019). Perovskites as Catalysts in Advanced Oxidation Processes for Wastewater Treatment. *Catalysts, 9*(3). doi:10.3390/catal9030230

Saravanan, A., Kumar, P. S., Jeevanantham, S., Karishma, S., & Kiruthika, A. R. (2021). Photocatalytic disinfection of micro-organisms: Mechanisms and applications. *Environmental Technology & Innovation, 24*. doi:10.1016/j.eti.2021.101909

Sun, X., Liu, Z., Yu, H., Zheng, Z., & Zeng, D. (2018). Facile synthesis of BiFeO3 nanoparticles by modified microwave-assisted hydrothermal method as visible light driven photocatalysts. *Materials Letters, 219*, 225-228. doi:10.1016/j.matlet.2018.02.052

Teh, Y. W., Chee, M. K. T., Kong, X. Y., Yong, S.-T., & Chai, S.-P. (2020). An insight into perovskite-based photocatalysts for artificial photosynthesis. *Sustainable Energy & Fuels, 4*(3), 973-984. doi:10.1039/c9se00526a

Thirumalairajan, S., Girija, K., Hebalkar, N. Y., Mangalaraj, D., Viswanathan, C., & Ponpandian, N. (2013). Shape evolution of perovskite LaFeO3 nanostructures: a systematic investigation of growth mechanism, properties and morphology dependent photocatalytic activities. *RSC Advances, 3*(20). doi:10.1039/c3ra00006k

V, R., D, M., C, L., & A, S. (2018). Activated carbon (prepared from secondary sludge biomass) supported semiconductor zinc oxide nanocomposite photocatalyst for reduction of Cr(VI) under visible light irradiation. *Journal of Environmental Chemical Engineering, 6*(6), 7327-7337. doi:10.1016/j.jece.2018.08.055

Vijayaraghavan, R. (2012). Zinc oxide based Inorganic Antimicrobial agents. *International Journal of Science Research, 1*(2).

Wang, F. L., Li, Y., Wang, N., Zhu, L., Jain, A., Wang, Y. G., & Chen, F. G. (2019). Enhanced magnetic, ferroelectric and optical properties of Sr and Co co-doped BiFeO3 powders. *Journal of Alloys and Compounds, 810*. doi:10.1016/j.jallcom.2019.151941

Wang, N., Luo, X., Han, L., Zhang, Z., Zhang, R., Olin, H., & Yang, Y. (2020). Structure, Performance, and Application of BiFeO3 Nanomaterials. *Nano-Micro Letters, 12*(1). doi:10.1007/s40820-020-00420-6

Wang, W., Zhou, C., Yang, Y., Zeng, G., Zhang, C., Zhou, Y., . . . Luo, H. (2021). Carbon nitride based photocatalysts for solar photocatalytic disinfection, can we go further? *Chemical Engineering Journal, 404*. doi:10.1016/j.cej.2020.126540

Wang, X., Mao, W., Zhang, J., Han, Y., Quan, C., Zhang, Q., . . . Huang, W. (2015). Facile fabrication of highly efficient g-C(3)N(4)/BiFeO(3) nanocomposites with enhanced visible light photocatalytic activities. *J Colloid Interface Sci, 448*, 17-23. doi:10.1016/j.jcis.2015.01.090

Wei, J., Yang, J., Wen, Z., Dai, J., Li, Y., & Yao, B. (2017). Efficient photocatalytic oxidation of methane over β-Ga2O3/activated carbon composites. *RSC Advances, 7*(60), 37508-37521. doi:10.1039/c7ra05692c

Wei, K., Faraj, Y., Yao, G., Xie, R., & Lai, B. (2021). Strategies for improving perovskite photocatalysts reactivity for organic pollutants degradation: A review on recent progress. *Chemical Engineering Journal, 414*. doi:10.1016/j.cej.2021.128783

Xing, B., Shi, C., Zhang, C., Yi, G., Chen, L., Guo, H., . . . Cao, J. (2016). Preparation of TiO2/Activated Carbon Composites for Photocatalytic Degradation of RhB under UV Light Irradiation. *Journal of Nanomaterials, 2016*, 1-10. doi:10.1155/2016/8393648

Xu, Y., Liu, Q., Liu, C., Zhai, Y., Xie, M., Huang, L., . . . Jing, J. (2018). Visible-light-driven Ag/AgBr/ZnFe2O4 composites with excellent photocatalytic activity for E. coli disinfection and organic pollutant degradation. *J Colloid Interface Sci, 512*, 555-566. doi:10.1016/j.jcis.2017.10.077

Yahya, N., Aziz, F., Jamaludin, A., Aizat, A., Mutalib, M. A., Jaafar, J., . . . Ismail, A. F. (2018). Effects of the Citric Acid Addition on the Morphology, Surface Area, and Photocatalytic Activity of LaFeO3 Nanoparticles Prepared by Glucose-Based Gel Combustion Methods. *Industrial & Engineering Chemistry Research, 58*(2), 609-617. doi:10.1021/acs.iecr.8b04263

Yamamoto, O., Sawai, J., & Sasamoto, T. (2002). Activated Carbon Sphere with Antibacterial Characteristics. *Materials Transactions, 43*(5).

Yan, H., Liu, L., Wang, R., Zhu, W., Ren, X., Luo, L., . . . Wang, J. (2020). Binary composite MoS2/TiO2 nanotube arrays as a recyclable and efficient photocatalyst for solar water disinfection. *Chemical Engineering Journal, 401*. doi:10.1016/j.cej.2020.126052

Yang, C. H., Kan, D., Takeuchi, I., Nagarajan, V., & Seidel, J. (2012). Doping BiFeO3: approaches and enhanced functionality. *Phys Chem Chem Phys, 14*(46), 15953-15962. doi:10.1039/c2cp43082g

Yek, P. N. Y., Liew, R. K., Osman, M. S., Lee, C. L., Chuah, J. H., Park, Y. K., & Lam, S. S. (2019). Microwave steam activation, an innovative pyrolysis approach to convert waste palm shell into highly microporous activated carbon. *J Environ Manage, 236*, 245-253. doi:10.1016/j.jenvman.2019.01.010

Yemmireddy, V. K., & Hung, Y. C. (2017). Using Photocatalyst Metal Oxides as Antimicrobial Surface Coatings to Ensure Food Safety-Opportunities and Challenges. *Compr Rev Food Sci Food Saf, 16*(4), 617-631. doi:10.1111/1541-4337.12267

Zhang, B., Zou, S., Cai, R., Li, M., & He, Z. (2018). Highly-efficient photocatalytic disinfection of Escherichia coli under visible light using carbon supported Vanadium Tetrasulfide nanocomposites. *Applied Catalysis B: Environmental, 224,* 383-393. doi:10.1016/j.apcatb.2017.10.065

Zhang, C., Li, Y., Shuai, D., Shen, Y., Xiong, W., & Wang, L. (2019). Graphitic carbon nitride (g-C3N4)-based photocatalysts for water disinfection and microbial control: A review. *Chemosphere, 214*, 462-479. doi:10.1016/j.chemosphere.2018.09.137

Zhang, G., Liu, G., Wang, L., & Irvine, J. T. (2016). Inorganic perovskite photocatalysts for solar energy utilization. *Chem Soc Rev, 45*(21), 5951-5984. doi:10.1039/c5cs00769k

Zhu, M., Miao, J., Guan, D., Zhong, Y., Ran, R., Wang, S., . . . Shao, Z. (2020). Efficient Wastewater Remediation Enabled by Self-Assembled Perovskite Oxide Heterostructures with Multiple Reaction Pathways. *ACS Sustainable Chemistry & Engineering, 8*(15), 6033-6042. doi:10.1021/acssuschemeng.0c0088

LIST OF PUBLICATIONS

Article paper

1. **Nur Atiqah Daub**, Farhana Aziz, Madzlan Aziz, Juhana Jaafar, Wan Norhayati Wan Salleh, Norhaniza Yusof & Ahmad Fauzi Ismail (2020). A Mini Review on Parameters Affecting the Semiconducting Oxide Photocatalytic Microbial Disinfection. Water, Air & Soil Pollution. 231 (461) https://doi.org/10.1007/s11270-020-04829-y

Conference proceeding

1. **Nur Atiqah Daub**, Farhana Aziz, Nor Azimah Mohd Zain, Lau Woei Jye, Norhaniza Yusof, Wan Norhayati Wan Salleh & Juhana Jaafar (2020). Photocatalytic disinfection under visible light irradiation by BFO photocatalyst. IOP Conf. Series: Materials Science and Engineering. 1142 (1) DOI:10.1088/1757-899X/1142/1/012002.

2. **Nur Atiqah Daub,** Farhana Aziz, Lau Woei Jye & Nor Azimah Mohd Zain (2022). Synthesis of Bismuth Ferrite-Activated Carbon (BFO-AC) Nanoparticle and Their Characterization. AIP Conference Proceedings.

Book chapter

1. **Nur Atiqah Daub**, Farhana Aziz, Arif Aizat, Norsyazwani Yahya (2020). Synthetic Polymer-based Membranes for Photodegradation of Organic Hazaedous Materials. Synthetic Polymeric Membranes for Advanced Water Treatment, Gas Separation, and Energy Sustainability. 53 (70) 10.1016/B978-0-12-818485-1.00004-6