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BIOMASS BASED SYNTHESIS OF NOVEL NANOPARTICLES FOR ANTIMICROBIAL FORMULATION TO TREAT SKIN INFECTIONS AND DISEASES

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THE UNIVERSITY OF QUEENSLAND AUSTRALIA
JULY 2026**

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***Biomass based synthesis of novel nanoparticles for antimicrobial formulation to
treat skin infections and diseases***

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Submitted

in fulfilment of the requirements for the joint degree of

DOCTOR OF PHILOSOPHY

to the

INDIAN INSTITUTE OF TECHNOLOGY DELHI

&

THE UNIVERSITY OF QUEENSLAND AUSTRALIA

July 2026



This thesis is dedicated, first and foremost, to my loved parents and my brother

Shreemati Laila & Shree Mohd. Israfil Noor

whose unseen sacrifices, enduring faith, and tireless efforts made the path of education possible for their children.

Every step I have taken was made possible by your patience, resilience, and the countless dreams you quietly set aside so that your children could dream without limits.

In moments of doubt and hardship, your belief in the power of knowledge, anchored in your deep faith in Almighty Allah, became my greatest strength and guiding light.

This work is not merely an academic achievement; it is a testament to your endurance, your values, and your lifelong commitment to dignity, learning, and hope.

This thesis is also a tribute to the people of Palestine'

to those whose lives are shaped by loss, displacement, and the denial of basic human rights, yet who continue to hold on to hope, identity, and resilience.

Their suffering is a reminder that science, medicine, and knowledge must serve humanity beyond borders and politics. May this work, rooted in sustainable and accessible healing technologies, carry the spirit of compassion and justice for those who are too often unheard.

To my parents and my siblings, whose silent sacrifices and unwavering faith made my journey possible and to the people of Palestine, who remind the world why humanity matters... this work is humbly dedicated.

Aisha Noor

Brisbane & London



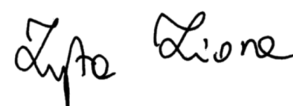
Certificate

This is to certify that the thesis entitled “**Biomass based synthesis of novel nanoparticles for antimicrobial formulation to treat skin infections and diseases**” being submitted by **Ms. Aisha Noor** to the “Indian Institute of Technology Delhi” and “The University of Queensland Australia” for the award of the degree of **Doctor of Philosophy** is a record of bonafide research work carried out by **Ms. Aisha Noor**. She has worked under our guidance and supervision and has fulfilled the requirements for the submission of this thesis, which, to our knowledge, has reached the requisite standard. The results in this thesis are original and have not been submitted, in part or full, to any other University or Institute for the award of any other degree or diploma.



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Abstract

The rapid emergence of antimicrobial resistance (AMR), coupled with the increasing burden of skin and wound infections, presents a critical global healthcare challenge. Conventional antibiotics are steadily losing efficacy, necessitating the development of alternative antimicrobial strategies that are effective, affordable, and environmentally responsible. In this context, nanomaterials particularly metal-based nanoparticles have emerged as promising antimicrobial agents due to their high surface area, tunable physicochemical properties, and ability to act through multiple antibacterial mechanisms. However, many nanoparticle synthesis routes rely on energy-intensive processes and toxic chemicals, raising concerns regarding environmental sustainability and biocompatibility. This doctoral research addresses these challenges by developing green, biomass-mediated nanoparticle synthesis pathways and evaluating their antimicrobial performance, safety, and environmental footprint.

This thesis investigates the biomass-based green synthesis of silver nanoparticles (AgNPs) and silver-zinc oxide (Ag@ZnO) nanocomposites as sustainable antimicrobial formulations for skin and wound-associated bacterial infections. Medicinal plant extracts and agro-industrial waste materials were utilized as sustainable reducing and stabilizing agents, aligning with circular bioeconomy principles. Specifically, *Azadirachta indica* (neem) leaf extract and grape pomace biomass (GPB), a major byproduct of the wine industry, were employed to synthesize nanoparticles using environmentally benign methodologies. These natural substrates are rich in phytochemicals such as polyphenols, flavonoids, and phenolic acids, which facilitate metal ion reduction while simultaneously capping and stabilizing the nanoparticles.

The research was structured into five interconnected studies. In the first study, neem leaf extract was used to synthesize silver nanoparticles via a conventional hot plate-assisted green method. The resulting AgNPs exhibited successful formation, confirmed through UV-Vis spectroscopy, X-ray diffraction (XRD), Fourier transform infrared spectroscopy (FTIR), and electron microscopy. These nanoparticles demonstrated notable antibacterial activity against both Gram-positive and Gram-negative bacteria, validating neem's potential as an effective green precursor.

In the second study, grape pomace biomass was explored as a sustainable alternative to fresh plant material, enabling waste valorization and reducing biomass exploitation. GPB was characterized for its total phenolic content and antioxidant activity, confirming its suitability for nanoparticle synthesis. Response Surface Methodology (RSM) was employed to optimize synthesis conditions, resulting in

AgNPs with improved size control and reproducibility. The GPB-derived nanoparticles exhibited broad-spectrum antibacterial activity against clinically relevant pathogens, including methicillin-resistant *Staphylococcus aureus* (MRSA), demonstrating the feasibility of agro-waste-based nanomaterial synthesis for biomedical applications.

The third study focused on enhancing antimicrobial and catalytic performance through the development of Ag-ZnO nanocomposites. Zinc oxide was incorporated with silver nanoparticles using an ultrasonic-assisted green synthesis approach. Ultrasonication significantly improved reaction kinetics, particle uniformity, and dispersion compared to conventional heating methods, yielding nanocomposites with narrow size distribution and enhanced surface activity. The synthesized ZnO@Ag nanocomposites showed superior antibacterial efficacy, producing substantially larger zones of inhibition than monometallic nanoparticles. In addition, these nanocomposites exhibited excellent catalytic activity, achieving rapid degradation of model organic dyes, thereby demonstrating multifunctionality relevant to both biomedical and environmental remediation applications.

To elucidate the antibacterial mechanism of action, the fourth study employed field emission scanning electron microscopy (FESEM) and inductively coupled plasma mass spectrometry (ICP-MS). The results revealed a multimodal antibacterial mechanism involving physical disruption of bacterial cell membranes, pore formation, and leakage of intracellular ions such as potassium and phosphorus. These effects were attributed to synergistic interactions between silver ions, zinc oxide-induced reactive oxygen species, and phytochemical capping agents derived from biomass extracts. Importantly, biocompatibility and hemocompatibility assessments confirm high cell viability in fibroblast cell lines, indicating that the developed nanomaterials are safe for potential topical and biomedical use.

Recognizing that green synthesis must also be environmentally sustainable at scale, the fifth study incorporated a comprehensive Life Cycle Assessment (LCA) to evaluate the environmental impacts of nanoparticle production. Using OpenLCA software, gate-to-gate analyses were performed to compare conventional hot plate synthesis with ultrasonic-assisted synthesis. The LCA results demonstrated that ultrasonication significantly reduced ecotoxicity, fossil fuel depletion, and global warming potential. Sensitivity and uncertainty analyses further identified solvent and energy consumption as key environmental hotspots, highlighting opportunities for process optimization through solvent recycling and energy-efficient strategy.

Overall, this research integrates green chemistry, waste valorization, antimicrobial nanotechnology, and environmental assessment into a unified framework. The findings demonstrate that biomass-

derived nanoparticles and nanocomposites can effectively combat pathogenic bacteria through multiple mechanisms while maintaining biocompatibility and reducing environmental burden. By transforming agricultural and industrial waste into high-value antimicrobial materials, this work supports sustainable innovation and contributes to global efforts to address AMR. The developed approaches offer a scalable, eco-friendly pathway for next-generation antimicrobial formulations, with relevance for skin infection treatment and healthcare applications in resource-limited settings.

सारांश

एंटीमाइक्रोबियल रेज़िस्टेंस (AMR) की तीव्र बढ़ती समस्या तथा त्वचा एवं घाव संक्रमणों का बढ़ता बोझ वैश्विक स्वास्थ्य के लिए एक गंभीर चुनौती बन चुका है। पारंपरिक एंटीबायोटिक्स की प्रभावशीलता लगातार कम होती जा रही है, जिससे ऐसे वैकल्पिक उपचारों की आवश्यकता उत्पन्न हुई है जो प्रभावी, किफायती, सुरक्षित तथा पर्यावरण की दृष्टि से टिकाऊ हों। इस संदर्भ में, धातु-आधारित नैनोकण अपने उच्च सतह क्षेत्र, अनुकूलन योग्य भौतिक-रासायनिक गुणों तथा बहु-आयामी जीवाणुरोधी क्रियाविधि के कारण एक प्रभावी समाधान के रूप में उभरे हैं। हालांकि, नैनोकणों के पारंपरिक संश्लेषण तरीकों में विषैले रसायनों और अधिक ऊर्जा की आवश्यकता होती है, जिससे पर्यावरणीय स्थिरता और जैव-संगतता पर प्रश्न उठते हैं। यह शोध इन्हीं चुनौतियों को ध्यान में रखते हुए हरित (ग्रीन) एवं जैव-आधारित नैनोकण संश्लेषण विधियों के विकास तथा उनके जीवाणुरोधी प्रदर्शन, सुरक्षा और पर्यावरणीय प्रभावों के मूल्यांकन पर केंद्रित है।

यह शोध त्वचा संक्रमणों के उपचार हेतु जैव-आधारित हरित विधियों द्वारा सिल्वर नैनोकण (AgNPs) तथा सिल्वर-ज़िंक ऑक्साइड (Ag-ZnO) नैनोकॉम्पोज़िट्स के विकास का अध्ययन करता है। इसमें औषधीय पौधों एवं कृषि-औद्योगिक अपशिष्ट को सतत रिड्यूसिंग और स्टेबलाइज़िंग एजेंट के रूप में उपयोग किया गया है, जो सर्कुलर बायोइकोनॉमी के सिद्धांतों के अनुरूप है। विशेष रूप से, *Azadirachta indica* (नीम) पत्ती अर्क तथा अंगूर के अवशेष (GPB), जो वाइन उद्योग का एक प्रमुख उप-उत्पाद है, का उपयोग पर्यावरण-अनुकूल नैनोकण संश्लेषण के लिए किया गया। ये प्राकृतिक स्रोत पॉलीफेनॉल्स, फ्लेवोनॉयड्स और अन्य फाइटोकेमिकल्स से भरपूर होते हैं, जो धातु आयनों को रिड्यूस करने के साथ-साथ नैनोकणों को स्थिरता प्रदान करते हैं।

इस शोध को पाँच प्रमुख अध्ययनों में विभाजित किया गया है। प्रथम अध्ययन में, नीम पत्ती अर्क का उपयोग कर पारंपरिक हॉट-प्लेट विधि द्वारा सिल्वर नैनोकणों का हरित संश्लेषण किया गया। UV-Vis स्पेक्ट्रोस्कोपी, XRD, FTIR तथा इलेक्ट्रॉन माइक्रोस्कोपी द्वारा नैनोकणों के सफल निर्माण की पुष्टि की गई। इन नैनोकणों ने ग्राम-पॉजिटिव और ग्राम-नेगेटिव दोनों प्रकार के जीवाणुओं के विरुद्ध उल्लेखनीय जीवाणुरोधी प्रभाव दर्शाया, जिससे नीम की हरित संश्लेषण क्षमता प्रमाणित हुई।

द्वितीय अध्ययन में, अंगूर के अवशेष (GPB) को एक वैकल्पिक और सतत जैव-स्रोत के रूप में उपयोग किया गया, जिससे ताज़े पौधों पर निर्भरता कम हुई और अपशिष्ट का मूल्यवर्धन संभव हुआ। GPB की कुल फेनोलिक सामग्री और एंटीऑक्सिडेंट गतिविधि का मूल्यांकन कर इसकी उपयुक्तता सिद्ध की गई। Response Surface Methodology (RSM) द्वारा संश्लेषण परिस्थितियों का अनुकूलन किया गया, जिससे कण आकार नियंत्रण और पुनरुत्पादकता में सुधार हुआ। GPB-आधारित सिल्वर नैनोकणों ने MRSA सहित कई बैक्टीरियल स्ट्रेन्स के विरुद्ध प्रभावी जीवाणुरोधी गतिविधि प्रदर्शित की।

तृतीय अध्ययन में, जीवाणुरोधी एवं उत्प्रेरक प्रदर्शन को बढ़ाने हेतु Ag-ZnO नैनोकॉम्पोज़िट्स का विकास किया गया। इसमें अल्ट्रासोनिकेशन आधारित हरित संश्लेषण तकनीक का उपयोग किया गया, जिसने पारंपरिक विधियों की तुलना में

बेहतर कण एकरूपता, तेज प्रतिक्रिया गतिकी तथा समान वितरण सुनिश्चित किया। विकसित ZnO@Ag नैनोकॉम्पोजिट्स ने उल्लेखनीय रूप से उच्च जीवाणुरोधी प्रभाव दिखाया तथा जैविक डाई अपघटन में भी उत्कृष्ट उत्प्रेरक प्रदर्शन किया, जिससे इनकी बहु-कार्यात्मक क्षमता प्रमाणित हुई।

चतुर्थ अध्ययन में, नैनोकणों की जीवाणुरोधी क्रियाविधि को समझने के लिए FESEM और ICP-MS तकनीकों का उपयोग किया गया। परिणामों से यह स्पष्ट हुआ कि नैनोकॉम्पोजिट्स जीवाणु कोशिका झिल्ली को भौतिक रूप से क्षतिग्रस्त करते हैं, जिससे छिद्र निर्माण और K^+ तथा P जैसे आंतरिक आयनों का रिसाव होता है। यह प्रभाव सिल्वर आयनों, ZnO द्वारा उत्पन्न ROS तथा जैव-आधारित फाइटोकेमिकल कैपिंग के संयुक्त प्रभाव से उत्पन्न होता है। साथ ही, फाइब्रोब्लास्ट कोशिकाओं पर किए गए जैव-संगतता परीक्षणों में उच्च कोशिका जीवितता पाई गई, जिससे इन नैनो-सामग्रियों की जैव-चिकित्सीय उपयोगिता प्रमाणित हुई।

पंचम अध्ययन में, नैनोकण उत्पादन की पर्यावरणीय स्थिरता का आकलन जीवन चक्र मूल्यांकन के माध्यम से किया गया। OpenLCA सॉफ्टवेयर का उपयोग कर cradle-to-gate विश्लेषण किया गया, जिसमें हॉट-प्लेट और अल्ट्रासोनिकेशन विधियों की तुलना की गई। परिणामों से यह विधि स्पष्ट हुई कि अल्ट्रासोनिकेशन में इकोटॉक्सिसिटी, जीवाश्म ईंधन की कमी और ग्लोबल वार्मिंग क्षमता में उल्लेखनीय कमी आती है। । संवेदनशीलता और अनिश्चितता विश्लेषण ने यह भी दर्शाया कि सॉल्वेंट और ऊर्जा खपत प्रमुख पर्यावरणीय प्रभाव कारक हैं, जिनमें सुधार की पर्याप्त संभावनाएँ मौजूद हैं।

समग्र रूप से, यह शोध हरित रसायन विज्ञान, अपशिष्ट प्रबंधन, जीवाणुरोधी नैनोटेक्नोलॉजी और पर्यावरणीय मूल्यांकन को एकीकृत करता है। यह सिद्ध करता है कि जैव-आधारित नैनोकण प्रभावी रूप से रोगजनक जीवाणुओं को नियंत्रित कर सकते हैं, साथ ही जैव-संगत और पर्यावरण-अनुकूल भी हैं। कृषि एवं औद्योगिक अपशिष्ट को उच्च-मूल्य जैव-चिकित्सीय सामग्रियों में परिवर्तित कर यह कार्य AMR से निपटने की दिशा में एक सतत, स्केलेबल और जिम्मेदार समाधान प्रस्तुत करता है, विशेषकर उन क्षेत्रों के लिए जहाँ स्वास्थ्य सुविधाएँ सीमित हैं।

Declaration by author

This thesis is composed of my original work and contains no material previously published or written by another person except where due reference has been made in the text. I have clearly stated the contribution of others to jointly authored works that I have included in my thesis.

I have clearly stated the contribution of others to my thesis, including statistical assistance, survey design, data analysis, significant technical procedures, professional editorial advice, financial support, and any other original research work used or reported in my thesis. The content of my thesis is the result of work I have carried out since the commencement of my higher degree by research candidature and does not include a substantial part of work that has been submitted to qualify for the award of any other degree or diploma in any university or other tertiary institution. I have clearly stated which parts of my thesis, if any, have been submitted to qualify for another award.

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20 January 2026

London, United Kingdom

Publications included in this Thesis

International Peer Review Journals

1. **Aisha Noor**, K. K. Pant, Anushree Malik, Peter Moyle, Zyta Ziora, Unearthing Industrial and Medicinal Potential of Fruit and Vegetable Waste derived Bioactive Compounds (**Process Safety and Env. Protection.**, 2024)
2. **Aisha Noor**, K. K. Pant, Anushree Malik, Peter Moyle, Zyta Ziora, Green Encapsulation of Metal Oxide and Nobel Metal ZnO@Ag for Efficient Antibacterial and Catalytic Performance (**ACS I&ECR.**, 2025)
3. **Aisha Noor**, Neethu TJ, K. K. Pant, Anushree Malik, Peter Moyle, Zyta Ziora, Quantifying Environmental Burden of Nanoparticle Synthesis Using Plant Extracts via Hot Plate and Ultrasonication method: A life cycle framework of ZnO-Ag (**ACS Sustainable Chemistry and Engineering.**, 2026)

Under submission

1. **Aisha Noor**, Manleen, K. K. Pant, Anushree Malik, Peter Moyle, Zyta Ziora. Neetu Singh, Statistical Optimization of grape pomace-mediated synthesis of silver nanoparticles to inhibit the growth of skin infecting bacteria, and its in-vitro biocompatibility evaluation (**Submitted to RSC Green Chem**)

Other publications during candidature

1. Neethu Joshikumar, **A. Noor**, K. K. Pant, F. Botha, R. Henry, Economic assessment and life cycle analysis of sugarcane bagasse valorization to bioethanol via one-pot deep eutectic solvent pretreatment, **Biofuels Bioproducts & Biorefinery**, 2025
2. Neethu Joshikumar, **A. Noor**, K. K. Pant, F. Botha, R. Henry, Biobutanol production from sugarcane bagasse via deep eutectic solvent pretreatment: Integrated process optimisation, techno-economic and life cycle assessment, **Chemical Engineering Research & Design**, 2026
3. M. Jain, R. Chauhan, P. Dubey, **A. Noor**, A. Sahoo, Omics-Driven Algal Intelligence in Revolutionizing Wastewater Treatment for a Sustainable Future (**submitted in Discover Sustainability**)

Book Chapters

1. Marut Jain, **Aisha Noor**, Abhishek Sahoo, K. K. Pant, Zyta Ziora, Mark Blaskovich, Microbial degradation of Petrochemical refinery wastewater. Francis & Taylor, 2024
2. Vallari R. Chourasia, Nidhi Kushwaha, **Aisha Noor**, Neethu Thoppil Joshikumar, K. K. Pant., Green and Sustainable routes for degradation of toxic chemicals: Carbon-based hybrid metal composites. Francis & Taylor, 2024

Poster/Oral presentations at International/National Conferences

1. Chemeca 2025, Adelaide, Australia **(28 Sep-01 Oct 2025)**
2. BSBB JNU **2024**, India
3. Symposium on Biomaterial, fuel and chemicals **(28 Apr-1 May 2024, USA)**
4. Drug Delivery Australia **(01-03 Dec 2023, Melbourne)**
5. 13th International Nanomedicine Conference **(19-21st June 2023, Sydney)**
6. International Conference on Biotechnology for Sustainable Bioresources and Bioeconomy **(7-11th Dec BSBB-2022 Guwahati, India)**
7. National Conference on Recent Trends in Chemistry and Nano-Biotechnology **(13th Dec 2022 New Delhi, India)**
8. International Conference on Applications of Natural Products Nanomaterials and Nanopharmaceuticals **(ICAN3) August 9-10, 2023, Chennai, India)**
9. Plant-mediated Green Synthesis of Metal-based Nanoparticles by Nano Science and Technology Consortium **(18th -20th July 2023, India)**

Contributions by others to the thesis

All chapters

I sincerely thank my supervisors for their invaluable editorial suggestions, conceptual guidance, and methodological insights throughout this endeavor. I am deeply grateful to Prof. K. K. Pant, Prof. Anushree Malik, Dr. Zyta M. Ziora, A/Prof. Peter Moyle, and the members of my PhD committee, Prof. Ali Haider, Prof. Sunil Khare, A/Prof. Harendra Parekh for their unwavering support and mentorship. Their expertise and guidance have been instrumental in shaping the trajectory of this work and have been indispensable to its success.

Chapter 5

I am grateful to Dr. Manleen Kaur and Prof. Neetu Singh's lab at IITD for her invaluable contribution towards biocompatibility evaluation of the designed material. I also acknowledge Prof. Hari Prasad Lab for helping me with reagent procurement. I also extend my gratitude to University College London for physicochemical assays and electron microscopy analysis.

Chapter 6

I sincerely thank Neethu Thoppil Joshikumar for her invaluable assistance in conducting the Life Cycle Assessment of the materials. Her expertise and dedication significantly enriched the rigor and depth of our analysis in this thesis.

*Further I would like to sincerely thanks and acknowledge Dr. Marut Jain for his consistent support from the early stages of my PhD journey, continuous discussions, and critical inputs throughout the chapters shaping.

Statement of parts of the thesis submitted to qualify for the award of another degree

No works submitted towards another degree have been included in this thesis.

Research involving human or animal subjects

No animal or human subjects were involved in this research.

Acknowledgements

Throughout my doctoral journey, I have been fortunate to receive guidance, encouragement, and support from numerous individuals who contributed significantly to both my academic development and personal growth. I wish to express my deepest gratitude to my principal supervisor and mentor, **Prof. Kamal K. Pant**, whose guidance extended well beyond formal supervision. His clarity of thought, academic insight, and steady direction were instrumental at every stage of my research. I remain profoundly grateful for his enduring influence and inspiration on my career and life. I am sincerely thankful to **Prof. Anushree Malik** (CRDT, IIT Delhi) and **A/Prof. Peter Moyle** (School of Pharmacy and Pharmaceutical Sciences) and **Dr. Zyta M. Ziora** (Institute of Molecular Biosciences) at The University of Queensland, whose mentorship and support were invaluable throughout my doctoral studies. Their insightful guidance, constructive criticism, and encouragement significantly influenced the direction and depth of my research. It has been a privilege to work under their supervision, and I am deeply appreciative of the trust and confidence they placed in me.

I would like to extend my heartfelt thanks to the Head of the Department of Chemical Engineering, IIT Delhi, and the Head of the School of Pharmacy and Pharmaceutical Sciences, The University of Queensland, for providing an enabling research environment and access to essential facilities. I am also grateful to my PhD research committee members, **Prof. Ali Haider**, **Prof. Sunil Khare** from IIT Delhi, and **A/Prof. Harendra Parekh** from UQ, whose valuable suggestions and critical perspectives greatly strengthened my research work. I gratefully acknowledge the support of the Central Research Facility (CRF), IIT Delhi, the Computer Services Centre (CSC), and the Centre for Microscopy and Microanalysis (CMM), The University of Queensland, EDI Centre for Microscopy at University College London for providing access to advanced instrumentation, computational resources, software Biorenders and technical expertise that were crucial for the successful completion of this research.

I also acknowledge with gratitude my seniors and fellow lab members, including **Dr. Ashutosh Kumar**, **Dr. Shreya Singh**, **Dr. Arindam Modak**, **Dr. Prashant Jadhao**, **Dr. Ramdayal Panda**, **Dr. Deepti Mishra**, **Dr. Snigdha Mishra**, **Dr. Sadaf Aiman Khan**, **Mr. Guguloth Venkanna**, **Ms. Shally Gupta**, **Mr. Shashank Shekhar**, **Mr. Abdul**, **Ms Nidhi Kushwaha**, **Mr. Abhishek Sahoo**, **Mr. Kaushik Kundu**, and **Mr. Pranit**, along with all other research scholars who collaborated with me at the CRE Laboratory, IIT Delhi, and the Peter Moyle lab at The University of Queensland. I am sincerely thankful for their cooperation, discussions, and camaraderie. I would also like to acknowledge the support of the Chemical Engineering Office staff and AML laboratory staff at IIT Delhi, whose assistance was consistently reliable and invaluable. I am particularly

thankful to **Mr. Vishesh Kumar, Mr. Krishna Kumar, Mr. Suchit Kumar Pal, and Mr. Sabal** respectively whose continuous assistance supported my research journey in numerous ways. I am deeply appreciative for my AML and Moyle Lab members and other seniors, friends and colleague from IITD and UQ namely, **Dr. Saurabh Samuchiwal, Dr Farah Naaz, Dr. Sumit, Dr. Harshita, Dr. Rahul Kumar, Dr. Vivek Dalvi, Dr. Vivek Nair, Dr. Aakansha Gupta, Dr. Koushi, Dr. Shoaib Anwaar, Mr Imran, Mr. Yuzhang, Mr. Frazer, Ms. Aisha Baig, Mr Aman, Mr Alok, Mr Suraj, and Mr Abhishek.** I am also thankful to my UQ PACE lab manager **Dr. Justine Haddrill** for her unwavering support during my stay at UQ. I also extend my heartfelt gratitude to my host supervisors (Dr. Dimitrios Evangelopoulos, Dr. Timothy McHugh and Dr. Sanjib Bhakta) and my colleagues at University College London and Birkbeck during my Commonwealth split site fellowship. I also dearly thank my friends **Fayeza, Catherine and Shabnam** for their support and companionship during the stay.

I wish to express my heartfelt gratitude to **Dr. Marut Jain**, whose presence has been one of the most defining influences of my PhD journey. More than a senior colleague and friend, he has been a mentor in the truest sense, patiently guiding me in conceptualizing ideas, writing with clarity, revising manuscripts, and navigating the process of academic publishing. His guidance, and belief in my potential helped to shape me into a more confident and capable researcher. Beyond academia, he has been a constant source of strength and friendship, standing by me during moments of doubt and pressure. His unwavering support, generosity with time and knowledge, and genuine support made even the most challenging phases of this journey manageable. I remain profoundly grateful for getting a true friend in PhD journey whose mentorship, friendship, has lasting impact on both my professional and personal growth.

I sincerely thank **Neethu Thoppil Joshikumar** for being a constant source of positivity, strength, and warmth throughout my PhD journey. Her thoughtfulness, encouragement, and presence especially during demanding phases brought balance and reassurance, and I remain deeply grateful for her unwavering support. Her companionship made the journey lighter and more joyful, transforming challenging days into moments of comfort and laughter. Through this journey, beyond a PhD colleague I got a true friend whose presence made my PhD experience far more meaningful.

I express my deep appreciation to the UQ-IITD Research Academy for providing an exceptional platform for global research, collaboration, and cultural exchange. Being part of this joint PhD program and representing it at national and international levels has been a unique privilege, and I am profoundly grateful for the academic exposure and opportunities it has offered. I respectfully acknowledge the encouragement and belief shown by our past and current leaders, **Prof. Naveen Garg, Prof. Nidhi Jain, Dr. Rajeev Shorey, Prof. Neetu Singh, and Prof. Vigneshwara, Dr.**

Nidhi Dubey whose mentorship and confidence in my abilities have been a continuous source of inspiration. I also sincerely appreciate the invaluable contributions of **Mrs. Ragini Gill and and Mrs. Ramya** whose warmth, dedication, and always ready to support has greatly enriched my experience at UQ-IITD.

I am very much thankful to my close friends **Mr. Abu Bakar, Ms. Nazia Afreen, Dr. Humna Rabiya Khan,** and **Ms. Aiman Afreen** who stood by me through every phase of my journey, celebrating achievements, offering comfort during challenges, and praying for my success. Your friendship has been a constant source of strength and meaning. Thank you for patiently listening, offering comfort during moments of self-doubt, celebrating milestones, and reminding me of perspective during difficult times. Your presence made this journey far less lonely and memorable.

Finally, I express my deepest respect and gratitude to my parents, **Mrs. Laila** and **Mohd. Israfil Noor** whose unwavering belief, sacrifices, and guidance have been the foundation of my journey. Your values, patience, and resilience have shaped who I am today. I am equally grateful to my dear sisters, **Farheena and Sanjeeda**, my precious nephews, for their unconditional love, support, encouragement, and companionship, which made even the most challenging moments lighter and more hopeful. I am deeply thankful to **my supportive brothers**, without whom this journey would not have been possible. Your constant encouragement, belief in me, and quiet strength carried me through moments of uncertainty and fatigue. Knowing that I always had your support gave me the courage to persist, dream bigger, and move forward with confidence. I am blessed to have you all. I extend my heartfelt thanks to my sister-in-law, **Mrs. Ishrat Fatima**, whose warmth, kindness, and cheerful spirit consistently uplifted me. Your ability to bring positivity and lightness, even during demanding times, meant more to me than words can express.

Above all, I humbly thank Almighty Allah for His countless blessings and guidance.

Jai Hind!

Aisha Noor

Financial support

This research was supported by an Indian Institute of Technology Delhi Research Scholarship and a Research grant from the UQ-IITD Research Academy. I acknowledge The University of Queensland Australia for the tuition fee and for providing the living stipend during my stay in Australia.

I express my sincere gratitude to the British Council, for awarding me the Commonwealth Split-Site Scholarship during my doctoral studies. This prestigious Scholarship has provided me with invaluable financial support and academic opportunities, enabling me to pursue advanced research during my stay at University College London.

I am deeply thankful to the Ministry of Education for its commitment to fostering excellence in research and higher education in India. The Institute fellowship at IITD has facilitated my academic journey and served as a source of motivation and encouragement throughout my doctoral study. I am indebted to my supervisor, Prof. K. K. Pant, for his guidance, support, and scholarly insights for all the fellowship, which have been instrumental in shaping my research endeavors. At every stage of my PhD, he consistently encouraged me to strive for excellence, motivated me to do better, and provided steady, balanced guidance during both progress and challenges. His mentorship extended beyond formal supervision, fostering confidence, independence, and critical thinking. I remain profoundly grateful for his enduring support and for the positive influence he has had on my academic growth.

Keywords

Antimicrobial Resistance, Silver nanoparticles, Dye Degradation, Life Cycle Assessment, Antibacterial Activity, Nanocomposites, Disk Diffusion

Australian and New Zealand standard research classifications (ANZSRC)

ANZSRC code: 090703 Environmental Technologies (45%)

ANZSRC code: 100703 Nanobiotechnology (35%)

ANZSRC code: 060599 Microbiology not elsewhere classified (20%)

Fields of research classification

FoR code: 1002 Environmental Biotechnology (70%)

FoR code: 1007 Nanotechnology (30%)

FoR code: 0605 Microbiology (10%)

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