1. A Concise Description of the Project

The discharge of organic pollutants, including dyes and pigments, from various industries such as textile, paper, plastic, wood, leather, pharmaceuticals, agriculture, and cosmetics poses significant environmental concerns [1,2]. These pollutants not only threaten aquatic ecosystems but also pose serious risks to human health. Consequently, their efficient degradation before environmental discharge is imperative. Several wastewater treatment techniques have been developed; however, many suffer from inefficiencies and high costs [3]. Conventional methods such as coagulation-flocculation require hazardous chemicals, while adsorption techniques generate secondary sludge and often rely on heavy metal-based removal processes. Similarly, ultrafiltration, particularly reverse osmosis, faces challenges related to membrane fouling, and electrochemical methods demand high energy input and costly reagents [4]. Advanced techniques, including photocatalytic reduction and Fenton-like oxidation, have emerged as viable alternatives but face limitations such as dependence on UV light, narrow bandgap energy constraints, and operational challenges at low pH due to catalytic precipitation.

To address these challenges, researchers are actively seeking cost-effective and eco-friendly wastewater treatment solutions. Metal-based nanocatalysts, particularly silver nanoparticles (AgNPs), have garnered significant attention due to their exceptional catalytic efficiency, optical properties, and antimicrobial activity [1]. However, AgNP synthesis often encounters obstacles such as aggregation, which compromises their stability and efficacy. Traditional synthesis methods, including chemical reduction, hydrothermal treatment, photochemical synthesis, and microwave irradiation, have limitations such as the requirement for toxic reducing agents, high-cost equipment, and energy-intensive processes [5]. Green synthesis approaches have been explored to overcome these limitations, with bioreduction using plant-derived polysaccharides emerging as a promising strategy. Tamarind Seed Polysaccharide (TSP), in particular, is an excellent candidate due to its rich functional groups, including hydroxyl and carboxyl moieties, which facilitate both reduction and stabilization of AgNPs. Unlike microbial-based synthesis, which requires stringent handling conditions, TSP offers a sustainable and scalable alternative [6]. Moreover, its high biocompatibility and renewable nature align with environmentally conscious nanotechnology.

This study aims to synthesize highly stable, crystalline, and uniformly spherical AgNPs utilizing TSP as a natural template (Figure 1a-b). A detailed kinetic analysis of the bioreduction process will be conducted using an OVAT (one-variable-at-a-time) approach to assess key parameters such as TSP concentration, reaction time, temperature, and solution pH. Additionally, the kinetics of the synthesized AgNPs will be examined using pseudo-first-order theory to develop eco-friendly nanocatalysts for azo dye degradation (Figure 1d). Furthermore, the antibacterial properties of AgNPs will be evaluated using agar disk diffusion assays to elucidate their potential mechanisms of action (Figure 1c). Overall, this research aims to advance the synthesis of green nanocatalysts, contributing to sustainable wastewater treatment and environmental remediation.

Research Gap: (a) The widespread application of AgNPs is significantly hindered by their tendency to aggregate, which compromises their stability and functional properties. Despite advancements in synthesis methods, achieving long-term stabilization remains a critical challenge that necessitates novel approaches to prevent agglomeration[7]. (b) Traditional optimization approaches, such as OVAT, fail to account for interactive effects among multiple factors influencing nanomaterial synthesis. This leads to suboptimal process conditions and inefficient resource utilization, highlighting the need for more robust, multifactorial optimization techniques[8]. (c) While the Taguchi method and statistical modeling offer efficient process optimization strategies, their application in AgNP synthesis and textile finishing remains limited. Existing studies primarily focus on optimizing absorbance at maximum wavelength (λ_{max}), neglecting other critical indicators like peak shifts and broadness, which are essential for ensuring nanoparticle quality and stability[9].

2. Measurable Impacts and Objectives

Long-term Impact: This project aims to enhance AgNP synthesis by addressing stabilization, process optimization, and statistical modeling challenges. *Key Issues:* (a) Preventing AgNP agglomeration for improved stability and functionality. (b) Overcoming the limitations of OVAT in nanoparticle synthesis. (c) Implementing advanced statistical modeling for optimized synthesis. *Likely Outcomes:* (a) More stable AgNP formulations with reduced agglomeration. (b) A systematic, efficient approach to synthesis optimization. (c) Better control over nanoparticle properties for improved applications. (d) Enhanced use of AgNPs in textiles, sensors, and antimicrobial materials. (e) Scientific publications and potential patents. **Objectives:** (a) Develop strategies to improve AgNP stability and prevent agglomeration. (b) Address OVAT limitations with a more effective optimization approach. (c) Implement statistical modeling (Taguchi, full factorial) for synthesis. (d) Optimize key parameters affecting nanoparticle yield and quality. (e) Explore AgNP applications in functional materials and textiles.

3. Timeframe and Major Tasks for the Project

Week 01–12: Literature review and knowledge advancements, *Week 01–04*: Study of AgNP stabilization and prevention of agglomeration, *Week 01–06*: Identifying limitations in OVAT and alternative optimization, *Week 03–08*: Implementation of Taguchi DoE for process optimization, *Week 05–10*: Statistical modeling and validation of optimized synthesis, *Week 05–10*: Physicochemical characterization of AgNPs, *Week 07–10*: Application of optimized AgNPs in dye and bacterial catalysis, and *Week 09–12*: Progress reports/ Publications/ Conference proceeding. A detailed description of research tasks has been provided in the *Supplementary Information*.

4. Enhancing Teaching and Research at Lincoln University

This project will provide undergraduate students with hands-on research experience in green chemistry, nanomaterial synthesis, and environmental remediation. Research findings will be integrated into chemistry and materials science courses, enhancing laboratory training and environmental awareness. Additionally, the project will support future research collaborations and grant applications in sustainable dyeing technologies. The details are: *(a)* The project will integrate hands-on research examples into General Chemistry and Advanced Chemistry to reinforce concepts in catalytic kinetics, synthetic chemistry, and structural techniques. *(b)* Undergraduates will engage in independent research, contributing to publications and external grant proposals. *(c)* This project will serve as a springboard for larger research initiatives, increasing opportunities for students to participate in summer research programs at UPenn and UDel under faculty mentorship. *(d)* Findings will be shared through seminars, workshops, and research presentations, fostering interdisciplinary discussions on nanotechnology and material science.

5. Measuring Project Success

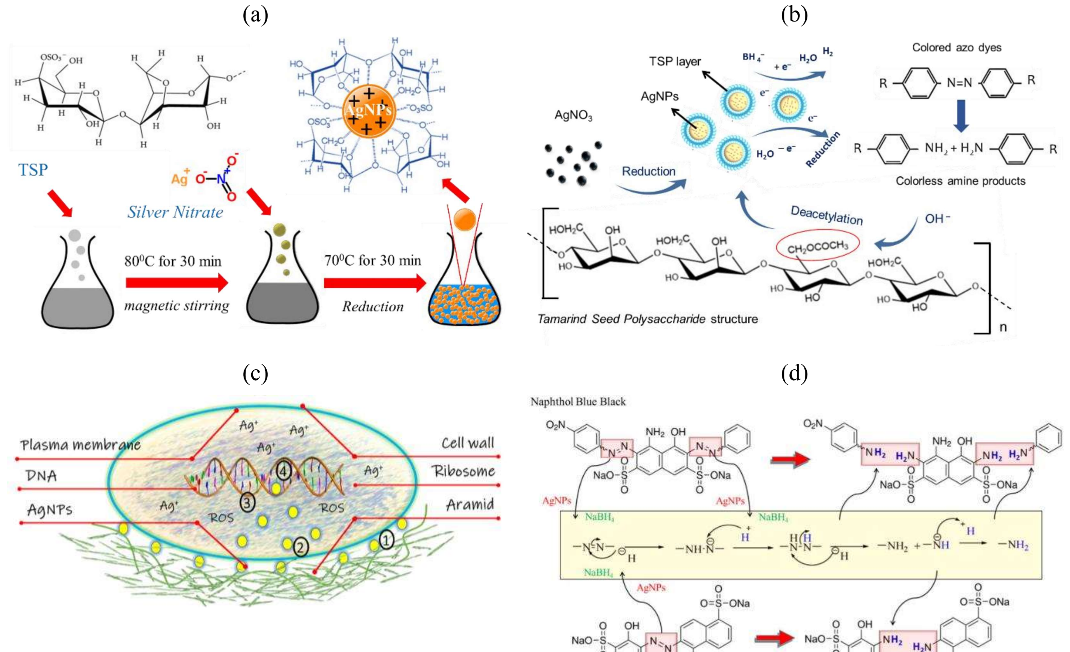
The project's success to be measured by: *(a)* the quality and reproducibility of the data will serve as key indicators, supporting external grant applications. *(b)* Success will be evaluated through student participation in research, resulting presentations, and publications. *(c)* The project's impact will be assessed by conference presentations, including the Annual Meeting, Lincoln's Science Fair, and the poster presentation.

6. Dissemination of Project Outcomes

(a) Where and When: Results will be presented at Lincoln University's Science Fair, Faculty Development Grant Seminar, and national conferences. *(b) With Whom:* Research findings will be shared with students, faculty, and the broader scientific community. *(c) Publication Plan:* The project outcomes will be submitted for peer-reviewed publication, with Lincoln University students as co-authors to highlight their contributions. *(d) Institutional Reports:* A project summary will be submitted to the Vice President of Academic Affairs and CETL to document research advancements and future directions.

[**Optional Attachment:** *Supplementary Information*]

Supplementary Information



1. Electrostatic attraction, 2. Production of free radicals, 3. Interaction with phosphorus-containing molecules, and 4. Stopping the DNA repetition.

Figure 1. (a) The synthesis of AgNPs, (b) reduction and stabilization of nanosilver in TSP, (c) antibacterial mechanism of AgNPs, and (d) catalysis of azo dyes. (All figures are reproduced from our previous reports [2,10-12])

Description of Research Tasks

Task 1. This task involves an extensive review of the existing literature on AgNP synthesis, stabilization, and catalytic applications. A detailed assessment of the limitations of traditional synthesis methods, including chemical reduction and hydrothermal techniques, will be conducted. Additionally, advancements in green chemistry approaches, particularly the use of biopolymeric stabilizers like TSP, will be analyzed to identify knowledge gaps and research opportunities.

Task 2. To enhance the long-term stability of AgNPs, this phase will investigate factors influencing aggregation, including pH, ionic strength, and reaction kinetics. The role of TSP in stabilizing AgNPs will be examined through spectroscopic and microscopic characterization methods such as UV-Vis, DLS, and TEM. The study will also compare the effectiveness of TSP with other stabilizers used in previous research.

Task 3. A critical evaluation of the OVAT approach in AgNP synthesis will be conducted. This task will highlight the shortcomings of OVAT, such as its inability to account for interactive effects between synthesis parameters. Alternative optimization techniques, including factorial design and response surface methodology, will be explored to improve process efficiency and nanoparticle quality.

Task 4. To achieve optimal synthesis conditions, the Taguchi Design of Experiments (DoE) method will be applied. This statistical approach will help determine the most significant parameters affecting AgNP properties, including precursor concentration, reaction time, temperature, and stabilizer-to-metal ratio. The goal is to maximize yield, stability, and catalytic efficiency.

Task 5. Once optimal synthesis parameters are established, statistical models will be developed to predict AgNP characteristics based on synthesis conditions. Regression analysis and ANOVA will be used to validate the reliability of the models. Experimental results will be cross-validated with theoretical predictions to ensure reproducibility.

Task 6. A comprehensive characterization of the synthesized AgNPs will be performed using TEM, SEM, XRD, and UV-Vis spectroscopy. These techniques will provide insights into particle size distribution, morphology, crystalline structure, and optical properties. The stability of the nanoparticles in different media will also be assessed using zeta potential measurements.

Task 7. The catalytic efficiency of the optimized AgNPs will be tested in the degradation of organic pollutants, specifically azo dyes, using $NaBH_4$ as a reducing agent. Reaction kinetics will be monitored using UV-Vis spectroscopy. Additionally, the antibacterial activity of AgNPs against gram-positive and gram-negative bacteria will be evaluated using the agar disk diffusion method.

Task 8. Regular progress reports will be compiled to document experimental findings and data analysis. Research outcomes will be disseminated through peer-reviewed journal publications and conference presentations. The results will contribute to advancing knowledge in nanotechnology applications for environmental remediation and catalysis.

Prior Proposal Outcomes

Goal 1. *Gradient Fiber Reinforced Self-Healing Polymer Composites*: Aimed at creating hybrid fiber composites with enhanced mechanical properties, self-healing, and shape-memory functionalities, promoting sustainability in advanced materials.

Outcome: *Mahmud Sakil* et al. Thermoset polymer composites with gradient natural and synthetic fiber reinforcement: Self-healing, shape-memory, and fiber recyclability. *Materials Today Communications* 35 (2023): 105950. https://doi.org/10.1016/j.mtcomm.2023.105950

Goal 2. *Coir/Glass Hybrid Composites with Self-Healing and Shape Memory*: Focused on combining natural coir fibers with glass fibers to develop thermoset composites with room-temperature self-healing and shape-memory properties.

Outcome: *Mahmud Sakil* et al. Coir/glass hybrid fiber reinforced thermoset polymer composite laminates with room-temperature self-healing and shape memory functions. *Industrial Crops and Products* 201 (2023): 116895. https://doi.org/10.1016/j.indcrop.2023.116895

Goal 3. *Hybrid Hemp/Glass Fiber Shape Memory Photopolymers*: Developed hemp and glass fiber-reinforced photopolymers with shape memory and flame retardancy, targeting high-performance, eco-friendly composite applications.

Outcome: *Mahmud Sakil* et al. Hybrid hemp/glass fiber reinforced high-temperature shape memory photopolymer with mechanical and flame-retardant analysis. *Scientific Reports* 13.1 (2023): 17830. https://doi.org/10.1038/s41598-023-44710-6

Goal 4. *Knitted Natural Fiber Structures for Crack Closure in Self-Healing Composites*: Explored the use of knitted natural fiber fabrics to improve crack closure and healing efficiency in polymer composites, enhancing material longevity and sustainability.

Outcome: *Mahmud Sakil* et al. Effect of Knitted Structure of Natural Fibers for Closing Cracks in Self-Healing Polymer Composites (May 2023) at the conference: *The Fourth International Conference on Damage Mechanics* (ICDM4), Baton Rouge, LA, USA

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