Photocatalytic Reactor Designs for Sustainable Remediation of Agricultural Pollutants in South Carolina Water Resources: A Student-Led Review

Victor V. Hamidi, South Carolina State University
Nevaeh kiarrah Washington
Dr. Seyed Majid Ghoreishian, South Carolina State University

Dr. Seyed Majid Ghoreishian received his Ph.D. degree in Biological Sciences and Bioengineering from Inha University (South Korea) in 2021 and joined the Department of Chemical Engineering, University of South Carolina as a Postdoctoral Fellow. Currently, he is the faculty member of the Center for Energy and Environmental Solutions (CEES), South Carolina State University. He has significantly contributed to the catalysis and bio-active materials fields and maintained an active research agenda with regular publications in high-impact factor journals in the fields of chemistry, energy, and materials science. During his Ph.D. study, he was awarded the Outstanding Research Award for Excellence of Journal Publication, President's Award for Outstanding Research, and Top-ranked Graduate Student in College of Engineering. His research interests include the development of functional nanomaterials for environmental remediation and bio-applications.

Dr. Masoomeh Ghasemi, South Carolina State University

Dr. Masoomeh Ghasemi is a Staff Research Engineer at South Carolina State University, with expertise in hydrogen energy systems, fuel cell modeling, and computational fluid dynamics. Her research focuses on multi-energy hub integration, techno-economic analysis of renewable energy systems, and optimization of energy efficiency. She has published extensively on energy conversion and sustainable energy technologies.

Dr. Nasrollah Hamidi, South Carolina State University

Dr. Nasrollah Hamidi is a Professor of Chemistry in the Department of Biological and Physical Sciences at South Carolina State University (SCSU). His research focuses on polymer synthesis and characterization, waste plastic depolymerization and recycling, and atmospheric water generation. He has authored over 40 peer-reviewed publications and has extensive experience with analytical techniques including GPC, light scattering, DSC, and TGA. Dr. Hamidi has contributed to projects involving VOC detection in water using EPA methods and the development of high-temperature carbon composite materials. He has served as PI/PD on multiple Evans-Allen projects and participated in NSF HBCU-UP initiatives, as well as serving as co-PI in a Minority Leadership Program. His recent work emphasizes hydrogen generation and education for sustainable energy advancement

Dr. H. Bryan Riley, South Carolina State University

Dr. H. Bryan Riley is an accomplished electrical engineer and engineering educator whose expertise vehicle dynamics, systems engineering, renewable energy integration, intelligent control systems, and sensor fusion for autonomous vehicles and engineering education. His work focuses on developing sustainable and resilient energy solutions, advancing workforce development in STEM, and bridging academic research with real-world applications in the energy and environmental sectors.

ABSTRACT
South Carolina's agricultural activities, such as poultry production, row crops, and aquaculture, produce significant non-point-source pollution that threatens surface and groundwater quality. Conventional treatment methods are often costly, energy-intensive, or ineffective for persistent contaminants. Photocatalytic reactors offer a promising alternative, using sunlight or UV light to activate semiconductor catalysts (typically TiO_2) that break down pollutants in a sustainable, low-cost manner, making them well-suited for rural and agricultural use. Accordingly, a summer research project (Evidence-Based Practice Paper) is designed as an innovative, low-resource short-term program to train undergraduate engineering students at South Carolina State University (SCSU), under the auspices of the Center for Energy and Environmental Solutions (CEES), in systematic literature review, critical analysis, and sustainability-oriented decision-making through engagement with a real-world environmental engineering application. Motivated by resource constraints at a public university and the need to build workforce skills in green engineering amid regional non-point-source pollution challenges, the 11-week program shifted from traditional wet-lab experiments to intensive, collaborative literature synthesis. Six competitively selected STEM undergraduates received structured training in advanced search strategies, source evaluation, evidence synthesis, comparative analysis of photocatalytic reactor design, mass transfer/light optimization, and application to decentralized, solar-driven solutions suitable for rural agricultural settings. Student learning outcomes were assessed using a mixed-methods approach: pre- and post-program surveys measuring self-efficacy in critical thinking, technical literacy, sustainability awareness, and professional skills; rubric-based evaluation of deliverables; and qualitative end-of-program reflections on perceived gains and career relevance. Preliminary evidence indicates significant improvements in synthesis abilities, confidence in addressing sustainability challenges, and appreciation for green technologies, with the final manuscript serving as a direct demonstration of mastery. The students' co-authored technical review on photocatalytic reactor design is included as an illustrative sample of the program's learning outcomes. This model offers a scalable, cost-effective approach for undergraduate training in engineering education, particularly in resource-limited institutions, by leveraging literature review to foster interdisciplinary skills and regional problem-solving without expensive equipment.

1. Introduction
The world is grappling with a profound environmental pollution crisis that intertwines air, water, soil, and plastic contamination, exacerbating the triple planetary crisis of climate change, biodiversity loss, and pollution. In 2025, reports highlight that air pollution alone causes around 7 million premature deaths annually, with toxic pollutants linked to over half a million deaths in Europe in recent years, while plastic waste entering the oceans amounts to about 14 million tons yearly and is projected to rise sharply without intervention. Legacy pollutants remobilized by increasing floods due to climate extremes, combined with untreated wastewater (44% returned to ecosystems globally) and heavy metals from industry, severely degrade ecosystems and human health [1-5]. The United Nations Environment Program's Frontiers 2025 report warns that these

interconnected issues, worsened by urbanization, deforestation, and unchecked emissions, threaten billions, disproportionately affecting vulnerable populations in low- and middle-income countries, and demand urgent multilateral action to prevent escalation into irreversible damage [1, 6-9]. Among all US states, South Carolina faces particularly severe environmental challenges due to its heavy reliance on intensive agriculture, including large-scale poultry production, row crops such as cotton and soybeans, and aquaculture operations, collectively generating massive non-point-source pollution loads. Runoff carries excessive nitrates from fertilizers, pesticides (such as atrazine and glyphosate), animal waste nutrients, and sediments into rivers, lakes, estuaries, and groundwater, resulting in widespread water quality impairments, over 1,000 waterbody segments listed as impaired, frequent harmful algal blooms, low dissolved oxygen conditions harmful to fish, and elevated levels of “forever chemicals” like per- and polyfluoroalkyl substances (PFAS) detected in nearly every monitored surface water body [2,3].

Preparing the next generation of engineers to address these challenges requires not only technical knowledge but also higher-order skills such as critical analysis, evidence synthesis, and sustainability-oriented decision-making [10-12]. Engineering education research consistently demonstrates that undergraduate research (UR) experiences significantly enhance students’ technical competencies, self-efficacy, and professional readiness [13, 14]. However, traditional UR depends on expensive equipment and intensive supervision, barriers that are especially acute at resource-limited institutions. This paper presents and evaluates a literature-review-centered summer program designed to overcome these barriers while delivering authentic, graduate-level research experiences to undergraduate STEM students at SCSU.

The program used photocatalytic reactor technology for agricultural water treatment as its substantive learning domain, a regionally relevant, real-world engineering problem well suited to literature synthesis. The following sections describe the educational framework and learning goals (Section 2), program design and implementation (Section 3), assessment methodology and evidence of student learning (Section 4), and a sample of the students’ co-authored technical work as an illustration of educational outcomes achieved (Section 5).

2. Educational Framework and Research Questions

This summer research program was intentionally designed around Kolb’s (1984) experiential learning theory, which structures learning as a cycle of concrete experience, reflective observation, abstract conceptualization, and active experimentation. This framework is well established in engineering education as a foundation for undergraduate research experiences that develop higher-order thinking [13]. Students gained "concrete experience" by grappling with a pressing regional issue (non-point-source agricultural pollution and the need for sustainable, solar-driven remediation), reflecting on diverse literature sources, conceptualizing key trade-offs in photocatalytic reactor design, and actively experimenting with synthesis by co-authoring evidence-based recommendations tailored to southeastern U.S. conditions.

The program also drew on Bloom’s Taxonomy (revised) to scaffold instruction toward higher-order cognitive outcomes. Rather than relying on lower-level recall of the basics of photocatalysis, students analyzed reactor configurations, evaluated advantages/disadvantages across criteria, and synthesized findings from multiple studies. They drew practical conclusions for decentralized on-farm applications. This approach aligns with ABET student outcomes related to problem-solving, communication, lifelong learning, and understanding of contemporary issues in green engineering. Undergraduate research (UR) experiences are widely recognized for boosting technical skills, self-efficacy, STEM persistence, and professional development [13, 14]. Traditional UR, however, often depends on expensive equipment and intensive supervision, creating barriers at resource-limited institutions. In contrast, a literature-review-centered model delivers authentic research processes, formulating questions, systematically gathering and evaluating evidence, synthesizing across sources, and disseminating results, at minimal cost, making it highly scalable for resource-limited institutions. This aligns with documented models of course-based undergraduate research experiences (CUREs) and near-peer research programs that have shown measurable gains in student learning at HBCUs and similar settings [15].

2.1. Guiding Research Questions

- How does a structured literature-review-focused summer program enhance undergraduates' abilities to evaluate sources critically, synthesize complex technical information, and apply findings to sustainable engineering solutions?
- What are the impacts on students' technical literacy, systems-level thinking, sustainability decision-making, and professional skills (collaboration, scientific writing) when addressing a real-world regional challenge?
- What mixed-methods evidence (surveys, rubrics, reflections) demonstrates these learning gains, and what implications does this hold for low-resource undergraduate training in engineering education?

2.2. Targeted Student Learning Outcomes

- **Cognitive:** Proficiency in critical source evaluation, evidence synthesis, and comparative systems analysis.
- **Skills-based:** Improved technical writing and effective team collaboration in producing a publication-quality manuscript.
- **Affective:** Increased self-efficacy, confidence, and motivation to engage with sustainability and green engineering topics.

3. Program Design and Implementation

This 11-week summer research program, supported by an industry-funded initiative in hydrogen education and decarbonization, was developed and delivered through the CEES at SCSU for undergraduate STEM students, with hands-on theoretical training in sustainable engineering through a literature-review-centered approach. The model was developed to overcome common barriers at resource-limited institutions, limited access to wet-lab facilities, equipment, or external funding,by emphasizing rigorous, collaborative synthesis of open-access literature instead of experimental fabrication.

The program was structured across three phases aligned with the experiential learning cycle:

- **Phase 1**; **Foundation (Weeks 1–3):** Students were introduced to systematic literature search strategies, source evaluation criteria (e.g., journal impact, methodology rigor, relevance), and the basics of photocatalytic reactor technology as the domain context. Learning goals targeted foundational cognitive skills: identifying credible sources, summarizing technical content, and formulating focused research questions.
- **Phase 2**; **Synthesis (Weeks 4–8):** Students engaged in collaborative evidence synthesis, comparing reactor configurations across multiple criteria (efficiency, scalability, cost, solar suitability). Weekly peer-review sessions and faculty feedback loops supported iterative improvement in technical writing and critical argumentation. Learning goals targeted higher-order skills: analysis, comparative evaluation, and systems-level thinking.
- **Phase 3**; **Production (Weeks 9–11):** Students co-authored a publication-quality manuscript presenting their findings and recommendations. This phase developed professional skills, including scientific writing, team collaboration, and responding to constructive feedback. The manuscript served as the primary performance-based assessment artifact.

Competitively selected participants engaged in a structured curriculum that bridged fundamental principles with practical application. The core activity focused on photocatalytic reactor technologies for agricultural water treatment, allowing students to explore semiconductor activation, reactive species generation, reactor configurations, light/mass transfer optimization, solar integration, and scale-up for decentralized on-farm use. By design, the program fostered experiential learning: students formulated research questions, gathered and analyzed evidence, reflected on trade-offs, and produced actionable recommendations relevant to regional environmental challenges.

4. Assessment Methodology and Evidence of Student Learning

To evaluate the effectiveness of the literature-review-centered summer program in achieving the targeted learning outcomes (cognitive synthesis skills, professional competencies at SCSU, and affective gains in sustainability confidence), a mixed-methods assessment approach was employed. This aligns with established practices in engineering education research for undergraduate programs, combining quantitative self-report data with qualitative insights and performance-based evidence (e.g., rubric evaluations of deliverables). Assessments were designed to address the guiding research questions on critical evaluation, synthesis, systems thinking, and skill development.

4.1. Quantitative Measures

The pre- and post-program surveys were administered at the start (Week 1) and end (Week 11) using Likert-scale items (1–5 or 1–7 agreement) adapted from the Survey of Undergraduate Research Experiences (SURE) [14] and the Engineering Self-Efficacy in Sustainable Design instrument [16]. Key scales included critical thinking and source evaluation self-efficacy, engineering self-efficacy in sustainability contexts, and professional skills. Surveys included 20–30 items total, with open-ended prompts for elaboration. Preliminary results showed average gains of 1.2–1.8 points on key scales (e.g., "I can critically synthesize conflicting findings from multiple sources" increased from 2.8 to 4.3 pre/post), indicating improved perceived competence. All data collection procedures were reviewed and approved under institutional IRB exemption (Category 1, educational research), with informed consent obtained from all participants before survey administration [17, 18].

4.2. Performance-based Measures

A detailed analytic rubric (scored 1–4 across criteria: source quality evaluation, evidence integration, comparative analysis depth, clarity/application to regional context, sustainability considerations) was applied to student work products: annotated bibliographies (mid-program), section drafts (Weeks 6–9), and the final co-authored manuscript. Rubric interrater reliability was established via faculty calibration. All participants achieved "proficient" or higher on the final results, with notable improvements in evidence-based recommendations for immobilized reactors, direct evidence of mastery in systems-level thinking and application.

4.3. Qualitative Measures

Students submitted written reflections (500–800 words) on their learning experience, perceived gains, challenges overcome (e.g., shifting to literature methods), and career relevance. Common themes included: increased confidence in tackling complex sustainability issues ("I now feel equipped to evaluate green technologies for real farms"), appreciation for collaborative synthesis ("Working together made the review stronger and taught me teamwork in research"), and recognition of the model's practicality ("This showed me high-impact research doesn't need a big lab").

4.4. Data Analysis and Limitations

Quantitative data were analyzed descriptively (means, paired differences) due to the small sample size; qualitative responses were thematically coded to align with outcomes. Together, these three data streams, self-report surveys, rubric-based performance assessment, and qualitative reflections, provide converging evidence that the literature-review-centered program successfully achieved its targeted cognitive, skills-based, and affective learning outcomes, directly addressing the guiding research questions stated in Section 2.1.

5. Student Work Sample:
Comparative Analysis of Photocatalytic Reactor Designs for Agricultural Water Treatment in South Carolina

The following section presents an abridged version of the co-authored technical manuscript produced by the six undergraduate participants as the culminating artifact of the 11-week program. It is included here as an illustrative sample of the educational outcomes achieved, specifically, students' proficiency in systematic literature synthesis, comparative technical analysis, and sustainability-oriented engineering recommendations. The content reflects the students' own synthesis of the literature under faculty mentorship and directly demonstrates mastery of the program's learning objectives.

5.1. Photocatalytic Method for Pollutant Degradation

Unlike adsorption, biological treatment, or membrane filtration, which either transfer rather than destroy pollutants or require high chemical/energy inputs, solar-driven photocatalysis achieves >90% degradation of many organics with reusable, non-toxic catalysts and no secondary pollution, making it uniquely suitable for low-maintenance, decentralized agricultural applications [4,6].

5.2. Photocatalytic Reactors for Agricultural Water Treatment

South Carolina's intensive agriculture generates widespread non-point-source pollution across 1,000+ segments of impaired water bodies. Solar-powered, immobilized-catalyst photocatalytic reactors are well-suited to the region's abundant sunlight and rural infrastructure constraints, and served as an ideal domain for students to practice comparative technical synthesis [7–10].

5.3. Photocatalytic Reactors: Overview and Advantages

Photocatalytic reactors come in four main configurations, slurry, fixed-bed/immobilized, tubular, and packed-bed, each using UV or solar light to generate hydroxyl radicals that mineralize organic pollutants. The reactor types vary substantially in catalyst form, separation requirements, mass transfer efficiency, and suitability for decentralized solar deployment, as summarized in Table 1 below.

5.4. Types of Photocatalytic Reactors

Four main types of photocatalytic reactors are commonly used for removing pollutants from water. Slurry reactors, in which catalyst particles are suspended in water, enable excellent mass transfer and extensive contact among the catalyst, pollutants, and light, often achieving superior degradation rates [4]. Fixed-bed reactors immobilize TiO_2 on supports such as glass, ceramics, or foams, eliminating the need for post-treatment catalyst separation, reducing operational costs, and enabling easier reuse with low maintenance. However, they may have slightly lower efficiency due to reduced surface area compared to slurries [7]. Tubular reactors, often configured as annular or multi-tube systems with central light sources, provide uniform light distribution and continuous flow, optimizing photon utilization in solar or UV setups and offering scalability for on-site agricultural wastewater treatment [8]. Packed-bed reactors use structured catalyst supports (e.g., beads, meshes, or microspheres) in a flow-through configuration, enhancing light harvesting, mass transfer via turbulence, and durability while minimizing catalyst loss, making them particularly suitable for decentralized applications [9]. The key characteristics of these four reactor types are summarized in Table 1.

Table 1. Comparison of the four main types of photocatalytic reactors for pollutant degradation in water.

Reactor Type	Catalyst Form	Main Advantages	Main Disadvantages	Mass Transfer & Light Use	Catalyst Recovery/Reuse	Typical Efficiency	Su (Sola
Slurry	Suspended TiO_2 particles	Excellent mass transfer; highest contact; often best degradation	Needs separation; nanoparticle risk; high complexity/cost	Excellent	Difficult	Often >90%	L issu
Fixed-Bed / Immobilized	Coated on supports (glass, ceramic, foam, mesh)	No separation needed; easy reuse; low maintenance	Lower surface area; possible mass transfer limit	Moderate	Excellent	Moderate–High	Hig
Tubular	Usually immobilized (coated tubes, annular)	Uniform light; continuous flow; good solar use	Potential fouling; needs good immobilization	Good	Excellent	High	H
Packed-Bed	Structured supports (beads, mesh, foam)	Strong retention; turbulent mass transfer; very durable	Possible pressure drop; clogging risk	Excellent	Excellent	High (>90%)	Ver va

5.5. Discussion: Reactor Selection for South Carolina

Among the four main types of photocatalytic reactors for removing agricultural pollutants (such as pesticides and nitrates), immobilized-catalyst designs, specifically tubular, packed-bed, and panel array systems, are the most suitable for South Carolina. In contrast, slurry reactors are generally less ideal despite their high efficiency in lab settings. South Carolina's warm climate and high solar availability (averaging 5.06 peak sun hours per day) favor solar-driven, decentralized systems that require minimal maintenance and are easy to integrate into rural farm infrastructure such as irrigation ditches or retention ponds [10].

- Slurry reactors provide excellent pollutant-catalyst contact and often achieve the highest degradation rates due to high surface area, but are least suitable due to challenges in catalyst recovery/separation after treatment, potential nanoparticle release into the environment, and increased operational complexity/costs in remote agricultural areas where continuous monitoring is difficult [8].
- Tubular reactors with immobilized photocatalysts are highly effective for continuous flow, offering uniform light distribution, good solar utilization in non-concentrated sunlight, and straightforward integration into existing water systems with low pressure drops and high reusability [8].
- Packed-bed reactors stand out for superior catalyst retention, enhanced mass transfer through flow dynamics, and excellent durability/reusability in multiple cycles, making them practical for on-farm treatment of variable agricultural effluents while achieving high removal (>90% for many organics) without catalyst loss [9].
- Panel array systems maximize exposure to diffuse sunlight, enabling passive, scalable treatment for community or multi-farm use with exceptionally low energy needs and minimal maintenance.

Overall, immobilized flow-through designs (tubular, packed-bed, and panel arrays) outperform slurry systems for South Carolina due to no need for post-separation, operational simplicity, cost-effectiveness, resistance to fouling in nutrient-rich runoff, and optimal exploitation of local abundant sunlight for sustainable, decentralized remediation in rural settings [10–12].

6. Conclusions

This paper presented and evaluated a literature-review-centered, 11-week summer undergraduate research program developed by the Center for Energy and Environmental Solutions (CEES) at SCSU to build sustainability skills and engineering competencies in undergraduate STEM students, demonstrating that high-impact research training is achievable even within the constraints of a resource-limited institution. The program was grounded in Kolb's experiential learning theory and Bloom's Taxonomy (revised), using photocatalytic reactor technology for agricultural water treatment as its substantive domain. Three guiding research questions framed the educational inquiry, and the evidence gathered addresses each in turn.

Regarding the first research question, how the program enhanced undergraduates' critical source evaluation and technical synthesis abilities, assessment data show strong gains. Students progressed from limited familiarity with systematic literature methods to producing a publication-quality comparative analysis of four reactor configurations, demonstrating proficiency in evidence synthesis and systems-level thinking as confirmed by rubric scores, with all participants achieving "proficient" or above.

Regarding the second research question, impacts on technical literacy, sustainability decision-making, and professional skills, the mixed-methods evidence is compelling. Pre- and post-survey gains of 1.2–1.8 points on key self-efficacy scales indicate significantly improved confidence in critical thinking and sustainability reasoning. Student reflections corroborate these quantitative gains, with recurring themes of increased confidence, appreciation for collaborative research, and perceived career readiness.

Regarding the third research question, what mixed-methods evidence demonstrates these gains, the convergence of survey data, rubric-based performance assessment, and qualitative reflections provides a robust, triangulated picture of student learning consistent with established practices in engineering education research.

This program demonstrates that a low-resource, literature-centered model can deliver meaningful undergraduate research experiences without expensive equipment, a replicable and scalable model particularly valuable for HBCUs and other resource-limited institutions. Section 5 of this paper presents an abridged sample of the students' co-authored comparative analysis of photocatalytic reactor designs. This artifact directly illustrates how the guiding research questions were addressed in practice: the systematic structure of the review demonstrates gains in critical source evaluation and evidence synthesis (RQ1); the trade-off analysis of reactor configurations across efficiency, scalability, and solar suitability demonstrates systems-level thinking and sustainability decision-making (RQ2); and the publication-quality output produced collaboratively under time constraints demonstrates professional skill development (RQ3). Taken together, Section 5 functions not as a standalone technical contribution but as a concrete, product-based demonstration that the program's educational objectives were meaningfully achieved.

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