# A Characterization of High School Students' Nanoscience Research

David K. Pugalee, Warren J. DiBiase

***Abstract*—**Nanoscience as an emerging area of science has the potential to contribute to revolutionary breakthroughs in multiple fields. High schools should recognize nanoscience as a critical topic for their curriculum. This paper reports on a nanoscience summer enrichment program for high school students. Paper and poster submissions were submitted and critically analyzed in terms of identification of a research problem, scientific thought, research design, discussion, and conclusions. Statement of research problems were generally specific identifying key components and a problem of interest. Students' scientific thought ranged from low to developing characterized by limited background research and development of scientific ideas related to nanoscience. Research design was generally well-conceptualized with clear procedures, identification of variables, and reproducibility. Discussion sections were well-written in stating the results of the experiments, identification of limitations, and relating the conclusion to the research relevance. Conclusions were presented with clarity and tied directly to the research problem.

***Index Terms*—** Curriculum, Education, Nanoscience, Nanotechnology

## I. Introduction

Researchers argue that since 2000 more discoveries have come from nanotechnology than any other scientific area with discoveries penetrating all areas of society [1]. In simple terms, nanosciences and nanotechnologies are concerned with the study of nano-sized objects [2] that can be shaped at the molecular level, enabling the manipulation of the physical world [3]. The implications of nanoscience research have been noted by global entities whose investments in the industry have reached a quarter of a trillion US dollars (USD) [4], and whose global market value was estimated at 75.8 billion USD in 2020 [5]. Further, it has been estimated that the number of nanotechnology jobs globally would exceed 6 million by 2020 [6] while the Triennial Review of the National Nanotechnology Initiative [7] found a 20 percent increase in the number of STEM jobs between 2000 and 2014 and the U.S. Bureau of Labor Statistics projected a 15% increase between 2012 and 2022 in science and engineering jobs [8]. The potential for nanoscience to revolutionize STEM education should play a significant role in secondary education curricula if we are to broaden access and increase interest in the field as part of expanding the STEM pipeline. As argued by scholars, an aim of science education should include the development of scientifically literate citizens and industry professionals, capable of using and contributing to nanotechnologies in responsible ways [3].

Governments around the world are making considerable efforts to be at the forefront of nanoscale science and engineering research. For instance, the National Nanotechnology Initiative (NNI), developed in 2001, involves 25 federal agencies committed to federal nanotechnology development and nanoscience educational initiatives [9, 10, 11]. At the center of the NNI's mission is the development of sustainable educational resources, a competent workforce, and supporting infrastructure to advance nanotechnology [9, 10]. To catalyze this movement, the NSF established The National Center for Learning and Teaching in Nanoscale Science and Engineering (NCLT) in 2004 [11, 12]. The NLCT is a multi-institutional organization concerned with the development of learning research and technology, professional development, dissemination, community building and evaluation [12]. The work of the NCLT has been instrumental in helping to establish a community of secondary and post-secondary nanoscience educators, offering professional development for practicing science teachers and defining learning goals (i.e. Big Ideas of Nanoscience) for nanoscience education [11, 13] that now serve as a framework for development of nanoscience education curricula for grades 7-16 [11].

Examples of large-scale secondary nanoscience curriculum development initiatives include the NSF funded projects. NanoLeap and NanoSense projects were established in 2004 [11, 14, 15, 16]. NanoLeap set out to develop, implement, and evaluate nanoscale science and engineering curricula to replace existing secondary school STEM lessons. Findings of the NanoLeap project included that the designed curriculum supported inquiry-based teaching and learning, significantly increased students' understanding of core science and core nanoscale STEM concepts and ideas, applications, and careers, but had no statistically significant increase in interest and engagement in the learning sciences, more broadly [11, 14, 15]. In contrast, the NanoSense project at SRI International set out to integrate nanoscale learning into secondary schools by building on concepts that exist within the current STEM curriculum and connecting core science concepts with the Big Ideas in Nanoscience [11, 13, 16]. The SRI team took a

Manuscript received September 14, 2022. This work was part of the Summer Ventures in Science and Mathematics program.

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constructivist approach to learning in which the lessons are centered around attractive applications of nanoscience to promote interest and motivation in the field. Evaluations of the NanoSense curriculum at the classroom level indicated that students were successful in their learning of simple nanoscience and engineering concepts, their use of nanoscale vocabulary, and ability to describe nanotechnology applications, though superficially. However, students struggled to describe the underlying scientific principles that underlie nanoscale properties, indicating areas for growth in secondary nanoscale curriculum design [11].

## II. Analysis of Student Research Papers

### A. *Overview of the Research Program*

Fifteen high school junior and seniors participated in a four-week course as part of a university STEM enrichment program. Students applied and were selected based on the strength of their applications as rated by a panel, so selection was competitive. Successful applicants were generally in the top 10 percent of their class and demonstrated active involvement in STEM courses and extracurricular activities. The program included three STEM courses, but this paper focuses only on the Nanoscale Science course and the students' research reports.

In addition to content development in each course, Students in the course were mentored by experts in nanoscience and also received mentoring in research processes and scientific communication. Students developed a topic for further study. Four papers were selected for analysis. Two of these papers had two authors. Several students submitted presented posters but did not complete formal papers.

A document analysis approach was used by the researchers to review the papers and then applying a thematic coding approach to identify text and illustration components that corresponded to the major components of a research paper. The Two researchers coded segments and reconciled any differences in codes and their related classification. Thematic analysis allowed for the characterization of the students' papers around the widely accepted components of a research paper [17, 18]. Each of the sections that follow provide a characterization of the students' research as reported in their formal papers.

### B. *Statement of Research*

While most students clearly identified research problems, there were notable differences in their clarity. For example, one student rated the potential risk of nanomaterials in cosmetic products. The problem was never explicitly stated, but was developed in the paper abstract and the background sections. Other papers, however, clearly identified their research statement or question. This is represented in a student's research statement about microplastics: "This research aims to investigate the impact of microplastics on double-stranded DNA to produce further evidence concerning microplastic pollution and clean-up." Students did not always demonstrate an understanding of the nuances between problem statement, research question or hypothesis. In the project on creating microplastics from milk and vinegar, the student talked about a hypothesis; however, there is no hypothesis clearly stated in the paper. "The subsequent research was used to back the hypothesis that casein plastic could be used as an alternative form of plastic that is more environmentally friendly than traditional plastics." Despite incongruencies, students identified research problems and what their investigations were intended to address.

### C. *Scientific Thought*

Most students struggled to show an in-depth understanding of the research problem evidenced through well formulated backgrounds for their problem. In most cases, background information and review of related research were based on three to five publications. Related research was not described or was absent, making it difficult for the reader to determine the innovation of students' research conceptualizations. However, several students did develop key ideas that properly connected their studies to relevant research studies and scientifically conceptual papers. In the study of nanoparticles in agriculture, the student adequately developed perspectives on two key variables – herbicide resistance and nanoparticle uptake. This student provided clear descriptions of the concepts and situated them within the scientific literature. Similarly, a study on the use of milk in production of environmentally friendly plastics explored sources on how to transform milk into plastic and the efficacy of related products. Yet, these discussions were sometimes surface level and provided limited details to illustrate a clear connection to nanoscience. Some students did elaborate on the science related to their project, clearly connecting to a problem that could be addressed through the research. "Recently microplastics have been discovered within the human anatomy due to digestion and absorption of the miniature particles. Multitude of health risks are associated with microplastic contamination in humans such as the denaturation of double-stranded DNA." The student goes on to connect scientific literature to their study of the influence of microplastics on DNAin response.

### D. *Research Design*

Research design sections were expected to convey clearly detailed development of procedures and methods. Variables should have been clearly identified and operationalized providing a clear pathway by which the research question could be addressed. It was anticipated that details would be sufficient for replicability of procedures utilized in the study. Most project provided clear details though some minor elements were absent – such as specific materials and their units of measurement. Most students identified and described the variables that were the focus of the study, but did not always provide enough information that would be required to truly operationalize them.

In the majority of papers, students incorporated visuals to demonstrate the methods employed. Figure 1 shows how plant roots were exposed to solutions with silver nanoparticles. The process of synthesizing the nanoparticles was detailed and replicable. Several students used numbered lists of steps to clearly convey the process used in their experiments. Such as

“Place 21 microcentrifuge tubes within a microcentrifuge tube rack in rows of five. With a thin permanent marker, individually label the tops of one row of tubes: DNA, $DNA_0$ , $DNA_1$ , $DNA_2$ , and $DNA_3$ . For another row of tubes, repeat this process, but label the tops, $P_0$ , $P_1$ , $P_2$ , and $P_3$ . Repeat this process with S1, S2, and S3. Lastly, label the extra tube with the letter B. See Figure 2a for reference.”

The specificity of the procedures used in the students’ studies was one of the strong points of their scientific communication. Generally, processes were described with enough detail that replicability was possible.


50 µL in 100 mL, 100 µL in 200 mL, control (left to right)

Fig. 1. Three Plant Samples in Solution

### E. Discussion

Discussion sections systematically provided some type of summary of the outcomes of the investigations. Some students included separate ‘Results’ sections prior to a ‘Discussion’ section which is appropriate. For our analysis we considered these as part of the larger discussion of the outcomes of the projects.

Students provided information on the results that connected clearly to the research problem. “Nanosized materials were proven to be more toxic when used in large amounts and immoderately.” While this was done with varying levels of clarity, there was consistent evidence that students were aware of the importance of these connections.

Students used tables to summarize data. These tables provided a tool for students in discussion the outcomes of their projects. This is illustrated in exploring the decomposition time of plastics.

TABLE I. Decomposition Times

| Type of plastic | How long it takes to decompose |
|---|---|
| Casein | 7 days (Bagares 2020) |
| Petroleum | 500-1,000 years (Wonderopolis n.d.) |
| Plant-Based Hydro-Biodegradable Plastic | 2-3 months (Wonderopolis n.d.) |
| Polyethylene Terephthalate | 500-700 years (Barak 2020) |

There were noted instances when students did not provide a clear analysis of their work. One student stated, “There is no formal conclusion to the question” without providing an explicated review of the data that would support such a broad statement. Despite these limited instanced, there was evidence that students’ discussions provided information on outcomes of their investigations, and these were generally described with details to understand how the data supported the research problem as described.

### F. Conclusions

Students’ conclusions captured the primary outcome of their work, though it was not always explicit which data supported the statements. For example, the use of micromaterials in cosmetics conclusion was stated “The range of toxicity between all nanomaterials used in cosmetic products is highly wide and extensive. Even so, being able to figure out the toxicity of an ingredient (specifically a nanomaterial ingredient) is quite simple. The most important things to look out for in cosmetics products is the usage of nanomaterials. In moderation, the effects of nanomaterials are nonexistent or at the very least significantly lower.” Students may have elaborated on their findings to interpret their findings as is seen in this statement: “Upon further observation, the blue fluorescence was attributed to the residue of fertilizer or small attached strands from other origins. If there were silver nanoparticles in the roots, there would be a reddish yellow glow”. Conclusions were generally tied back to the primary focus of the research problem.

Most students were successful in stating results of their experiments and providing supporting evidence. “The results of this experiment suggest that longer incubation time resulted in smaller DNA bound to the microplastics in the solution over the time. interval The DNA samples also became smaller with longer incubation periods. This supports the idea that as the incubation progressed, more DNA would bind to the microplastics.”

## III. Perspectives and Next Steps

This research sought to better understand high school students’ STEM research capabilities in a summer enrichment program in nanoscience. Through analysis of students’ research reports, a characterization of these capabilities was developed. Overall, the findings from this study suggest that STEM educators and research should focus on opportunities for high school students to participate in discipline specific STEM research projects.

Student STEM research is critical in promoting engagement with STEM content but also in developing the next generation of STEM academics, researchers, and professions. Research demonstrates that STEM research opportunities promote students understanding of research while improving their scientific knowledge, develops the type of critical thinking related to analyzing and solving problems. Students also develop professional understanding of subject matter and extend personal and social skills through collaboration and independent research [19].

Researchers understand the nanoscience field as being positioned at the intersection of multiple scientific and engineering disciplines [3]. Its interdisciplinary nature allows for the exploitation of connections between fields that has the potential to yield interesting and ground- breaking discoveries [3]. For a high school teacher, however, these connections are not always apparent [3, 11, 19]. According to scholars, nanoscience is challenging for the many teachers who likely have not encountered nanoscience concepts in their own coursework and do not feel supported in their implementation of nanoscience activities [3, 11]. The current generation of science teachers have had little (if any) exposure to nanoscience concepts, and thus, we must rely on professional development opportunities to enable practicing teachers to understand nanoscale concepts at a deep enough level to support the implementation of nanoscience-focused learning materials [11]. To support teachers in the implementation of nanoscience curricula, researchers urge for well-designed materials and effective professional development that attends to both content and effective pedagogy, to help illuminate those connections and make classroom integration of nanoscience learning more feasible [3, 11, 20].

## Acknowledgment

The authors recognize the contributions of the course faculty: Jenny Kent (Lead Instructor), Alex Robland (Co-Instructor), and Yizhou Wang (Co-Instructor). These instructors and course designers are Ph.D. candidates in Nanoscience at University of North Carolina Charlotte, Department of Chemistry. We also appreciate the support from the program research mentors: Alisa Wickliff (Center for STEM Education) and Dr. Christopher Gordon (Lenoir-Rhyne University); and scientific communication specialists: Dr. Gregory Wickliff (Department of English) and Paul Hunter (Purdue University).

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