Final Summary Report for NIST Award # 70NANB22H206

Project Title

Integrating Standards Education into the Nanomaterials Engineering Curriculum

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1. Description of the Project and Its Importance

This final summary report presents the major accomplishments and conclusions of NIST Award #70NANB22H206 – Integrating Standards Education into the Nanomaterials Engineering Curriculum. This project was conducted over the period of September 2022 to August 2025 and was led by PI Stacey Louie and Co-PI Jiming Bao in the Cullen College of Engineering (CCOE) at the University of Houston (UH).

The main project goal was to develop and implement standards education in the nanomaterials engineering curriculum for two undergraduate and graduate level courses. Standards are of critical importance in all stages of engineering, including research and development, process evaluation, and product testing. However, formal education in standards has not typically been introduced in the engineering curriculum. For example, although instructors may refer to documentary standards when developing course lectures or laboratories, they may not necessarily provide opportunities for students to search for relevant standards, read the standards, or purposefully apply the guidance from the standards as part of the course activities. This project aimed to address this major education gap by developing approaches to deliberately integrate standards reading and application throughout course lectures, assignments, and hands-on laboratories.

The topical focus on nanomaterials engineering was selected because of the rising importance of nanomaterials in real-world, commercial applications. The nanotechnology field has rapidly matured over the past decade, with a number of nanotechnology-enabled products now on the market or in use in engineering settings. These applications include biomedical applications (e.g., gold nanoparticles in COVID test assays and mRNA-lipid nanoparticles in COVID vaccines), environmental applications (e.g., reactive nanoscale iron particles for groundwater remediation), and electronic applications (e.g., quantum dots in display screens). This project is therefore important in providing knowledge and practical training to engineering students who may enter these fields and utilize nanomaterials in their future careers.

2. Project Goals

2.1. Major Goals

As noted above, the major goals of the curriculum development program were to develop new standards education modules in the nanomaterials engineering curriculum and train the next generation of nanotechnology engineers with a strong core education in documentary standards. The program was implemented in two courses at UH in Civil and Environmental Engineering and Electrical and Computer Engineering: CIVE 7397 (Experimental Methods in Nanomaterials Engineering), a new course that provides both fundamental and practical training in the characterization of nanomaterials, and ECE 5320/6307 (Nanomaterials and Solar Energy), an existing course that provides foundational education on the basic properties of nanostructured materials and their applications in renewable energy, e.g. solar energy devices.

2.2. Specific Objectives

Both courses included lecture and laboratory sessions that were designed to accomplish the following aims: (1) integrate nanotechnology-related standards throughout the course curriculum to develop within students an understanding of standards pertaining to vocabulary, classifications, and characterization and performance testing of nanomaterials; (2) provide innovative hands-on training through laboratories and classroom demonstrations to develop student skills and confidence in implementing and critically evaluating standard test methods for nanomaterials; (3) promote an appreciation for the value of standards and the standards development process through collaborations with industry and NIST scientists; and (4) maximize the educational impact of the new curriculum through the participation of external collaborators and continual evaluation and improvement of the curriculum.

3. Project Outcomes

3.1. Major Activities

The two engineering courses incorporating the standards education modules (CIVE 7397 and ECE 5320/6307) were both offered concurrently over two semesters – Spring 2023 and Spring 2025. PI Louie developed and delivered CIVE 7397 as a graduate-level course. Standards education and the use of documentary standards published by ASTM and ISO were fully integrated into the course lectures, assignments, and laboratories. Co-PI Bao taught ECE 5320/6307 (Nanomaterials and Solar Energy), which introduced documentary standards to a combined undergraduate and graduate level student cohort. Standards were integrated into lecture and laboratory sessions on nanomaterials characterization, including joint sessions with CIVE 7397. The PIs arranged guest lectures from Dr. Vincent A. Hackley (NIST Associate / Research Chemist, and project lead in ASTM Committee E56 on Nanotechnology and ISO TC 229 on Nanotechnologies) and Dr. Nemal Gobalasingham (Principal Scientist, Waters | Wyatt Technology). A course evaluator (Dr. Andrew Kapral, Director of the Engaged Data Science program at the Hewlett Packard Enterprise Data Science Institute (HPE DSI), University of Houston) assisted with designing and conducting pre-/post- surveys of students enrolled in the courses.

3.2. Significant Results – Curriculum Development and Delivery

The new curriculum that was developed and delivered for the project included (1) several lectures and in-class activities that introduced the concept of documentary standards and integrated reading and discussion of various nanotechnology-related standards with the technical course content; (2) guest lectures from NIST (delivered by Dr. Vincent Hackley) and industry (delivered by Dr. Nemal Gobalasingham from Waters – Wyatt Technology) on standards organizations and the standards development process; (3) two assignments focused on identifying nanotechnology-related standards, reading standards and discussing their purpose and benefits, and understanding the standards development process; and (4) six laboratories, each focused on a different nanomaterial characterization method, with accompanying laboratory handouts and report assignments that include reading and interpretation of documentary standards. The curricular materials have also been published as an open educational resource (OER) that is freely available online via the UH Pressbooks publishing service and can be accessed at the following URL: https://uhlibraries.pressbooks.pub/nanoengineering/

An overview of the course structure is presented in **Figure 1**, demonstrating how the standards-focused curriculum was deliberately paired with relevant theory in the general curriculum. This curriculum was delivered in full for the CIVE 7397 course, with the ECE 5320/6307 participating in four of the hands-on laboratories or in-class activities (along with the corresponding theory lectures) and the guest lecture on standards development by Dr. Vincent A. Hackley.

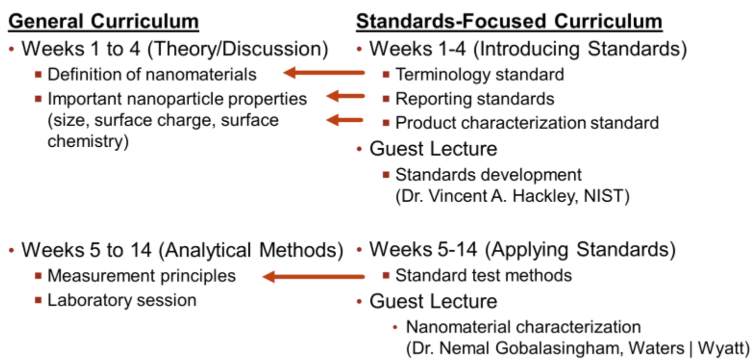


Figure 1. Overview of the integration of the standards-focused curriculum with corresponding theory and laboratories in a general curriculum on nanomaterials characterization.

The specific documentary standards utilized in curriculum are provided in **Figure 2.**

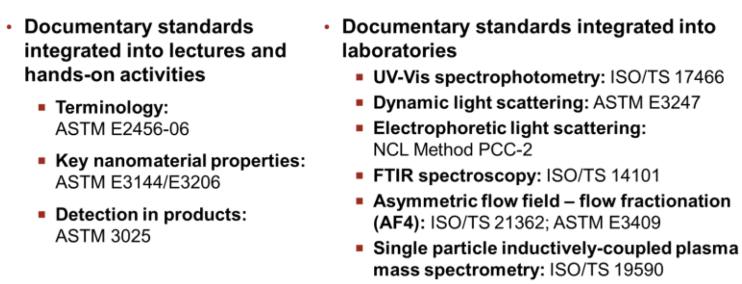


Figure 2. Listing of documentary standards utilized in the curriculum.

The project provided direct training in standards and nanotechnology to 21 undergraduate and graduate students in the first cohort of the classes (Spring 2023) and 17 undergraduate and graduate students (14 enrolled, 3 auditing) in the second cohort of the classes (Spring 2025). Students from a wide range of engineering disciplines participated in the courses (environmental engineering, electrical engineering, civil engineering, and geotechnical engineering), demonstrating a broad applicability of nanotechnology and standards education across multiple fields. Evaluations of student outcomes (performance on standards-related assignments and self-reported confidence in knowledge related to nanotechnology and standards) are detailed in Section 4 below.

As noted above, all curricular materials incorporating standards education have been published as OER at https://uhlibraries.pressbooks.pub/nanoengineering/. **Figures 3 to 5** shows examples of how documentary standards were integrated into the lecture content and assignments (with interactive activities and exercises in the online coursebook representing discussions held in class and homework assignments for the course) and laboratories (both in-class reading assignments and integration into discussion questions).

Exercise 2.2: Classifying Documentary Standards Related to Nanotechnology

Review the examples provided in The ABCs of Standards Activities of the different types of documentary standareds. Then, open the links below to review the lists of nanotechnology-related standards that have been published by ASTM and ISO:

- ASTM Committee E56 on Nanotechnology
- ISO Technical Committee (TC) 229 on Nanotechnologies:

Based on the title and abstract (freely available for standards published by either organization), provide one example from the available nanotechnology standards that can be categorized as the following types of standards:

(i) Terminology standard

(ii) Testing standard

(iii) Product standard

(iv) Process standard

(v) Standard on data to be provided

Figure 3. Example exercise from the OER coursebook, in which students investigate catalogs of published documentary standards related to nanotechnology and categorize them by purpose.

Exercise 3.1: Terminology standards for nanotechnology

Review the following two documentary standards related to definitions of nanomaterials:

- ASTM E2456-06(2020) — Standard Terminology Relating to Nanotechnology
- ISO 80004-1:2023(en) — Nanotechnologies – Vocabulary — Part 1: Core vocabulary

It is noted that ASTM standards may be freely accessible at institutions with an ASTM COMPASS subscription. At the time of this writing, the text of ISO 80004-1:2023(en) is accessible from the ISO catalog page linked above by selecting "Read Sample."

1. How is a "nanomaterial" defined in each standard?

2. Read the definitions for "transitive" and "non-transitive" in the ASTM standard, as well as "nanoscale phenomenon" in the ISO standard. Is it required for a nanomaterial to exhibit a "transitive" property or "nanoscale phenomenon" to meet the definition of a nanomaterial?

3. What is the definition of a "primary particle," an "agglomerate," and an "aggregate"? *Test your knowledge on this concept using Interactive Question 3.2 at the end of this chapter.*

Interactive Question 3.2

The Certificate of Analysis for **NIST Standard Reference Material® 1898 (Titanium Dioxide Nanomaterial)** presents the following set of TEM and SEM images demonstrating three different levels of structure: individual crystallites with sizes < 50 nm (arrows on top image), fused particle structures with sizes ≈ 100 nm (middle images), and large clusters of particles with microscale sizes (bottom images) that can be fragmented into the smaller structures with energy input, e.g., sonication.

1. Drag and drop the terms "primary particle," "agglomerate," and "aggregate" to label the appropriate structure in the image.

Note that the drop zone for the upper image refers to each individual crystallite indicated with an arrow (not the entire structure shown).

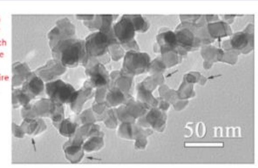
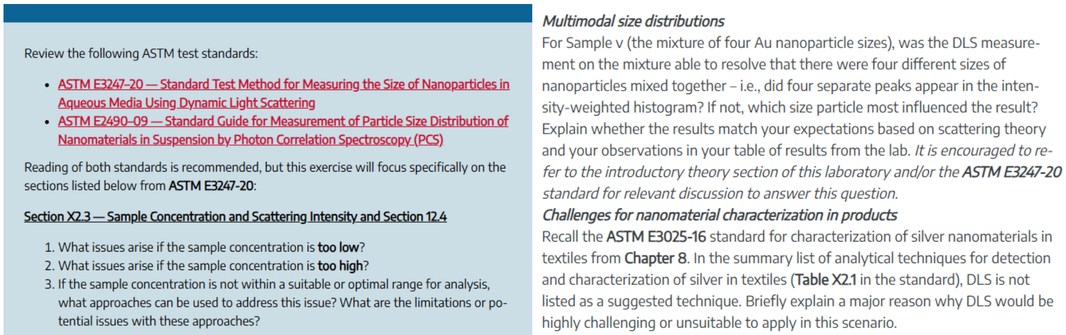


Figure 4. Example exercise and interactive activity from the OER coursebook, in which students identify key definitions from terminology standards for nanotechnology and test their knowledge by applying them to a real data set (image in interactive exercise from National Institute of Standards and Technology, Certificate of Analysis – Standard Reference Material® 1898 – Titanium Dioxide Nanomaterial, **2020**, https://tsapps.nist.gov/srmext/certificates/1898.pdf**).**



Review the following ASTM test standards:

- ASTM E3247-20 — Standard Test Method for Measuring the Size of Nanoparticles in Aqueous Media Using Dynamic Light Scattering
- ASTM E2490-09 — Standard Guide for Measurement of Particle Size Distribution of Nanomaterials in Suspension by Photon Correlation Spectroscopy (PCS)

Reading of both standards is recommended, but this exercise will focus specifically on the sections listed below from **ASTM E3247-20**:

Section X2.3 — Sample Concentration and Scattering Intensity and Section 12.4

1. What issues arise if the sample concentration is **too low**?
2. What issues arise if the sample concentration is **too high**?
3. If the sample concentration is not within a suitable or optimal range for analysis, what approaches can be used to address this issue? What are the limitations or potential issues with these approaches?

Multimodal size distributions

For Sample v (the mixture of four Au nanoparticle sizes), was the DLS measurement on the mixture able to resolve that there were four different sizes of nanoparticles mixed together – i.e., did four separate peaks appear in the intensity-weighted histogram? If not, which size particle most influenced the result? Explain whether the results match your expectations based on scattering theory and your observations in your table of results from the lab. *It is encouraged to refer to the introductory theory section of this laboratory and/or the **ASTM E3247-20** standard for relevant discussion to answer this question.*

Challenges for nanomaterial characterization in products

Recall the **ASTM E3025-16** standard for characterization of silver nanomaterials in textiles from **Chapter 8**. In the summary list of analytical techniques for detection and characterization of silver in textiles (**Table X2.1** in the standard), DLS is not listed as a suggested technique. Briefly explain a major reason why DLS would be highly challenging or unsuitable to apply in this scenario.

Figure 5. Example laboratory from the OER coursebook, in which students begin with a directed standards-reading exercise and then apply their understanding of the standards to interpreting the results of their laboratory measurements. The example shown is for the dynamic light scattering lab, with discussion questions related to evaluating the robustness of the method for application to complex samples or product analysis.

3.3.Dissemination of Results to Communities of Interest

Beyond the curriculum delivery to formally enrolled students at UH, curricular materials were broadly disseminated through national conferences and meetings – specifically, education sessions at the American Chemical Society National Meeting and Sustainable Nanotechnology Organization Conference in 2023, an invited presentation at the ASTM International Committee Week meeting for Committee E56 on Nanotechnology in 2024, and a presentation in the NIST SSCD Awardees meeting in 2025. These presentations are listed in Section 3.4 below.

Direct engagement was undertaken with three professors at external institutes of higher education (IHEs): Utah State University (Department of Civil and Environmental Engineering), Swarthmore University (Department of Chemistry), and Houston Christian University (Department of Chemistry). Professors at the first two institutes were provided with digital copies of all curricular materials, with a physical kit of materials for the laboratories also provided to Swarthmore University. The collaborators provided valuable feedback on challenges and areas for improvement related to implementation of the materials at their institution, such as limited access to laboratory facilities that could be designated for course use. In the third collaboration, two undergraduate students in chemistry were hosted for a research project at UH led by PI Louie and mentored by a graduate student at UH who had participated in the course. The research project relied heavily on measurements covered in three of the laboratories (dynamic light scattering, electrophoretic light scattering, and field flow fractionation). As part of the research experience, the students were guided through the standards-reading exercises. Furthermore, they were asked to apply the standards to evaluating the data quality in their measurements and identifying potential approaches to improve the data quality. Based on the results of these outreach activities, it is expected that the most beneficial use of the curricular materials can be in the direct (hands-on) training of undergraduate and graduate research assistants who apply nanomaterial analysis techniques on a regular basis, while the utilization of the materials in a formal course setting will be dependent on the availability of teaching laboratories.

For longer-term and broader dissemination to the general public, the course materials have been published as freely available OER as noted above and can be accessed at the following URL:

https://uhlibraries.pressbooks.pub/nanoengineering/. The publication was designed as a combined coursebook and laboratory manual, in which key properties of nanomaterials are discussed in a concise form, while also integrating standards throughout the entirety of the coursebook. This publication will be promoted through brochures to be disseminated at relevant conferences, including the joint Sustainable Nanotechnology Organization / International Water Association meeting in November 2025. Brochures will be targeted toward undergraduate and graduate research assistants and will advertise the utility of standards and the coursebook for understanding and improving methods for nanomaterial characterization.

3.4. Products

The following products have been published or delivered as a result of this project:

3.4.1. Publications

Meiraba Chirom, Chengzhen Qin, Feng Lin, Aniqa Lim, Steven Baldelli, Francisco Robles-Hernandez, Dong Liu, Viktor G. Hadjiev, Xiaonan Shan, Stacey Louie, and Jiming Bao. Non-contact thermometer for measuring surface temperature of photothermal catalysts using near-infrared black-body radiation spectrum. *Device*, 100467, DOI: 10.1016/j.device.2024.100467.

Haoran Wu, Alaia Homawoo, Saba Shariati, Carlos E. Astete, Debora F. Rodrigues, Cristina M. Sabliov, Elham H. Fini, and Stacey M. Louie. Evaluation of drug release from polymeric nanoparticles in simulated saliva and gastric media by asymmetric flow field–flow fractionation (AF4). *RSC Pharmaceutics*, 2024, 1, 994-1007, DOI: 10.1039/D4PM00175C.

3.4.2. Dissertations

Riya A. Mathew, Effects of Heterogeneous Foulant Layers on the Photoreactivity and Aggregation of Titanium Dioxide Nanoparticles, Doctoral dissertation, 2023.

Haoran Wu, Evaluation of Drug Release from Polymeric Nanoparticles in Gastrointestinal Media, Doctoral dissertation, 2025.

3.4.3. Conference and Meeting Presentations

Stacey M. Louie, Jiming Bao, and Andrew Kapral. Integrating nanotechnology standards education into analytical methods curricula for engineers. American Chemical Society (ACS) Fall National Meeting, August 2023, San Francisco, CA.

Stacey M. Louie, Jiming Bao, and Andrew Kapral. Curriculum development for education in nanotechnology-related standards. Sustainable Nanotechnology Organization (SNO) National Meeting, November 2023, Los Angeles, CA.

Stacey M. Louie, Curriculum development to integrate standards into nanomaterials engineering education. ASTM International Committee Week (Committee E56 on Nanotechnology), November 2024, Orlando, FL (hybrid mode).

Stacey M. Louie, Jiming, Bao, and Andrew Kapral. Integrating standards education into the nanomaterials engineering curriculum. NIST SSCD Awardees Meeting, September 2025, Virtual meeting.

3.5.Summary of Key Outcomes

A major outcome of the project was the delivery of the curriculum developed for the NIST SSCD project to the cohorts of students in CIVE 7397 and ECE 5320/6307. Students in both years of course offerings (Spring 2023 and Spring 2025) have reported interest in participating further in standards development activities. In particular, graduate students with careers in engineering (for example, municipal water treatment) have demonstrated interest in applying standards beyond those covered in the course toward their work. Furthermore, graduate researchers who participated in the courses and have requested further use of course materials to utilize in their research, including graduate teaching/research assistants who received training through their role in the project, not only in the technical content of the curriculum but also teaching experience in leading demonstrations and laboratories that can be used in their future careers.

Other key outcomes since the start of the project include two peer-reviewed journal articles and two PhD dissertations published by PhD students who participated in this project. These students conducted research relevant to the project topic, i.e. analytical methods to characterize nanomaterials for photocatalytic energy, biomedical, or environmental applications.

4. Project Evaluation

Course evaluation was conducted via (1) instructor grading of the standards-related homework and standards-related questions on the laboratory reports assigned in CIVE 7397, and (2) “pre” and “post” surveys that were designed and distributed by the evaluator, Dr. Andrew Kapral (UH Hewlett Packard Enterprise Data Science Institute), to students in both CIVE 7397 and ECE 5320/6307.

The instructor evaluation for the combined results across two semesters of offerings for CIVE 7397 is reported in **Table 1**, with student performance ranked High (≥ 85), Medium (70 to 85), or Low (<70).

Table 1. Instructor evaluation of student performance on standards-related assignments – Combined data for Spring 2023 and Spring 2025

Assessment Tool	**% High (> 85)**	**% Medium (70 to 85)**	**% Low (< 70)**
Homework assignments (identifying/classifying standards; reading/evaluating a product standard; benefits of standards; standards development process)	85%	15%	0%
Lab 1 (UV-Vis Spectrophotometry)	83%	17%	0%
Lab 2 (Dynamic Light Scattering)	62%	31%	8%
Lab 3 (Electrophoretic Light Scattering)	46%	54%	0%
Lab 4 (Fourier Transform Infrared Spectroscopy)	43%	43%	14%
Lab 5 (Field Flow Fractionation)	69%	15%	15%
Lab 6 (Single Particle Inductively Coupled Plasma Mass Spectrometry)	83%	0%	17%

Notes:
For the laboratory reports, only the assessment of the standards-related data analysis tasks or standard-related discussion questions is reported.
*Lab 4 was only offered in Spring 2023, and Lab 6 was only offered in Spring 2025.

In all cases, the majority of students scored either Medium or High. Less than 20% of students scored Low per assignment. In general, the Low scores were attributable to misinterpretation of a question or not providing any answer.

For evaluation of student learning, "pre" and "post" surveys were distributed by the evaluator, Dr. Andrew Kapral, to students in both courses to self-report their understanding of standards and confidence in being able to find and apply relevant standards. The surveys included the following items, which students ranked from "strongly disagree" to "strongly agree":

- I feel that I can define what a technical standard is.
- I feel that I can locate technical standards in online databases.
- I feel that I can determine what type of technical standard to use as I conduct engineering work.
- I feel that I can utilize and implement technical standards as I conduct engineering work.
- I feel that I can define what a nanomaterial is.
- I feel confident in characterizing and reporting key properties of nanomaterials.

Survey results for the six items listed above are plotted in **Figure 6**.

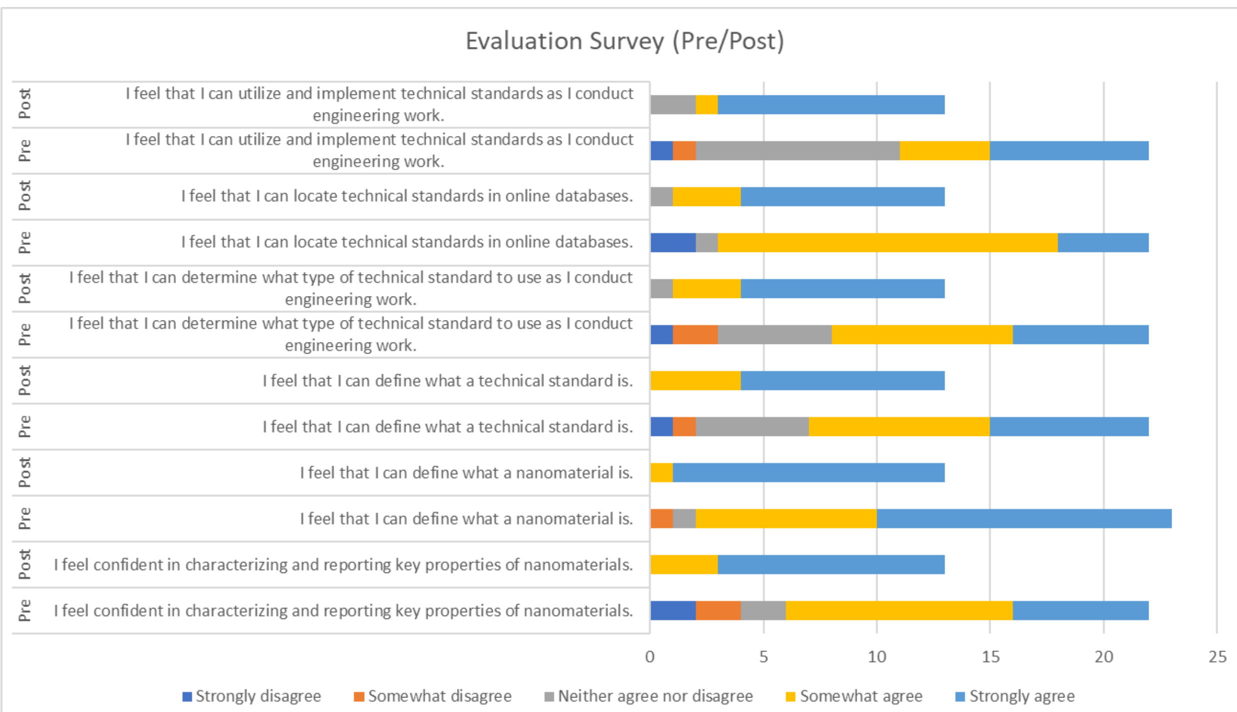


Figure 6. Results of the "pre"/"post" evaluation surveys – Combined data for Spring 2023 and Spring 2025.

In general, students reported a range of understanding of each item on the "pre" survey distributed at the beginning of the course, from "strongly disagree" to "strongly agree." A higher proportion of "agree" and "strongly agree" responses were observed in the "post" survey albeit with a lower number of responses received for evaluation. Even with the reduction in numbers of responses from the "pre" to "post" survey, increases in the number of "strongly agree" responses were observed for the following items:

- I feel that I can define what a technical standard is.
- I feel that I can locate technical standards in online databases.
- I feel that I can determine what type of technical standard to use as I conduct engineering work.
- I feel that I can utilize and implement technical standards as I conduct engineering work.
- I feel confident in characterizing and reporting key properties of nanomaterials.

In the “post” surveys, students were also asked to respond on the following question: “For each of the course activities listed below, please use the scale provided (not at all useful, slightly useful, moderately useful, very useful, extremely useful) to indicate how useful these activities were in developing your understanding of technical standards and their applications:”

- In-class readings/discussions of nano-related standards
- Guest lectures
- Standards-related homework assignments
- Laboratory sessions (conducting the labs and recording data)
- Laboratory reports (performing data analysis and answering discussion questions)

Nearly all student responses (54 of 60, counting each course activity separately) indicated that the course materials and activities were “very useful” or "extremely useful."

5. Findings and Lessons Learned

Based on the course evaluation results, the project was successful in its primary goal of integrating standards education into the nanomaterials engineering curriculum and enhancing student understanding of standards pertaining to vocabulary, classifications, and characterization and performance testing of nanomaterials. The PIs completed in full all of the project tasks, including developing lectures, laboratories, and classroom demonstrations that develop student skills and confidence in applying documentary standards related to nanotechnology. Guest lectures were provided by scientists representing NIST and industry that introduced the standards development process and encouraged students to engage in standards organization. In addition to presenting the project at conferences and meetings, the curricular materials have been fully disseminated for use by collaborators at external IHEs and published as freely available OER at https://uhlibraries.pressbooks.pub/nanoengineering/.

Several pedagogical lessons were learned related to the standards curricular content:

First, given the number of laboratories incorporated into the course (five per semester), it was generally not feasible to assign full standards for reading. A successful method for utilizing the standards was to pre-identify sections of the standards that directly relate to key theory from the lectures or measurement issues that will be evaluated in the laboratories, develop targeted questions related to these sections, and divide these questions among the class for students to read and report during in-class time. Summaries of the discussions could then be provided to students to refer to when preparing their laboratory reports.

Second, evaluation of responses to laboratory discussion questions initially showed that students did not necessarily consider to refer to the standards utilized during the laboratory pre-lectures when completing their reports. Improvements were observed when students were explicitly encouraged to cite relevant sections of the standards that support their response to each discussion question – in particular, this approach was used in Laboratories 2 and 3 (Table 1), where all except one score was in the Medium to High range.

Student performance was further strengthened when supplementary materials were provided to support the standards. For example, Laboratories 5 and 6 (Table 1) cover advanced methods with substantial data processing needs. Coupling the standards readings with a direct training and work session on data processing enabled students to better implement the standards guidance and accomplish these advanced tasks.

Finally, the homework assignments in which students were assigned to search for standards or identify useful information from a product standard were generally all successful (> 85% scores of High), and student confidence in this skill was likewise reflected in the "post" evaluation surveys. It is expected that these standards awareness exercises could be easily implemented in other courses and institutions with high impact and likelihood of success.

6. Project Suitability and Potential for Adoption in Other Educational Organizations, Communities, or Fields of Practice

The curricular materials can be suitable for a wide range of audiences at the upper undergraduate to graduate levels and across several engineering and science disciplines. This assessment was made by considering the wide background of students who engaged in the project, along with the student evaluations showing improvements in student confidence with standards and nanomaterial characterization.

The approaches developed here to introduce standards awareness into lectures and homework assignments should be suitable to be easily adopted in other educational organizations, communities, or fields of practice. As noted above, students from all engineering and science backgrounds were capable to investigate standards catalogs and identify standards that could be useful or relevant for various purposes. The greatest challenge to adoption in other IHEs, as identified through the dissemination activities conducted during the project period, was the limited availability of teaching laboratories at other IHEs in order to implement the lab-based modules. Therefore, the laboratory modules are expected to be most suitable for researchers (including graduate and undergraduate research assistants) and potentially practicing scientists and engineers who directly utilize the methods in their work.

The OER coursebook that has been published as part of this project is expected to have the most broad and long-term potential for adoption. The publication compiles the majority of the content that was delivered in the UH courses, including all standards-related activities. The intent of the coursebook has been to present technical content in a concise manner that can be more easily readable than textbooks on the subject. The implementation of interactive activities is intended to encourage direct engagement with standards. Finally, the laboratories provide a substantive amount of practical guidance (based on directed readings of documentary standards) that is not presented in traditional textbooks. The coursebook will be promoted to communities of interest, including students, faculty members at IHEs, and practitioners, through the distribution of brochures at relevant conferences. Student researchers will especially be encouraged to reflect on questions they may have about their research measurements that could be answered in the standards incorporated in the coursebook. The impact and adoption of the coursebook by students or instructors at other IHEs will continue to be assessed as the resource is advertised more widely.