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Environmental Engineering Grand Challenges Revisited: Integrative Review of Educational Efforts 2019 to 2024

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Abstract

In 2019, leaders in the discipline of environmental engineering completed an inclusive process and offered a report entitled, "Environmental Engineering for the 21st Century: Addressing Grand Challenges," which highlighted five technical areas where environmental engineers were poised to make significant contributions. Educating the next generation of environmental engineers was included as a sixth challenge. According to a search of available online databases, including SCOPUS, PubMed, and Google Scholar, between 2019 and June 2024, a total of 89 articles appearing in the peer reviewed scientific literature have cited the Environmental Engineering: Grand Challenges report. The two-fold purpose of this article includes: 1) using an integrative review format to analyze the 22 articles (of 89 total) that focus on education; and 2) highlighting the relationship among these 22 articles with the Engineering for One Planet (EOP) framework.

Introduction

In 2017, after a series of meetings (i.e., [1]) and consultations, the National Academy of Engineering (NAE) released a forward looking report entitled, "NAE Grand Challenges in Engineering," [2]. As part of a broad, consensus building effort, the Grand Challenges report highlighted 14 areas where engineers could, "…make the world not only a more technologically advanced and connected place, but also a more sustainable, healthy, and joyous – in other words, better – place," [2]. The publication of the report was accompanied by the publication of a supporting web site as well as the hosting of events and competitions as well as the launch of a variety of educational programs, worldwide.

In parallel to these broader efforts, leaders in the field of environmental engineering developed a similar, more targeted approach for the discipline of environmental engineering. Three separate multi-day events were held in May 2017, September 2017, and in January 2018. After a period of approximately one year, a final report was released in 2019 entitled, "Environmental Engineering for the 21st Century: Addressing Grand Challenges," [3]. The Environmental Engineering report identified five technical areas where environmental engineers were believed to be uniquely positioned to offer substantial contributions. These five technical areas included: 1) sustainably supply food, water, and energy; 2) curb climate change and adapt to its impacts; 3) design a future without pollution and waste; 4) create efficient, healthy, resilient cities; and 5) foster informed decisions and actions [3]. Educating future engineers was a sixth area identified in the report.

Not everything that was proposed by the environmental engineering community was explicitly highlighted in the final report (see [4] [5]). For example, Mihelcic and co-authors argued in their article that achieving sustainability in developing regions of the world required environmental engineers to address ten grand challenges, which spanned from, “understand[ing] the historical perspective of the discipline’s connection with public health as the field transitions forward,” to, “educat[ing] globally competent engineers,” [6]. Similarly, Blaney and co-authors argued in their article that improving diversity in science, technology, engineering, and math (STEM) both was conspicuously absent as well as critical to enable transformative solutions [7].

Since the publication of the discipline specific report on environmental engineering in 2019, a number of calls for papers have solicited articles on technical topics directly or indirectly related to the report. For example, Ling and Hornbuckle [8] described a collection of eight research articles and critical reviews published in the third edition of the journal *ACS Environmental Au*, which addressed the first four of challenges in environmental engineering. The journal *Environmental Engineering Science*, the official journal of the Association of Environmental Engineering and Science Professors (AEESP), has published a number of special issues associated with the grand challenges. These special issues have included: the food-water-energy nexus (described in [9]); addressing society’s water and energy challenges with reactive transport modeling (described in [10]); global environmental engineering for and with historically marginalized communities (described in [11]); life-cycle thinking in environmental sustainability; microbial and chemical processes in natural and engineered systems [12]; and a recent, two-part special issue on the sources, fate, and remediation strategies for microplatics [13].

To compliment these special issues focused on specific technical topics, this current integrative review examines peer reviewed articles that focus on education, which all cite the original discipline specific report on environmental engineering published in 2019 [3]. And these articles are mapped to the Engineering for One Planet (EOP) framework [14]. The purpose of this current article includes summarizing the educational efforts related to the sixth Environmental Engineering: Grand Challenge, namely: educating future engineers.

Methods

While there are many types of review articles, one of the most common formats that often appears in the environmental engineering literature is the “narrative review”. The narrative review often relies upon the expert synthesis of an *ad hoc* selection of literature. In contrast to the narrative review, a systematic review relies upon a well-defined and reproducible methodology to identify, evaluate, and synthesize published literature on a specific question. Systematic reviews often are more typical in the healthcare literature, where evidence-informed best practice is common. Previously, a workshop was used to introduce faculty of environmental engineering to systematic reviews as part of a pre-conference workshop of the biennial gathering of the AEESP [15]. Leveraging prior experience with systematic reviews, including [16] [17] [18], the following systematic procedure was followed.

A librarian assisted search was performed to identify articles appearing in the peer reviewed literature which cite “Environmental Engineering for the 21st Century: Addressing Grand Challenges,” [3]. This included searches using variations of authorship including “National Academy of Engineering,” “National Academies of Sciences, Engineering, and Medicine,” as well as, “Domenico Grasso,” who chaired the committee that authored the consensus report. The databases that were examined included SCOPUS, PubMed, and Google Scholar. The dates for published articles were limited to the period, January 2019 through June 2024, inclusive. Articles not published in English, duplicates, and erroneous references were excluded. A total of 89 articles appearing in the peer reviewed scientific literature have cited the Environmental Engineering: Grand Challenges report in the period January 2019 through June 2024, inclusive.

A PDF copy of all 89 articles was acquired, and the Dedoose platform was used to evaluate the articles.

A total of 18 articles appeared in the proceedings of the American Society for Engineering Education Annual Conference and Exposition, 14 articles appeared in journals published by the American Chemical Society (ACS), 13 articles appeared in the journal *Environmental Engineering Science* (i.e., the official journal of AEESP), 5 articles appeared in the *Journal of Environmental Engineering* (i.e., published by the American Society of Civil Engineers, or ASCE), 4 articles appeared in the *Journal of Cleaner Production*, 2 articles appeared in proceedings of the Global Humanitarian Technology Conference (GHTC), and the remaining 33 articles appeared in 33 different journals or conference proceedings.

A total of 20 articles were editorials or viewpoints, 21 articles were related to goal 1 (sustainably supply food, water, and energy), 4 articles were related to goal 2 (curb climate change and adapt to its impacts), 7 articles were related to goal 3 (design a future without pollution and waste), 4 articles were related to goal 4 (create efficient, healthy, resilient cities), 7 articles were related to goal 5 (foster informed decisions and actions), and the remaining 22 articles were related to goal 6 (educating future engineers).

The 22 articles related to goal 6 (educating future engineers) were further analyzed to identify the author's stated primary purpose, focus, or objective. Where the author had not explicitly indicated such, a summary of purpose was created as part of the systematic review process.

A thematic analysis was performed of the titles, abstracts, and key words of each article. The purpose of this thematic analysis was to map each of the articles to the Engineering for One Planet (EOP) framework, which has been proposed as an approach to emphasize the uptake of sustainability across the breadth of engineering education   This included the construction of frequency tables for individual words and word fragments (i.e., "sustain*") as well as key phrases (i.e., "sustainable development") [19].

Results

A summary of the 22 articles identified through the systematic evaluation of the peer reviewed literature are provided in Table 1. The titles and primary purpose, focus, or objective, as explicitly identified by the author or summarized by the reviewer, are grouped by publication type (beginning with ASEE Conference Proceedings and followed by journals) and listed in chronological order (beginning with articles published in 2019 and continuing through articles published in June 2024). Within Table 1, terms that are **bolded** in the article title or primary purpose, focus, objective, etc. were used in the subsequent construction of Figure 1 (below).

Table 1. Titles and primary objective of each of the 22 articles examined in the current systematic review. (Note: terms that are **BOLDED** in the article title or primary purpose, focus, objective, etc. were used in the subsequent construction of Figure 1.)

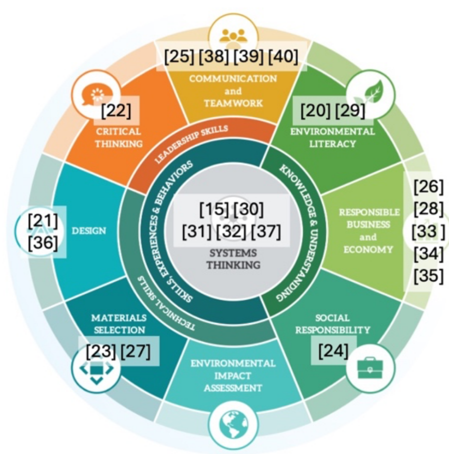
Article Title	Primary Purpose, Focus, Objective, etc.	Reference
Long-term impact on environmental attitudes and knowledge assessed over three semesters of an environmental engineering sequence	"…The focus of this study is to evaluate the ability of an environmental engineering sequence to enable students from multidisciplinary fields of study and a range of diverse demographic backgrounds to gain environmental engineering disciplinary breadth that provides background to mature their **attitudes toward environmental issues** over an 18-month period…"	[20]
Location, location, location: The value of **disciplinary adjacency** in enhancing environmental engineering programs	"…Our objective in this study was to examine the departmental alignments of ABET accredited engineering programs, and faculty perspectives on the advantages and disadvantages of specific program adjacencies…"	[21]
Preliminary results from implementing a data driven team project in introductory risk and uncertainty analysis class for sophomore civil and environmental engineering students	"…In this paper, I focus on a required engineering **risk and uncertainty** (ER&U), sophomore level class for civil and environmental engineering (CEE) students…"	[22]
Engaging students through an interactive mass balance fundamentals demonstration	This study reports on the effectiveness of a demonstration to improve understanding of and proficient use of the concept of the **mass balance**.	[23]
Short-term Study Abroad: Engineers Gaining **Intercultural Competency**	"…This study provides detailed information about program development, content, evaluation and longer-term student outcomes of the program "Sustainability Across Sectors-Sweden."…"	[24]
Who will Lead Us out of Climate Crisis? Gender, Race, and Early Career Pathways in Environmental Engineering	"…we consider how diverse groups of **women** majoring in environmental engineering are positioned for **leadership** in the field…"	[25]
Workshop Result: Teaching **Structured Reviews** to Environmental Engineering Researchers	"…The purpose of this paper is to share: 1) workshop content and format that could be used by other conveners of similar workshops; 2) results of the analysis of the RAT [readiness assessment] and CATs [comprehension assessment]; and 3) the author's experience with mentoring/coaching workshop participants on the use of structured reviews…"	[15]
Virtual Summer Research Program with Professional Development and **Financial Literacy** Training	This study reported on the effectiveness of a virtual format for a summer research institute.	[26]
Using Modified Mastery Learning to Teach Sustainability and **Life-Cycle Principles** as Part of Modeling and Design	"…this article provides a case report of the content and pedagogy of two courses. It includes summary results of student characteristics and feedback collected over a total of seven separate course offerings … the expectation is that other environmental engineers will adopt modified mastery learning as a framework to exceed ABET program criteria for environmental engineering…"	[27]
Early Engagement and Vertically-Integrated Learning:	"…We aim to develop holistic and **entrepreneurially-minded** engineers through a vertically-integrated spine of	[28]

Developing Whole-Person and Entrepreneurially-Minded Engineers	interactive courses in the first, second, third and fourth years … we discuss our approach to early engagement and vertically-integrated teaching and learning in the School…”	
Examination of Environmental Engineering Topics Taught in United States Federal Service Academies and Senior Military Colleges	“…The purpose of this study is to examine the current state of **environmental engineering topics** taught at all eleven Federal Service Academies and Senior Military Colleges…”	[29]
Framework for Defining and **Mapping to Key Words** in ABET Engineering Accreditation Commission Student Outcomes 1 - 7	“…The purpose of this study, therefore, is threefold. The first is to provide a linguistic crosswalk of terminology between SOs a – k and SOs 1 – 7. The second is to provide definitions of key terminology used in SOs 1 – 7. The third is to provide a framework for mapping embedded indicators within an environmental engineering curriculum to key words in SOs 1 – 7 for assessment and evaluation purposes…”	[30]
Developing an **Integrated** Environmental Engineering Curriculum	“…This paper reviews the lessons learned from the process of developing knowledge threads, competency strands and domains, and specific program outcomes with a multidisciplinary group of faculty, as well as the challenges of developing integrated and project-based courses within an established undergraduate curriculum…”	[31]
A Framework to Assess an Undergraduate Environmental Engineering Curriculum in Addressing the Grand Challenges for Environmental Engineering in the 21st Century	“…The purpose of this study is to propose a **framework** to assess how an undergraduate environmental engineering curriculum prepares students to address the environmental engineering Grand Challenges…”	[32]
Board 247: Designing Learning Environments for Knowledge, Skills, and Mindset Development	“…In our efforts to develop more holistic engineers with **entrepreneurial mindset**, faculty in the School of Civil and Environmental Engineering at Georgia Institute of Technology have been exploring what it takes to create and refine effective learning environments for knowledge, skills and mindset development. This poster discusses promising approaches being implemented to support such development and identifies emerging effective practices, challenges and future work…”	[33]
Applications of Teams and Stories: Augmenting the Development of Entrepreneurial Mindset in Engineers	“…We present two accounts of how story-driven learning and focused team development were integrated into different courses and highlight how they can amplify the impacts of activities fostering curiosity, connections, and value creation (the 3Cs), which nurture **entrepreneurial mindset**…”	[34]
Exploring the Role of Mentorship in Enhancing Engineering Students' Innovation Self-Efficacy	“…In this study, the innovation self-efficacy of undergraduate environmental engineering students is explored in a target course before and after a curricular intervention which has been shown to have the potential to enhance **innovation self-efficacy**…”	[35]
Designing Local Food Systems: Results from a Three-Year Pilot	“…The purpose of this paper is to share the format and the experiences gained from three offerings of a pilot course focused on **designing** local food systems…”	[36]
Workshop Result: Environmental Engineering Faculty Learning Boyer's Model of Scholarship	“…The purpose of this paper is to share: 1) workshop content and format that could be used by other conveners of similar workshops; 2) results of the analysis of the RAT [readiness assessment], CAT0 [comprehension assessment], and additional feedback; and 3) the authors’ experience with	[37]

	mentoring/coaching workshop participants on **Boyer's model of scholarship** in higher education, which contribute to suggestions for an educational module that could be used to introduce Boyer's Model and career cartography to graduate students as well as early and mid-career faculty of environmental engineering…"	
Teaching students to collaborate with communities: expanding engineering education to create a sustainable future	"…This article shares how the Serve-Learn-Sustain (SLS) initiative at the Georgia Institute of Technology has been introducing new approaches to problem-solving into engineering and technology-focused education to better prepare students to address the sustainability challenges of our moment, in collaboration with **community partners**, especially those from historically marginalized communities of color…"	[38]
Client-Driven Project on Sustainability within First-Year Cornerstone Design	"…During the second half of the spring 2020 semester, students across 19 sections of the course were presented with the same design prompt: How can you improve sustainability at Penn State and in the local communities?..."	[39]
Educating Engineers to Work Ethically with Global Marginalized **Communities**	"…This article presents faculty perspectives on the ethical and societal issues (ESI) that should be taught and the pedagogies that are used to prepare students for development engineering…"	[40]

The relationship between each article in Table 1 and the EOP Framework [20] is provided in Figure 1. The EOP Framework centers "system thinking" as interconnected with all other learning outcomes. At the core, the EOP framework considers two broad areas, which are: (1) knowledge and understanding; and (2) skills, experiences, and behaviors. Knowledge and understanding are linked to three topics, specifically: (1a) environmental literacy; (1b) responsible business and economy; and (1c) social responsibility). Skills, experiences, and behaviors are further subdivided into (2a) technical skills and (2b) leadership skills. Within the area of technical skills, the topics include: (2ai) environmental impact; (2aii) materials selection; and (2aiii) design. Within the area of leadership skills, the topics include: (2bi) critical thinking; and (2bii) communication and teamwork.

Figure 1. Pictorial representation of the relationship between each article listed in Table 1 and the EOP Framework [20].



Discussion

Of the 22 articles, 18 appeared in the proceedings of the ASEE Annual Conference and Exposition; 2 appeared in the journal *Environmental Engineering Science*; 1 appeared in the proceedings of the IEEE Global Humanitarian Technology Conference; and 1 appeared in the journal *Engineering Studies*. Excluding the terms "environmental" and "engineering", as well as generic terms directly related to education such as "teaching" and "students", a word cloud analysis of the 22 articles showed that "sustainable development" was the most common key word and "workshop" was the most common word occurring in the abstracts.

A thematic analysis of the titles, abstracts, and keywords of all 22 articles resulted in the identification of four themes, namely: 1) Improving programs (i.e., accreditation, curriculum mapping); 2) Developing faculty (i.e., interdisciplinary collaboration, research skills); 3) Analyzing students (i.e., demographics, learning styles, self-efficacy, whole person); and 4) Sharing specific content and pedagogy (community engagement, cultural competency, entrepreneurship, food systems, mass balance, risk, sustainability, uncertainty).

While the, EOP Framework [20] is not explicitly included in these 22 articles, aspects of the framework are noted in the articles. A map linking the 9 components of the framework – from systems thinking to communication and teamwork – to these 22 articles shows similar level of connection with the core of systems thinking (5 articles) as well as the broad areas of knowledge and understanding (8 articles) and skills, experiences, and behaviors (9 articles). It is interesting to note that it appears that none of the 22 articles is closely related to the topic of environmental impact assessment.

One of the driving questions used to identify the category of knowledge and understanding within the EOP Framework was, "why should students learn these theories or concepts?". Therefore, while only a preliminary hypothesis, we do suggest that a significant portion of the effort input to teaching related to the Environmental Engineering: Grand Challenges report is focused on helping faculty, students, and the partners understand "why" sustainability is important. This hypothesis is consistent with prior results, which suggest that environmental engineering is a "caring profession" [41] [42], and that answers to the question of "why" are powerful motivators for the practice of environmental engineering to address the challenges of the Anthropocene [43]. Future work should explore the differences among the knowledge and skills as compared to the attitudes of environmental engineering faculty and student who pursue solutions to the Environmental Engineering: Grand Challenges.

Conclusion

The environmental engineering community invested a substantial amount of time, talent, and treasure to produce the Environmental Engineering: Grand Challenges report. Prior efforts have included the publication of collections of articles with a focus on solving one or more of the Grand Challenges. In this current student, education related articles that cite the report were identified and analyzed. The articles were mapped to the EOP Framework. The results of this study compliment prior efforts to summarize the results of published reports in the peer reviewed literature, which cite the Environmental Engineering: Grand Challenges report. The results of this study show promise for establishing a connection between the EOP Framework and the Environmental Engineering: Grand Challenges report.

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