Online STEM Education Before COVID-19: An Integrative Review and Thematic Framework for Higher Education

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Abstract
Scholarship on online STEM education in higher education has been dispersed across disciplinary and educational research communities. This integrative literature review synthesized studies published from 2011 through early 2020 to establish a historical baseline for online STEM teaching and learning before the COVID-19 pandemic. Searches were conducted in EBSCO, ERIC, and Web of Science using terms related to STEM education, online and distance learning, and higher education. The final body of literature comprised 33 studies published across 31 scholarly outlets. Inductive thematic synthesis produced eight categories: (1) Online STEM Learner Support; (2) Integrated Online STEM Education; (3) Online STEM Course Quality, Design, and Learner Success; (4) Strategies for Improving Online Learner Engagement in STEM; (5) Communication in Online STEM Environments; (6) Equity and Inclusion for Underrepresented Learners in Online STEM; (7) Online STEM Education and Workforce Development; and (8) Online STEM Faculty Preparation. Across asynchronous, synchronous, combined-online, and selected blended contexts, the reviewed literature linked learner experiences and outcomes more closely to the integration of instructional design, interaction, facilitation, authenticity, assessment, learner support, access, and equity than to modality alone. These dimensions operated interdependently across the eight themes. The review also revealed uneven methodological scale and theoretical grounding across the literature. By synthesizing this body of research, the review provides a thematic framework for interpreting pandemic-era and post-pandemic developments and advancing more rigorous, theoretically grounded, and equity-centered research in online STEM education.

Keywords: Online STEM education; online learning; higher education; integrative literature review; equity in STEM; faculty development

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Introduction

Since its emergence through the National Science Foundation (NSF) in the 1990s and its increased visibility in the early 2000s, STEM education has become a familiar and influential term in higher education. Yet conceptual ambiguity and inconsistency persist in how STEM is defined and enacted (Breiner et al., 2012; Honey et al., 2014). Even the NSF has treated STEM as four distinct disciplines rather than as an integrative framework. Breiner et al. (2012) found that many faculty interpret STEM primarily in siloed disciplinary terms, while others misidentify the acronym altogether. Sanders (2009) described this proliferation of competing definitions as *STEMmania*, warning that without conceptual clarity, meaningful reform remains difficult to achieve.

Although *STEM* is often used to denote the individual disciplines of science, technology, engineering, and mathematics, many scholars argue that *STEM education* implies purposeful connections across those disciplines (Breiner et al., 2012; English, 2016; Gibbons, 1979; Honey et al., 2014; Kysilka, 1998; Sgro et al., 2020). In practice, however, U.S. educational systems remain largely organized around discrete subject areas. A common critique is that STEM is not taught in the integrated way it is practiced in professional contexts (Schwartz & Lederman, 2002). Courses are typically offered in isolation, reinforcing the perception that disciplines are independent rather than overlapping and mutually dependent, despite the interdisciplinary demands of STEM careers.

Sanders (2009) argues for the use of the term *integrative STEM education* to reflect the reality of professional STEM practice, defining it as "teaching and learning between/among any two or more of the STEM subject areas, and/or between a STEM subject and one or more other school subjects" (p. 21). He characterizes integrative STEM as a constructivist pedagogy of purposeful design and inquiry, engaging learners in authentic problem solving as a response to persistent weaknesses in STEM preparation and participation. Longstanding critiques underscore that these challenges are not new and remain closely tied to broader struggles over educational reform and entrenched disciplinary structures (Gibbons, 1979; Kysilka, 1998; Sanders, 2009). Sanders further cautions that unless conventional assumptions about STEM preparation and instructional contexts are fundamentally challenged, meaningful reform is unlikely to occur.

More than three decades later, the knowledge gap articulated by Gibbons (1979) persists. Honey et al. (2014) reaffirmed that despite strong arguments for STEM integration, there remains limited research on how integration should be enacted or whether it improves learning, retention, or other valued outcomes. These unresolved challenges are further compounded when STEM teaching and learning move online, where disciplinary complexity intersects with additional demands related to technology, course design, learner support, and faculty readiness.

At the same time, online education has been steadily expanding. Early efforts to support science education online emphasized content delivery over inquiry and collaboration, limiting opportunities for authentic engagement (Davis & Snyder, 2012). By fall 2017, more than 6.6 million postsecondary learners, approximately one-third of total enrollment, had taken at least one distance education course, with 15.7% enrolled exclusively online (National Center for Education Statistics, 2018; Seaman et al., 2018). Online enrollments increased for fourteen consecutive years, while campus-based enrollments declined by more than one million between

2012 and 2016. Despite this growth, little national data documented the participation and experiences of STEM majors in online programs, leaving an important gap in understanding how STEM is taught and learned online.

Because online learning has been defined in varied and sometimes contradictory ways, clear modality distinctions are important (Singh & Thurman, 2019). Online education encompasses several distinct instructional modalities. Formal institutional reporting definitions classify a course as fully online when 100% of direct instruction is delivered online, whether asynchronously, synchronously, or through a combination of both. In contrast, hybrid courses combine online instruction with required face-to-face direct instruction, while HyFlex courses allow learners to participate through face-to-face, synchronous online, or asynchronous online options (State University of New York [SUNY], 2025). These modalities are related but not interchangeable because they structure time, place, participation, and instructional interaction differently.

Modality should also be distinguished from course formats, pacing structures, technologies, and pedagogical approaches, such as self-paced learning, MOOCs, simulations, adaptive learning, and competency-based education, each of which may be implemented within more than one instructional modality. In this review, online STEM education functions as an analytic umbrella for scholarship in which online teaching, learning, instructional design, learner support, or faculty development was a substantive focus rather than merely a background technology or categorical variable. The included literature represents asynchronous, synchronous, combined-online, and some blended or mixed-modality contexts. Consistent with the integrative purpose of the review, these studies were retained when their online dimensions contributed meaningfully to understanding online STEM teaching and learning in higher education.

Across these modalities, effective online teaching and learning depend on the intentional design and facilitation of learner–content engagement; reciprocal learner–instructor interaction; purposeful independent learning activities; structured learner–learner interaction; and assessment and feedback. These opportunities make learners’ thinking and learning visible and open to feedback from instructors and peers through activities that require reflection, application, explanation, questioning, analysis, synthesis, self-assessment, and peer evaluation. Online learning is therefore not simply the delivery of content through technology; it requires coherent instructional design that aligns course content, interaction, engagement, feedback, assessment, and learner support with intended learning outcomes.

The Community of Inquiry framework locates meaningful online learning in the interdependence of social, teaching, and cognitive presence (Garrison et al., 2000). Anderson’s (2011) model similarly emphasizes interactions among learners, instructors, and content while recognizing both collaborative, community-based learning and independent study. Picciano (2017) extends these foundations by emphasizing that pedagogical purpose, rather than technology alone, should guide the integration of content, interaction, reflection, collaboration, assessment, and independent learning.

These pedagogical demands are particularly consequential in STEM fields, where laboratory experiences, quantitative and procedural reasoning, collaborative problem solving, and disciplinary communication may require substantial adaptation for online environments. They also make faculty preparation and institutional support central to the quality and inclusiveness of online STEM education. However, even prominent pre-COVID STEM reform initiatives that centered faculty development and learner-centered pedagogy did not explicitly address preparation for online teaching or use online professional development as a scalable means of preparing STEM faculty (Elrod, 2010).

National policy reports and statistical briefs further underscore the urgency of a number of issues. The National Academies of Sciences, Engineering, and Medicine (NASEM, 2020) identified persistent barriers to the participation of women in STEM and recommended evidence-based practices for broadening access. Longitudinal data similarly reveal high rates of attrition among learners who initially pursue STEM majors, particularly those from underrepresented groups (Chen, 2013). More recently, the NSF's National Center for Science and Engineering Statistics (2023) documented that women, racial and ethnic minorities, and persons with disabilities remain significantly underrepresented across STEM education and workforce pipelines. Together, these developments positioned STEM and online education as converging priorities for U.S. higher education policy and practice on the eve of the COVID-19 pandemic.

Prior reviews have established broad patterns in online teaching and learning in higher education but have not synthesized the multidisciplinary literature on online STEM education as a distinct body of scholarship. Wallace (2003) found extensive attention to social interaction, community, and online presence but comparatively little research connecting these constructs to subject-specific interactions and learning. Subsequent reviews identified recurring concerns related to course design, instructor–learner interaction, learning community, instructor preparation and support, learner engagement, and institutional conditions (Martin et al., 2020; Sun & Chen, 2016). Martin et al. (2020), for example, mapped 619 studies published from 2009 through 2018 across 12 online-learning and educational-research journals but did not include discipline-specific journals. More recently, van Dorresteijn et al. (2025) synthesized 47 reviews and meta-analyses across course, learner, instructor, and institutional levels, further demonstrating the maturity and breadth of the online higher education review literature. However, these syntheses examined online higher education broadly, general conditions for effectiveness, or field-wide research themes rather than integrating how online STEM teaching and learning had been studied across disciplines and pedagogical concerns during the pre-COVID period. The present review addresses this gap by synthesizing that historically bounded and widely dispersed literature as a distinct field of inquiry.

Online Education and the COVID-19 Era

The COVID-19 pandemic profoundly altered higher education in spring 2020, as an estimated 4,200 institutions serving more than 25 million learners shifted courses online with little preparation (Entangled Solutions & Alexander, 2020). Surveys indicated that nearly all U.S. colleges moved the majority of face-to-face instruction into remote formats within weeks, with many investing rapidly in new digital tools to support continuity (Lederman, 2020). National higher education organizations underscored the unprecedented scale of disruption and the need for coordinated institutional and federal responses (American Council on Education, 2020). Unlike purposefully designed online education, which typically involves extended faculty preparation, instructional design support, and iterative course development, emergency remote teaching was implemented under crisis conditions with little opportunity for planning or choice, raising widespread concerns about readiness, engagement, attrition, equity, and instructional quality. This distinction is consequential for interpreting the literature because pandemic-era scholarship often encompassed both conventional online education and emergency remote teaching despite their conceptual and historical differences (Doo et al., 2023).

The pandemic also changed the scale and emphasis of online learning research. In a systematic review of 191 studies published from February 2020 through April 2022, Doo et al. (2023) found that attention shifted from the pre-pandemic concentration on learners toward courses and instructors, with substantially greater emphasis on course design and technology, while engagement remained prominent. The authors characterized technology acceptance and learners' and instructors' perceptions of online learning as newly emerging topics within the pandemic-era literature. These questions, however, were not new to online education research. Rather, they resurfaced in a rapidly expanding body of scholarship that often treated online education as a newly encountered phenomenon and revisited longstanding questions about modality, quality, effectiveness, and perceptions with limited connection to decades of prior research. While valuable for documenting institutional and instructional responses to crisis, much of this work was descriptive, context-specific, and disconnected from the well-established scholarship on online teaching and learning. The emergency pivot consequently redirected substantial research attention away from the pre-pandemic emphasis on learners and toward technology, immediate implementation challenges, and the experiences of instructors suddenly required to teach online. This review therefore focuses on studies published from 2011 through early 2020 to identify what was known about online STEM education before that disruption and to establish a historical baseline against which pandemic-era and post-pandemic developments can be interpreted.

Purpose and Significance of the Review

Although prior reviews have synthesized broad themes, effective practices, and pandemic-era developments in online higher education, the multidisciplinary literature on online STEM teaching and learning has not been integrated as a distinct pre-COVID body of scholarship. This review therefore examines scholarship published from 2011 through early 2020, a period in which online education matured alongside STEM's rise as a national priority. It asks: What does the pre-COVID literature collectively reveal about online STEM teaching and learning in higher education?

Using an integrative review methodology, the study identifies recurring patterns, relationships, inconsistencies, and gaps across the literature and synthesizes them into eight thematic categories. The resulting framework encompasses instructional design, learner support, communication, engagement, interdisciplinary integration, equity and inclusion, workforce preparation, and faculty preparation across disciplines and instructional modalities.

By isolating scholarship developed before the emergency shift of 2020, the review makes three contributions. First, it establishes a historical baseline against which pandemic-era and post-pandemic research can be interpreted. Second, it brings coherence to a literature dispersed across disciplinary and educational publication venues. Third, the eight thematic categories provide an integrative framework for organizing future research and identifying persistent gaps in theory, methodological scale, and equity-centered design.

Methodology

This study employed an integrative literature review methodology (Whittemore & Knafl, 2005), selected for its capacity to synthesize heterogeneous empirical, applied, and conceptual scholarship across multiple research traditions. This approach was well suited to the multidisciplinary field of online STEM education and to the review's purpose of identifying patterns, relationships, inconsistencies, and gaps across a varied body of literature.

Searches were conducted in Education Research Complete (EBSCO), the Education Resources Information Center (ERIC), and Web of Science. Searches combined the following terms: STEM education AND online education AND higher education; integrated STEM AND online learning AND higher education; and STEM education AND (online learning OR e-learning OR distance learning) AND (higher education OR college OR university). The searches covered scholarship published from 2010 through early 2020 and returned more than 200 records. The earliest included study was published in 2011. Search results were reviewed for topical relevance, and potentially eligible publications were examined in full text.

The author conducted the database searches, full-text eligibility review, coding, and thematic synthesis during spring 2020. Decisions were documented in structured review matrices throughout the process. The review included English-language scholarly publications in which online STEM teaching, learning, instructional design, learner support, or faculty development was a substantive focus.

For this review, online STEM education functioned as an analytic umbrella encompassing studies in which the online dimension contributed meaningfully to understanding STEM teaching and learning in higher education. Eligible studies could examine asynchronous, synchronous, combined-online, blended, or mixed-modality contexts, as well as online STEM-related professional development. Conceptual and design-oriented scholarship was also eligible when it directly informed how online STEM teaching and learning could be designed, supported, or understood.

Studies were excluded if they focused on K–12 education; informal or otherwise non-scholarly publications; virtual or immersive technologies as the primary object of study; professional development not explicitly connected to STEM teaching and learning; or contexts lacking clear implications for online STEM instruction in higher education. Studies in which online learning functioned solely as a background context, delivery mechanism, or categorical variable rather than a meaningful component of the analysis were also excluded.

The initial review yielded a provisional corpus of 38 publications. As the review was refined, the full texts were reassessed against the eligibility criteria. Five publications were excluded because they focused on K–12 populations, general STEM education or policy, or technology-supported contexts in which online STEM teaching and learning in higher education was not a substantive focus. The final analytic corpus comprised 33 studies.

The included studies were documented in structured review matrices and compared by publication venue, study type and design, instructional modality, target population, substantive focus, and contribution to understanding online STEM education. Studies were classified as either core pedagogical studies, which empirically examined online STEM teaching and learning processes, or contextual/supporting studies, which addressed curriculum design, faculty preparation, program evaluation, or conceptual frameworks directly shaping online STEM education.

The 33 studies were coded using an inductive thematic analysis process. Through iterative reading and constant comparison, patterns in research focus, instructional context, theoretical framing, and analytic emphasis were identified and refined. For purposes of analytic presentation, each study was assigned to the thematic category representing its primary contribution, while relationships across categories were considered during synthesis. The categories were refined through repeated cycles of comparison across studies, with analytic decisions documented and revisited throughout the process rather than established in advance. The interpretation considered the nature and scale of the evidence, methodological design, theoretical grounding, and contribution of each study to the developing body of knowledge on online STEM education.

Findings

This review synthesized 33 studies of online STEM teaching and learning in higher education published between 2011 and early 2020. The studies appeared across 31 scholarly outlets and comprised 30 peer-reviewed journal articles, two peer-reviewed conference papers published in scholarly proceedings, and one formal working paper issued by an established university research center. Sixteen studies appeared in STEM-focused or discipline-specific STEM outlets, and 17 appeared in broader education venues, including distance and online education, higher education, pedagogy, and education policy. Three appeared in journals devoted specifically to online or distance education. These publication counts are used descriptively to characterize the dispersion of the reviewed scholarship across disciplinary and educational research communities.

Table 1

*Analytic Distribution of Scholarly Outlets in the Review (*N *= 33 studies; 31 scholarly outlets)*

Analytic Outlet Category	Sub-Category	Scholarly Outlets (*n*)	Studies (*n*)
STEM-Focused Scholarly Outlets	Interdisciplinary STEM Education	4	4

Analytic Outlet Category	Sub-Category	Scholarly Outlets (*n*)	Studies (*n*)
STEM Discipline – Focused Scholarly Outlets	Science Education	2	2
	Technology (Educational Technology)	3	3
	Technology (Computing Education)	5	5
	Engineering Education	1	1
	Mathematics Education	1	1
	Subtotal: STEM & STEM Discipline Focus	**16 Outlets**	**16 Studies**
Non-STEM Education Outlets	Distance / Online Education	3	3
	Education (General)	2	2
	English / Language Education	1	1
	Higher Education	6	7
	Pedagogy / College Teaching	2	3
	Education Policy & Practice	1	1
	Subtotal: Non-STEM Focus	**15 Outlets**	**17 Studies**
	TOTAL	**31 Outlets**	**33 Studies**

The analysis resulted in eight thematic categories that structure the synthesis of findings: (1) Online STEM Learner Support; (2) Integrated Online STEM Education; (3) Online STEM Course Quality, Design, and Learner Success; (4) Strategies for Improving Online Learner Engagement in STEM; (5) Communication in Online STEM Environments; (6) Equity and Inclusion for Underrepresented Learners in Online STEM; (7) Online STEM Education and Workforce Development; and (8) Online STEM Faculty Preparation. The following sections synthesize findings within each category. Studies were assigned to the category representing their primary contribution, although several findings intersect across themes.

1. Online STEM Learner Support

Learner support is widely recognized as a critical factor in academic success, persistence, and retention in STEM education. Retention theory emphasizes the importance of institutional and social supports (Tinto, 2012), national data document persistent STEM attrition patterns (Chen, 2013), and the Community of Inquiry framework highlights the importance of social presence and support in online environments (Garrison et al., 2000). Research on STEM persistence further underscores the need to examine how learner supports are enacted in online settings, particularly for underrepresented groups (Seymour & Hunter, 2019). Five of the 33 studies in this review addressed online STEM learner support.

Several studies examined academic supports for underprepared, disadvantaged, or underrepresented learners enrolled in high-risk online STEM courses. Spaniol-Mathews et al. (2016) found asynchronous supplemental instruction effective for improving performance and persistence among online STEM learners. Similarly, Rennar-Potacco and Orellana (2018) and Rennar-Potacco et al. (2019) reported that synchronous videoconferencing-based tutoring produced retention outcomes comparable to in-person support for academically underprepared learners.

Other research highlighted the needs of adult and disadvantaged learners. Butcher et al. (2019) evaluated an online “maths for science” access module combining asynchronous skill development with individualized phone tutoring and found it effective in preparing disadvantaged adult learners for subsequent study in science.

The perspective of tutors was also examined. Campbell et al. (2019) identified challenges associated with synchronous online tuition, including technological barriers to interaction and mismatched expectations, with learners often anticipating direct instruction rather than facilitated learning.

These studies identify two complementary functions of learner support in online STEM: strengthening performance and persistence within high-risk courses and preparing learners for further STEM study. The studies were concentrated in high-risk course and widening-participation contexts, and several addressed the needs of disadvantaged, underrepresented, and nontraditional learners or sought to reduce barriers to participation in academic support. Across the studies, support included structured supplemental instruction, synchronous tutoring, preparatory modules, and individualized assistance addressing academic skills and non-academic conditions affecting participation. The tutor-focused evidence further indicates that technological barriers and mismatched expectations about learner and facilitator roles can constrain synchronous support. Collectively, the findings position learner support as an integral component of online STEM course design, particularly in high-risk and widening-participation contexts. Because the evidence was drawn from varied but largely context-specific studies, it does not establish the scalability or sustained effects of these approaches across STEM disciplines and institutions (see Table 2).

Table 2

Online STEM Learner Support

Authors	Type of Study	Targeted Modality	Target Population	Analytic Classification
Spaniol-Mathews et al. (2016)	Empirical, quantitative (randomized controlled trial)	Online supplemental instruction (synch. with asynch. supports)	Learners (undergraduate STEM)	Core Pedagogical
Rennar-Potacco & Orellana (2018)	Evidence-based practice, case study	Synch. online video	Learners (undergraduate STEM)	Core Pedagogical

Authors	Type of Study	Targeted Modality	Target Population	Analytic Classification
Rennar-Potacco et al. (2019)	Empirical, quantitative (quasi-experimental, nonequivalent posttest-only design)	Synch. online video	Learners (undergraduate STEM; high-risk courses)	Core Pedagogical
Butcher et al. (2019)	Empirical, mixed methods (institutional case study)	Asynch. online & one-on-one phone calls	Learners (adult, nontraditional)	Core Pedagogical
Campbell et al. (2019)	Empirical, qualitative (thematic analysis; grounded theory–informed)	Synch. online video	Instructors (STEM tutors)	Core Pedagogical

Note. Targeted modality refers to the instructional modality explicitly examined or addressed in each study. Asynch. = asynchronous; Synch. = synchronous.

2. Integrated Online STEM Education

Integrated STEM approaches are increasingly viewed as essential for preparing learners for real-world problem solving; however, their application in online environments introduces additional instructional and conceptual complexities (English, 2016; Honey et al., 2014). Four of the 33 studies in this review addressed integrated STEM education in online higher-education contexts. Collectively, these studies offer primarily contextual, design-oriented, and conceptual insights into how integrated STEM learning can be structured and supported online, with limited empirical attention to enacted teaching and learning across contexts.

Two studies addressed learner-facing curriculum and learning design. Reid and Wilkes (2016) conducted an applied empirical study mapping quantitative skills across STEM curricula delivered through multiple instructional modes. Their analysis demonstrated how curriculum mapping can identify gaps and redundancies in where quantitative skills are taught, practiced, and assessed and support more coherent integrated STEM curricula. Hossain et al. (2018) employed design-based research to study an Open edX MOOC integrating experimentation, modeling, and data analysis through asynchronous, cloud-based biology laboratories. Their findings showed that inquiry-based, lab-centered science learning can be designed and scaled in online environments, supporting authentic scientific practices.

Two additional studies addressed instructor-focused design considerations and conceptual frameworks for integrated STEM education. Geiger et al. (2018) described and evaluated the interdisciplinary process used to develop an online mathematical-modeling module for preservice educators. The evaluation was generally positive but also identified the need for more meaningful involvement of preservice educators and other stakeholders in the design process. Yang and Baldwin (2020) synthesized prior research on integrated STEM learning to identify technology-use strategies that support learning, including the use of authentic problem contexts, web-based inquiry environments, immersive and interactive technologies, and approaches that position learners as active creators of knowledge. They also highlighted persistent challenges, such as disciplinary boundaries, uneven instructor expertise, and the cognitive demands of cross-disciplinary integration, which are especially relevant in online settings.

Together, these studies position integrated online STEM primarily as a curriculum and design challenge rather than as a well-established instructional model. Across empirical and conceptual work spanning mixed-modality and asynchronous settings, curriculum mapping, interdisciplinary module development, and technology-supported problem solving offered different mechanisms for coordinating disciplinary knowledge and authentic inquiry. The literature also identifies challenges related to disciplinary boundaries, uneven instructor expertise, and the cognitive demands of integration. Because the evidence was largely design-oriented, case-based, or conceptual, it does not establish comparative outcomes or how integrated STEM operates across disciplines and online modalities (see Table 3).

Table 3

Integrated Online STEM Education

Authors	Type of Study	Targeted Modality	Target Population	Analytic Classification
Reid & Wilkes (2016)	Empirical, quantitative (curriculum mapping study)	Mixed modalities (& F2F)	Learners (higher education STEM; Australia)	Contextual/ Supporting
Hossain et al. (2018)	Empirical, design-based research (iterative)	Asynchronous online (MOOC; cloud-based labs & simulations)	Learners (higher education STEM)	Contextual/ Supporting
Geiger et al. (2018)	Evidence-based practice (design-based case study)	Asynchronous online	Instructors (preservice educators)	Contextual/ Supporting
Yang & Baldwin (2020)	Conceptual synthesis (integrative literature review)	Conceptual (includes online & technology-mediated contexts)	Instructors (integrated STEM education)	Contextual/ Supporting

Note. Targeted modality refers to the instructional modality explicitly examined or addressed in each study. Contextual/supporting studies contribute design, curricular, or conceptual insights without empirically examining enacted online STEM teaching and learning processes.

3. Online STEM Course Quality, Design, and Learner Success

Course quality and instructional design are consistently identified in the online learning literature as central to learner success and satisfaction. Foundational frameworks position design as a core element of teaching presence (Garrison et al., 2000), large-scale syntheses demonstrate positive effects of well-designed online and blended instruction (Means et al., 2013), and engagement research emphasizes the role of intentional design in persistence (Meyer, 2014). Six of the 33 studies in this review examined how course structures, evaluation practices, and design features were conceptualized and studied in online STEM contexts, with particular attention to asynchronous environments.

Several studies focused on evaluation practices and predictors of success in online STEM courses. Downs (2014), in a multi-case evaluation of three online graduate STEM programs, identified limitations in reliance on informal feedback, inconsistent use of satisfaction surveys, and outcome measures that sometimes disadvantaged online learners. Hachey et al. (2015) found that prior online course outcomes, or the absence of online experience, were associated with success in subsequent online STEM courses, indicating that early online learning experiences may be consequential. Similarly, Wladis et al. (2014) reported higher success rates in online STEM major courses than in elective courses, suggesting that enrollment characteristics played a greater role than course content.

Other studies examined learner perceptions of online STEM course quality. Ramlo (2017) identified three learner perspectives in physics courses: a preference for face-to-face instruction; conditional acceptance of online learning; and resistance based on perceived limits to authentic, hands-on activity. These findings highlighted authenticity as a central factor shaping perceptions of online STEM course quality and contrasted with institutional narratives emphasizing strong demand for online STEM offerings, suggesting possible misalignment between administrative assumptions and learner experiences.

Design-oriented studies further underscored the role of instructional features and technological supports. Chen et al. (2018) identified design elements learners perceived as beneficial, including active learning strategies, interactive engagement, and robust assessment practices, and highlighted the role of Universal Design for Learning (UDL) to enhance accessibility and inclusivity, particularly for learners with disabilities and other underrepresented groups. In a MOOC field experiment, DeBoer et al. (2019) found that low-cost at-home lab kits improved exam scores and self-efficacy relative to controls, suggesting a feasible approach for supporting problem-centered, experiential learning at scale.

These studies identify three interrelated dimensions of quality in online STEM education: institutional evaluation practices, learner histories and perceptions, and instructional design for active, authentic, and accessible learning. Quality was therefore not a property of modality alone; it reflected how courses and programs were evaluated, how prior online experience and enrollment contexts were associated with learner success, and whether instructional features supported engagement, accessibility, assessment, and hands-on STEM activity. At the same time, divergent learner perceptions and uneven evaluation practices indicate that institutional narratives emphasizing demand for online STEM offerings may not align with learners' experiences of quality. Because most evidence came from individual courses or institutional settings, the findings do not establish how these dimensions operate across STEM disciplines and programs (see Table 4).

Table 4

Online STEM Course Quality, Design, and Learner Success

Authors	Type of Study	Targeted Modality	Target Population	Analytic Classification
Downs (2014)	Empirical, qualitative (multi-case program evaluation)	Asynchronous online	Learners (graduate STEM)	Core Pedagogical
Hachey et al. (2015)	Empirical, quantitative (predictive analysis)	Asynchronous online	Learners (community college STEM)	Core Pedagogical
Wladis et al. (2014)	Empirical, quantitative (course-level analysis)	Asynchronous online	Learners (online STEM course enrollees)	Core Pedagogical
Ramlo (2017)	Empirical, qualitative (Q methodology)	Asynchronous online	Learners (first-year undergraduate physics)	Core Pedagogical
Chen et al. (2018)	Empirical, quantitative (exploratory survey)	Asynchronous online	Learners (online STEM course)	Core Pedagogical
DeBoer et al. (2019)	Empirical, quantitative (randomized controlled trial)	Asynchronous online	Learners (engineering MOOC participants)	Core Pedagogical

4. Strategies for Improving Online Learner Engagement in STEM

Learner engagement and community-building are widely recognized as essential to persistence, satisfaction, and success in online learning. Engagement is central to the Community of Inquiry framework (Garrison et al., 2000), is understood as multidimensional (Dixson, 2015), and has been associated with specific instructional strategies in online courses (Martin & Bolliger, 2018). Two of the 33 studies in this review addressed strategies for improving engagement in online STEM contexts, representing asynchronous and blended instructional models.

One study examined engagement through instructional structure and delivery. Johnston (2018) conducted an experimental study of a blended, flipped model across seven core undergraduate engineering courses in a low-resource setting. Findings indicated equivalent levels of reported engagement and satisfaction and comparable overall performance relative to traditional instruction. However, assignment to the blended format was also associated with greater withdrawal or disengagement, particularly among lower-achieving learners. The findings suggest that blended, flipped approaches may offer cost-effective alternatives in resource-constrained contexts while indicating that some learners may require additional scaffolding when adapting to the format.

A second study foregrounded community-building as an engagement strategy. Hutton and Robson (2019) reported a case study of a preparatory website designed for distance learners in a summer science program. Evaluation findings indicated that non-academic interaction with peer mentors and opportunities for low-stakes self-disclosure were central to community formation. Learners reported valuing social contact and peer connections as much as, or more than, academic development in sustaining engagement.

Together, these studies identify two complementary dimensions of engagement in online STEM education: participation structured through course design and active-learning opportunities, and belonging cultivated through peer connection and low-stakes social interaction. The findings suggest that engagement was supported not only by participatory and social opportunities but also by the scaffolding and contextual conditions surrounding learners' participation. Because the studies examined different populations, purposes, modalities, and research designs, the evidence does not establish the relative effectiveness or transferability of either approach across online STEM settings (see Table 5).

Table 5

Strategies for Improving Online Learner Engagement in STEM

Authors	Type of Study	Targeted Modality	Target Population	Analytic Classification
Johnston (2018)	Empirical, quantitative (experimental study with supplementary qualitative interviews)	Blended (F2F & asynchronous online)	Learners (undergraduate engineering, Mongolia)	Core Pedagogical
Hutton & Robson (2019)	Empirical, qualitative (case study)	Asynchronous online	Learners (incoming undergraduate science)	Core Pedagogical

Note. F2F = face-to-face, referring to traditional in-person classroom-based instructional modalities.

5. Communication in Online STEM Environments

Communication is central to STEM learning because it supports disciplinary reasoning, collaboration, and participation in academic and professional communities (National Academies of Sciences, Engineering, and Medicine [NASEM], 2018; National Research Council [NRC], 2012). In online environments, purposeful communication, instructor presence, and structured interaction also support belonging and collaborative knowledge-building (Garrison et al., 2000; Swan et al., 2000). Three of the 33 studies in this review examined communication in online STEM environments, focusing on language development, teamwork, and professional communication.

One study addressed language development. Arno-Macià and Rueda-Ramos (2011) presented a qualitative case study of *Quantum LEAP*, an online autonomous learning environment integrating English for Academic Purposes (EAP) with interdisciplinary science, technology, and society content. Their findings challenged assumptions that EAP instruction is limited to language development, showing how language learning can support interdisciplinary STEM engagement and critical reflection.

A second study examined communication for collaboration and teamwork. Fiore et al. (2012) introduced *uCollaborator,* a prototype framework designed to support geographically distributed engineering and technology teams through integrated synchronous and asynchronous communication, shared visualization, and collaborative decision-making. As a proof-of-concept, the study illustrated how communication tools can support team-based problem solving in online STEM contexts.

The third study focused on professional communication. Baim (2016) reported a qualitative course-intervention case study designed to support undergraduate STEM learners' transition from informal social media practices to academically and professionally appropriate communication through self-paced modules and peer-driven wiki activities, highlighting the role of structured online scaffolding and peer interaction in supporting professional communication development.

These studies identify three interrelated functions of communication in online STEM education: supporting disciplinary reflection through language, coordinating collaborative problem solving, and developing professional discourse practices. Across the three studies, communication supported teamwork, made disciplinary thinking visible for reflection and coordination, and developed professional discourse practices relevant to distributed STEM collaboration. Because the evidence consisted of two case studies and a proof-of-concept, it does not establish the effects of these communication designs on learning, teamwork, or transfer to professional practice across settings (see Table 6).

Table 6

Communication in Online STEM Environments

Authors	Type of Study	Targeted Modality	Target Population	Analytic Classification
Arno-Macià & Rueda-Ramos (2011)	Empirical, qualitative (case study)	Asynchronous online (self-paced learning materials)	Learners (engineering)	Core Pedagogical
Fiore et al. (2012)	Empirical, design-based (proof-of-concept)	Synchronous & asynchronous online collaboration	Learners & Instructors (STEM project teams)	Core Pedagogical
Baim (2016)	Empirical, qualitative (course-intervention case study)	Asynchronous online	Learners (undergraduate STEM)	Core Pedagogical

6. Equity and Inclusion for Underrepresented Learners in Online STEM

Equity and inclusion remain critical challenges in STEM education, with persistent gaps in access, participation, and outcomes across gender, race, disability, and other learner characteristics. National reports and meta-analyses document systemic barriers faced by women and learners of color (Corbett & Hill, 2015; Hill et al., 2010), while research on stereotype threat and structural inequities highlights mechanisms that undermine persistence (Rozek et al., 2019; Vakil et al., 2016). More recent evidence underscores the urgency of these concerns: NASEM (2020) identified enduring barriers to women's participation in STEM, and the NSF (2023) reported continued underrepresentation of women, racial and ethnic minorities, and persons with disabilities across STEM education and workforce pipelines. Online education offers new possibilities for broadening access, but it also raises questions about whether inequities are mitigated or reproduced. Eight of the 33 studies in this review addressed equity and inclusion in online STEM education. The studies primarily examined asynchronous online environments, while also including comparative, blended, and online-supported instructional contexts. None focused primarily on online faculty preparation or examined institutional policy or systemic reform.

Several studies examined outcomes and enrollment patterns in online STEM environments. Bosch et al. (2019) found that underrepresented learners in an online introductory science course began with lower exam scores but showed comparable improvement over the semester, suggesting both gaps in prior preparation and the potential for online environments to support similar learning gains. Wladis, Conway, et al. (2015) reported that older learners performed better online, while women performed worse than expected relative to face-to-face settings; importantly, gaps for Black and Hispanic learners did not widen online. A second study by Wladis, Hachey, et al. (2015) analyzed enrollment trends, showing underrepresentation of Black and Hispanic men in online STEM courses, overrepresentation of women, and strong links between nontraditional risk factors and online enrollment, with patterns differing by institutional sector.

Other research focused on learners with disabilities and nontraditional needs. Graves et al. (2011) found that learners with learning disabilities (LD) and attention-deficit/hyperactivity disorder (ADHD) reported benefits associated with asynchronous online access, including improved clarity, organization, convenience, and opportunities for self-accommodation. Maldonado and Pearson (2013) described the TECH-FIT project, which combined online resources with faculty development to adapt STEM curricula for women and art/design learners and became institutionalized within its program context as a model for broadening participation.

Several studies examined technology-enabled supports and online interventions aimed at expanding participation. Krishnamurthi and Richter (2013) suggested that low-cost mobile technologies could increase access and interaction for women and underrepresented learners, particularly in resource-limited contexts. Sanga et al. (2013) found that e-learning was associated with improved access, flexibility, and collaboration opportunities for women, although broader socio-cultural and policy changes were required for sustained equity. Similarly, Dawson et al. (2015) described *CareerWISE*, a fully self-paced online resilience training program that provided scalable psychosocial support for women in STEM and offered an alternative to traditional mentoring.

These equity-focused studies distinguish expanded access to online STEM education from equitable participation and outcomes within STEM pathways. Flexible delivery, accessible asynchronous design, mentoring, resilience training, and technology-enabled supports were associated with expanded access and support for some underrepresented and nontraditional STEM learners. At the same time, patterns of participation and benefit remained uneven across gender, race and ethnicity, age, disability, prior preparation, and institutional context. The collective evidence therefore positions online STEM education as a potential site for targeted equity-oriented intervention, but not as an automatic remedy for structural inequities across STEM education and workforce pathways (see Table 7).

Table 7

Equity and Inclusion for Underrepresented Learners in Online STEM

Authors	Type of Study	Targeted Modality	Target Population	Analytic Classification
Bosch et al. (2019)	Empirical, quantitative (correlational analysis)	Asynchronous online	Learners (underrepresented undergraduate STEM)	Contextual / Supporting

Authors	Type of Study	Targeted Modality	Target Population	Analytic Classification
Wladis, Conway, et al. (2015)	Empirical, quantitative (exploratory correlational analysis)	Asynchronous online	Learners (community college STEM)	Core Pedagogical
Wladis, Hachey, et al. (2015)	Empirical, quantitative (secondary data analysis)	Online vs. F2F (comparative; modality not disaggregated)	Learners (community college STEM majors)	Core Pedagogical
Graves et al. (2011)	Empirical, qualitative (semi-structured interviews)	Asynchronous online	Learners (postsecondary STEM learners with LD and/or ADHD)	Core Pedagogical
Maldonado & Pearson (2013)	Descriptive (program design case study)	Blended (asynchronous online resources supporting F2F instruction)	Learners (undergraduate women in STEM)	Contextual / Supporting
Krishnamurthi & Richter (2013)	Practitioner-oriented, descriptive (conference paper)	Asynchronous mobile learning	Learners (underrepresented and nontraditional in STEM)	Contextual / Supporting
Sanga et al. (2013)	Empirical, mixed methods (survey and interviews)	Asynchronous online (supplemental to F2F)	Learners (women in higher education STEM, Tanzania)	Contextual / Supporting
Dawson et al. (2015)	Descriptive (program evaluation case study)	Asynchronous online (self-paced mentoring and resilience training)	Learners (undergraduate women in STEM)	Contextual / Supporting

7. Online STEM Education and Workforce Development

Concerns about STEM workforce capacity and projected shortages have long been documented in national reports and policy initiatives, which emphasize the need for improved preparation, persistence, and participation across diverse learner populations (Carnevale et al., 2011; National Science Board, 2018; National Science Foundation [NSF], 2023). These reports consistently highlight inequities in STEM pathways, particularly for learners from groups historically underrepresented in STEM. Together, these conditions frame the question of whether and how online STEM education may expand access to workforce preparation and advanced credentials for learners who might otherwise have limited access to conventional pathways.

Two of the 33 studies directly addressed STEM workforce development in online higher education contexts. Both examined asynchronous online environments: one involved a contextualized workforce-training intervention, and the other examined a large-scale online graduate degree program delivered through Udacity's MOOC infrastructure. Mohammadi et al. (2019) examined an online Contextualized Teaching and Learning (CTL) intervention that used experiential learning to connect skills development with real-world occupational training. Using a nonrandomized comparison-group design, they found that learners in the CTL condition achieved higher credentialing rates and demonstrated learning gains across multiple measures relative to a comparison group. Nontraditional and historically underrepresented learners, including older adults, women, and learners from racial and ethnic minority groups, were overrepresented in the CTL condition. Although the study design does not fully disentangle intervention effects from group composition, the findings indicate that online CTL environments are associated with positive workforce-oriented outcomes for diverse populations.

Goodman et al. (2019) investigated whether online delivery can expand access to higher education by examining the Georgia Institute of Technology's Online Master of Science in Computer Science (OMSCS), developed with Udacity and AT&T. Using a regression discontinuity design, the authors found that online access substantially increased overall enrollment, attracting mid-career learners who would likely not have enrolled in the traditional on-campus program. Because OMSCS was offered by a highly ranked department at a fraction of the cost of its in-person equivalent, the findings provide rigorous evidence of previously unmet demand for affordable graduate STEM education. Their estimates suggest that the program could increase the annual production of U.S. computer science master's degrees by approximately 7%, underscoring the broader potential of low-cost online graduate STEM programs to expand access and degree attainment.

These studies identify two complementary workforce functions for online STEM education: creating alternative pathways into occupational training and expanding access to advanced credentials for learners unable or unlikely to enter conventional programs. Contextualized experiential learning and a low-cost, large-scale online graduate degree program illustrate how distinct pedagogical and program models can broaden access to workforce-oriented education for nontraditional and mid-career learners. The collective evidence is strongest for expanded access and, in one study, credentialing and near-term learning outcomes; the studies do not establish whether expanded access translated into equitable persistence or longer-term workforce outcomes (see Table 8).

Table 8

Online STEM Education and Workforce Development

Authors	Type of Study	Targeted Modality	Target Population	Analytic Classification
Mohammadi et al. (2019)	Empirical, quantitative (nonrandomized comparison-group design)	Asynchronous online	Learners (adult, nontraditional STEM workforce trainees)	Core Pedagogical
Goodman et al. (2019)	Empirical, quantitative (descriptive and quasi-experimental causal inference)	Asynchronous online (large-scale graduate degree program)	Learners (graduate-level, mid-career STEM professionals)	Contextual/ Supporting

8. Online STEM Faculty Preparation

The preparation and ongoing professional development of STEM faculty are widely recognized as critical to improving teaching quality, learner engagement, and persistence in STEM education (Derting et al., 2016; Ebert-May et al., 2011; Henderson et al., 2011; NRC, 2012). Three of the 33 studies in this review addressed STEM faculty preparation, including one focused on preservice educators; all three examined online, asynchronous professional development environments.

Davis and Snyder (2012) investigated the Science Education Online (SEO) graduate-level program and found that its online courses met university quality standards while providing inquiry-based learning opportunities. Participants reported that purposeful learner–faculty and peer discussion positively influenced their own teaching practices. Christe (2015) designed an asynchronous workshop focused on learner persistence and retention in STEM, introducing evidence on learner–faculty rapport and classroom climate (including the Wilson–Ryan Rapport Scale) to prompt reflection and buy-in. Although not all faculty were persuaded, the case suggested that evidence-informed framing can strengthen commitment to persistence-oriented teaching practices. Wu et al. (2019) tested an online training intervention to scaffold design-thinking competence for collaborative STEM learning design among preservice educators, finding that different scaffolding modes shaped collaborative design discussions, underscoring the importance of instructional design choices in faculty preparation for interdisciplinary STEM teaching.

These studies identify three functions of online faculty preparation: supporting inquiry-oriented pedagogy, prompting reflection on learner–faculty rapport and persistence, and scaffolding collaborative design competence for interdisciplinary STEM learning. The evidence, however, is drawn from a small number of context-specific studies and does not establish whether the documented professional-learning outcomes translated into sustained changes in teaching practice or were associated with learner outcomes (see Table 9).

Table 9

Online STEM Faculty Preparation

Authors	Type of Study	Targeted Modality	Target Population	Analytic Classification
Davis & Snyder (2012)	Empirical, quantitative (quasi-experimental)	Asynchronous online	Instructors (graduate-level science educators)	Core Pedagogical
Christe (2015)	Empirical, qualitative (case study)	Asynchronous online (self-paced)	Instructors (STEM faculty)	Core Pedagogical
Wu et al. (2019)	Empirical, quantitative (experimental design)	Asynchronous online	Instructors (pre-service STEM teacher candidates)	Core Pedagogical

Across asynchronous, synchronous, combined-online, and selected blended contexts, the reviewed literature linked learner experiences and outcomes to intentional course design, interaction, facilitation, authenticity, assessment, learner support, and access. The themes were interdependent: learner support intersected with engagement and persistence; communication with collaboration and disciplinary participation; faculty preparation with design and facilitation; and equity considerations across these dimensions.

At the same time, the evidence base was uneven. Experimental and quasi-experimental studies provided stronger evidence concerning learner outcomes and course design, while large-scale studies provided broader evidence concerning program access and workforce pathways; much of the literature, however, remained small-scale, descriptive, case-based, or lightly theorized. Attention to underrepresented learners was more visible than attention to institutional policy, systemic reform, or faculty capacity. Taken together, the pre-COVID literature portrays online STEM education as a set of interrelated design, teaching, interaction, and support practices situated within disciplinary, pedagogical, institutional, and equity contexts.

Discussion

The eight themes show that the central concerns represented in the reviewed literature were not isolated problems but interdependent dimensions of online STEM teaching and learning. Applying established online-learning principles within STEM disciplines required attention to laboratory activity, quantitative and procedural reasoning, authentic problem solving, and disciplinary communication. These disciplinary demands help explain why course design, learner support, engagement, communication, equity, and faculty preparation repeatedly intersected across the reviewed studies.

The publication pattern among the included studies also helps explain why online STEM scholarship has remained difficult to recognize as a coherent body of research. Only three of the 33 studies appeared in journals devoted specifically to online or distance education, while the remainder were dispersed across STEM-specific, disciplinary, and broader education venues. These counts describe the composition of the reviewed literature rather than establish a longitudinal publication trend. Nevertheless, the pattern is consistent with Wallace's (2003) observation that online-learning research had done comparatively little to connect general online constructs with subject-specific teaching and learning. It also complements Martin et al.'s (2020) broad review of online-learning research, which did not include discipline-specific journals. Together, these comparisons position the present review at the intersection of STEM education scholarship and the broader online-learning literature.

Across the themes, intentional design and facilitation appeared more consequential than any single delivery format. In asynchronous environments, active learning, assessment, accessibility, authentic laboratory activity, learner support, and community-building were associated with learner experiences and outcomes. Synchronous and combined-online studies showed how real-time interaction could extend tutoring and collaboration, while also introducing technological barriers and differing expectations about instructor and learner roles. The blended studies contributed evidence about active learning, instructional structure, and access in particular contexts, underscoring the importance of interpreting findings in relation to the modality and setting examined. Across modalities, the findings reinforce established online-learning frameworks that position interaction, teaching presence, community, and coherent instructional design as mutually supporting conditions for learning (Anderson, 2011; Garrison et al., 2000; Picciano, 2017; Sun & Chen, 2016).

The findings also complicate the assumption that expanded online access necessarily produces equity. Flexible and accessible asynchronous design, mentoring, resilience-oriented support, contextualized learning, and lower-cost degree pathways were associated with expanded access and support for underrepresented, nontraditional, and mid-career learners. At the same time, differences in prior preparation, enrollment patterns, institutional structures, and broader sociocultural conditions continued to shape participation and outcomes. Equity in online STEM education therefore requires more than making courses or programs available; it requires intentional attention to accessibility, belonging, learner support, assessment, and the institutional conditions through which learners enter and progress through STEM pathways.

Faculty preparation was a comparatively small part of the reviewed literature, but its significance extends across the themes. The included studies suggest that online professional development can support inquiry-oriented pedagogy, purposeful interaction, learner–faculty rapport, persistence-focused practice, and collaborative STEM learning design. This limited attention is especially consequential when viewed alongside Elrod's (2010) account of *Project Kaleidoscope 2.0,* a national cross-disciplinary initiative that placed learner-centered pedagogy, faculty development, and leadership for sustained reform at the center of STEM improvement.

Yet the initiative did not address preparation for online teaching or consider online professional development as a scalable means of preparing STEM faculty. This contrast suggests that online education and STEM reform were developing largely as parallel rather than integrated agendas, leaving unresolved how faculty would be prepared to teach effectively in online STEM environments.

The strength of the evidence varied considerably across the 33 studies. Experimental and quasi-experimental studies provided stronger evidence concerning learner outcomes and course design, while large-scale studies provided broader evidence concerning program access and workforce pathways; much of the literature, however, remained small-scale, descriptive, case-based, or lightly theorized. This unevenness limits comparison across disciplines, modalities, learner populations, and institutional settings and constrains cumulative knowledge building. Bringing these dispersed studies together nevertheless clarifies how online STEM questions developed across research communities that were not always in direct conversation. The eight-theme framework also provides a structured basis for examining whether later research extends, reframes, or overlooks this earlier knowledge base.

Limitations

This review has several limitations that shape the scope of its findings. First, the search was restricted to three databases: EBSCO, ERIC, and Web of Science, and to English-language scholarly publications. These boundaries may have excluded relevant studies indexed elsewhere, published in other languages, or disseminated through grey literature such as dissertations. In addition, discipline-specific studies that did not use STEM-related terminology may not have been identified through the search strategy.

Second, much of the evidence base was small-scale, descriptive, case-based, or lightly theorized, with relatively few longitudinal or multi-institutional studies. These characteristics limit the transferability of individual findings and the extent to which broader patterns in online STEM teaching and learning can be compared across disciplines, learner populations, and institutional settings.

Finally, each study was assigned to the thematic category representing its primary contribution for purposes of analytic presentation. Because many studies addressed interrelated dimensions of online STEM teaching and learning, their findings often crossed thematic boundaries. The categories should therefore be understood as an organizing framework for synthesis rather than as mutually exclusive divisions within the literature.

Future Research

Future research on online STEM education should build on the thematic framework and pre-COVID baseline established in this review. Five cross-cutting priorities emerge.

First, stronger theoretical grounding is needed. Future studies should use established online learning, persistence, motivation, adult learning, sociocultural, and identity-oriented frameworks to guide research design and interpretation rather than applying theory only after findings have been generated. Relevant traditions include persistence and motivation theory (Bandura, 1977; Bean, 1982; Tinto, 1975), adult learning theory (Knowles, 1973), established online learning models such as the Community of Inquiry (Garrison et al., 2000; Shea & Bidjerano, 2010), and sociocultural and identity-oriented perspectives (Brown et al., 1989; Luehmann, 2007; Wenger, 1998). Such perspectives may help explain how disciplinary culture, interaction, belonging, self-efficacy, resilience, epistemic beliefs, pedagogical conceptions, and professional identity shape teaching, learning, and participation in online STEM environments.

Second, more diverse and rigorous research designs are needed in online STEM research. Multi-institutional, longitudinal, experimental, and mixed-methods studies could strengthen understanding of how instructional design, learner support, faculty preparation, and program structures influence learning, persistence, and workforce pathways across disciplines and institutional contexts. Studies should clearly define the instructional modalities examined and use terminology consistently, distinguishing among asynchronous, synchronous, combined-online, blended or hybrid, and other relevant contexts. Where appropriate, researchers should investigate modality-specific and cross-modality patterns.

Third, equity should be examined as a cross-cutting dimension of online STEM education rather than confined to studies focused specifically on underrepresented populations. Research should consider how accessibility, prior preparation, interaction, assessment, belonging, course design, faculty preparation, and institutional policy shape participation and outcomes for diverse learners in online STEM environments. Social justice, critical, feminist, culturally responsive, and accessibility-oriented perspectives can help researchers examine how power, agency, inclusion, and relationality operate in digitally mediated learning environments (Freire, 1970; Gay, 2000; Kumi-Yeboah & Amponsah, 2023; Woodley et al., 2017).

Fourth, research should examine how artificial intelligence is reshaping online STEM teaching and learning. AI-enabled tools may influence instructional design, feedback, learner support, assessment, accessibility, simulation, and disciplinary problem solving, while raising questions about accuracy, bias, data privacy, academic integrity, learner agency, ethical use, and the changing roles of faculty and instructional designers. Research should examine these developments across specific STEM disciplines and learner populations, including how AI is integrated into learning platforms and institutional policy, how it affects preparation for AI-mediated STEM work, and whether it reduces or reproduces existing inequities.

Finally, the pre-COVID literature synthesized here provides a lens for examining how online STEM scholarship changed during and after the pandemic. Comparative reviews could identify which established concerns and practices were extended, reframed, or overlooked and which longstanding questions resurfaced without connection to the earlier knowledge base.

Conclusion

This integrative review synthesized 33 studies to establish a historical baseline of online STEM teaching and learning in higher education before the COVID-19 pandemic. The eight thematic categories bring coherence to scholarship published across STEM-specific, disciplinary, and broader education venues and show that online STEM education is best understood as a set of interrelated design, teaching, interaction, and support practices. Across the reviewed literature, learner experiences and outcomes reflected how instructional design, facilitation, authenticity, communication, assessment, learner support, access, and equity were addressed within particular disciplinary and institutional contexts.

The synthesis also reveals persistent gaps in theoretical grounding, methodological scale, faculty preparation, institutional capacity, and the integration of equity across online STEM teaching and learning. These gaps limit cumulative knowledge building across disciplines and institutional contexts.

The pre-COVID boundary should therefore be understood not as an endpoint, but as a lens for interpreting subsequent developments. The thematic framework provides a basis for examining whether pandemic-era and post-pandemic scholarship extends, reframes, or overlooks the earlier knowledge base. As online and hybrid learning remain integral to higher education, building on this foundation through more rigorous, theoretically grounded, and equity-centered research can strengthen online STEM education by advancing workforce pathways that are more accessible, effective, and equitable; strengthening institutional capacity and faculty practice; and better supporting the success of diverse online learners.

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The author declares no conflicts of interest related to the research, authorship, or publication of this article.

References

American Council on Education. (2020, April 9). *Higher education fourth supplemental letter to Senate Majority Leader McConnell and Minority Leader Schumer* [Letter]. https://www.acenet.edu/Documents/Letter-Senate-Higher-Ed-Supplemental-Request-040920.pdf

Anderson, T. (Ed.). (2011). The theory and practice of online learning (2nd ed.). AU Press.

Arno-Macià, E., & Rueda-Ramos, C. (2011). Promoting reflection on science, technology, and society among engineering students through an EAP online learning environment. *Journal of English for Academic Purposes*, *10*(1), 19–31. https://doi.org/10.1016/j.jeap.2010.12.004

Baim, S. A. (2016). Building professional social media communications skills: A STEM-originated course with university-wide student appeal. *Journal on Excellence in College Teaching*, *27*(2), 155–182. https://eric.ed.gov/?id=EJ1104014

Bandura, A. (1977). Self-efficacy: Toward a unifying theory of behavioral change. *Psychological Review*, *84*(2), 191–215. https://doi.org/10.1037/0033-295X.84.2.191

Bean, J. P. (1982). Student attrition, intentions, and confidence: Interaction effects in a path model. *Research in Higher Education*, *17*(4), 291–320. https://doi.org/10.1007/BF00977899

Bosch, N., Huang, E., Angrave, L., & Perry, M. (2019). Modeling improvement for underrepresented minorities in online STEM education. In *Proceedings of the 27th Conference on User Modeling, Adaptation and Personalization (UMAP '19),* Association for Computing Machinery (ACM) (pp. 327–335). https://doi.org/10.1145/3320435.3320463

Breiner, J. M., Harkness, M., Johnson, C. C., & Koehler, C. M. (2012). What is STEM? A discussion about conceptions of STEM in education and partnerships. *School Science and Mathematics*, *112*(1), 3–11. https://doi.org/10.1111/j.1949-8594.2011.00109.x

Brown, J. S., Collins, A., & Duguid, P. (1989). Situated cognition and the culture of learning. *Educational Researcher, 18*(1), 32–42. https://doi.org/10.3102/0013189X018001032

Butcher, J., Clarke, A., Wood, C., McPherson, E., & Fowle, W. (2019). How does a STEM access module prepare adult learners to succeed in undergraduate science? *Journal of Further and Higher Education, 43*(9), 1271–1283. https://eric.ed.gov/?id=EJ1228873

Campbell, A., Gallen, A. M., Jones, M. H., & Walshe, A. (2019). The perceptions of STEM tutors on the role of tutorials in distance learning. *Open Learning: The Journal of Open, Distance and e-Learning*, *34*(1), 89–102. https://doi.org/10.1080/02680513.2018.1544488

Carnevale, A. P., Smith, N., & Melton, M. (2011). *STEM: Science, technology, engineering, mathematics*. Georgetown University Center on Education and the Workforce. https://cew.georgetown.edu/wp-content/uploads/2014/11/stem-complete.pdf

Chen, B., Bastedo, K., & Howard, W. (2018). Exploring design elements for online STEM courses: Active learning, engagement & assessment design. *Online Learning*, *22*(2), 59–75. https://doi.org/10.24059/olj.v22i2.1369

Chen, X. (2013). *STEM attrition: College students' paths into and out of STEM fields* (NCES 2014-001). National Center for Education Statistics, Institute of Education Sciences, U.S. Department of Education. https://nces.ed.gov/pubs2014/2014001rev.pdf

Christe, B. (2015). Implementation of an asynchronous workshop for STEM educators designed to enhance professor-student rapport. *Journal on Excellence in College Teaching, 26*(4), 9–28. https://eric.ed.gov/?id=EJ1082710

Corbett, C. & Hill, C. (2015). *Solving the equation: The variables for women's success in engineering and computing.* American Association of University Women (AAUW), Washington, D.C. https://eric.ed.gov/?id=ED580805

Davis, K. S., & Snyder, W. (2012). Fostering science education in an online environment: Are we there yet? *Journal of College Science Teaching*, *42*(2), 24–31. https://eric.ed.gov/?id=EJ999485

Dawson, A. E., Bernstein, B. L., & Bekki, J. M. (2015). Providing the psychosocial benefits of mentoring to women in STEM: CareerWISE as an online solution. *New Directions for Higher Education*, *2015*(171), 53–62. https://doi.org/10.1002/he.20142

DeBoer, J., Haney, C., Atiq, S. Z., Smith, C., & Cox, D. (2019). Hands-on engagement online: Using a randomized control trial to estimate the impact of an at-home lab kit on student attitudes and achievement in a MOOC. *European Journal of Engineering Education*, *44*(1–2), 234–252. https://eric.ed.gov/?id=EJ1203328

Derting, T. L., Ebert-May, D., Henkel, T. P., Maher, J. M., Arnold, B., & Passmore, H. A. (2016). Assessing faculty professional development in STEM higher education: Sustainability of outcomes. *Science Advances*, *2*(3), e1501422. https://doi.org/10.1126/sciadv.1501422

Dixson, M. D. (2015). Measuring student engagement in the online course: The online student engagement scale (OSE). *Online Learning*, *19*(4). https://doi.org/10.24059/olj.v19i4.561

Doo, M. Y., Zhu, M., & Bonk, C. J. (2023). A systematic review of the research topics in online learning during COVID-19: Documenting the sudden shift. *Online Learning, 27*(1), 15–45. https://doi.org/10.24059/olj.v27i1.3405

Downs, H. A. (2014). Evaluation in STEM online graduate degree programs in agricultural sciences and engineering. *Journal of Case Studies in Education*, *5*, 1–18. https://files.eric.ed.gov/fulltext/EJ1060613.pdf

Ebert-May, D., Derting, T., Hodder, J., Momsen, J., Long, T., & Jardeleza, S. (2011). What we say is not what we do: Effective evaluation of faculty professional development programs. *BioScience*, *61*(7), 550–558. https://doi.org/10.1525/bio.2011.61.7.9

Elrod, S. (2010). Project Kaleidoscope 2.0: Leadership for twenty-first century STEM education. *Liberal Education, 96*(4), 24–33. https://eric.ed.gov/?id=EJ923879

English, L. D. (2016). STEM education K–12: Perspectives on integration. *International Journal of STEM Education, 3,* Article 3. https://doi.org/10.1186/s40594-016-0036-1

Entangled Solutions, & Alexander, B. (2020, April 27). *COVID-19: Higher education resource center*. Entangled Solutions. https://www.entangled.solutions/coronavirus-he

Fiore, S. M., Rodriguez, W. E., & Carstens, D. S. (2012). uCollaborator: Framework for STEM project collaboration among geographically-dispersed student/faculty teams. *Journal of STEM Education: Innovations and Research*, *13*(2), 84–92. https://eric.ed.gov/?id=EJ978729

Freire, P. (1970). *Pedagogy of the oppressed*. Herder & Herder.

Garrison, D. R., Anderson, T., & Archer, W. (2000). Critical inquiry in a text-based environment: Computer conferencing in higher education. *The Internet and Higher Education*, *2*(2–3), 87–105. https://doi.org/10.1016/S1096-7516(00)00016-6

Gay, G. (2000). *Culturally responsive teaching: Theory, research, and practice*. Teachers College Press.

Geiger, V., Mulligan, J., Date-Huxtable, L., Ahlip, R., Jones, D., May, E. J., Rylands, L. J., & Wright, I. (2018). An interdisciplinary approach to designing online learning: Fostering pre-service mathematics teachers' capabilities in mathematical modelling. *ZDM Mathematics Education*, *50*(2), 217–232. https://doi.org/10.1007/s11858-018-0920-x

Gibbons, J. A. (1979). Curriculum integration. *Curriculum Inquiry, 9*(4), 321–332. https://eric.ed.gov/?id=EJ216032

Goodman, J., Melkers, J., & Pallais, A. (2019). Can online delivery increase access to education? *Journal of Labor Economics, 37*(1), 1–34. https://doi.org/10.1086/698895

Graves, L., Asunda, P. A., Plant, S. J., & Goad, C. (2011). Asynchronous online access as an accommodation on students with learning disabilities and/or attention-deficit hyperactivity disorders in postsecondary STEM courses. *Journal of Postsecondary Education and Disability, 24*(4), 317–330. https://eric.ed.gov/?id=EJ966132

Hachey, A. C., Wladis, C., & Conway, K. M. (2015). Prior online course experience and GPA as predictors of subsequent online STEM course outcomes. *The Internet and Higher Education, 25*, 11–17. https://doi.org/10.1016/j.iheduc.2014.10.003

Henderson, C., Beach, A., & Finkelstein, N. (2011). Facilitating change in undergraduate STEM instructional practices: An analytic review of the literature. *Journal of Research in Science Teaching*, *48*(8), 952–984. https://doi.org/10.1002/tea.20439

Hill, C., Corbett, C., & St. Rose, A. (2010). *Why so few? Women in science, technology, engineering, and mathematics.* American Association of University Women. https://www.aauw.org/app/uploads/2020/03/why-so-few-research.pdf

Honey, M., Pearson, G., & Schweingruber, H. (2014). *STEM integration in K–12 education: Status, prospects, and an agenda for research.* National Academies Press. https://doi.org/10.17226/18612

Hossain, Z., Bumbacher, E., Brauneis, A., Diaz, M., Saltarelli, A., Blikstein, P., & Riedel-Kruse, I. H. (2018). Design guidelines and empirical case study for scaling authentic inquiry-based science learning via open online courses and interactive biology cloud labs. *International Journal of Artificial Intelligence in Education*, *28*(4), 478–507. https://doi.org/10.1007/s40593-017-0150-3

Hutton, C., & Robson, J. (2019). Breaking barriers, building community: Improving student engagement with preparation for studying online multidisciplinary science by distance learning—A case study. *New Directions in the Teaching of Physical Sciences, 14*(1). https://doi.org/10.29311/ndtps.v0i14.3217

Johnston, J. (2018). *The effects of blended online learning in higher education STEM courses: Experimental evidence from Mongolia* (CEPA Working Paper No. 18–11). Stanford Center for Education Policy Analysis. https://cepa.stanford.edu/content/effects-blended-online-learning-higher-education-stem-courses-experimental-evidence-mongolia

Knowles, M. S. (1973). *The adult learner: A neglected species.* Gulf Publishing. https://eric.ed.gov/?id=ED084368

Krishnamurthi, M., & Richter, S. (2013, March). Promoting STEM education through mobile teaching and learning. Paper presented at the International Association for Development of the Information Society (IADIS*) International Conference on Mobile Learning,* Lisbon, Portugal. https://eric.ed.gov/?id=ED562382

Kumi-Yeboah, A., & Amponsah, S. (2023). An exploratory study of instructors' perceptions on inclusion of culturally responsive pedagogy in online education. *British Journal of Educational Technology*, *54*(4), 878–897. https://doi.org/10.1111/bjet.13299

Kysilka, M. L. (1998). Understanding integrated curriculum. *The Curriculum Journal, 9*(2), 197–209. https://doi.org/10.1080/0958517970090206

Lederman, D. (2020, April 27). Presidents' biggest COVID-19 worries? Low-income students and colleges' financial strain. *Inside Higher Ed.* https://www.insidehighered.com/news/survey/presidents-biggest-covid-19-worries-low-income-students-and-colleges-financial-strain

Luehmann, A. L. (2007). Identity development as a lens to science teacher preparation. *Science Education,* 91(5), 822–839. https://doi.org/10.1002/sce.20209

Maldonado, E., & Pearson, K. R. (2013). Building STEAM in design-related technology. *Journal of Educational Technology Systems*, *42*(2), 133–140. https://doi.org/10.2190/ET.42.2.e

Martin, F., & Bolliger, D. U. (2018). Engagement matters: Student perceptions on the importance of engagement strategies in the online learning environment. *Online Learning*, *22*(1), 205–222. https://doi.org/10.24059/olj.v22i1.1092

Martin, F., Sun, T., & Westine, C. D. (2020). A systematic review of research on online teaching and learning from 2009 to 2018. *Computers & Education, 159,* Article 104009. https://doi.org/10.1016/j.compedu.2020.104009

Means, B., Toyama, Y., Murphy, R., & Baki, M. (2013). The effectiveness of online and blended learning: A meta-analysis of the empirical literature. *Teachers College Record: The Voice of Scholarship in Education*, *115*(3), 1–47. https://doi.org/10.1177/016146811311500307

Meyer, K. A. (2014). *Student engagement in online learning: What works and why* (ASHE Higher Education Report, 40). Wiley. https://doi.org/10.1002/aehe.20018

Mohammadi, A., Grosskopf, K., & Killingsworth, J. (2019). Workforce development through online experiential learning for STEM education. *Adult Learning*, *31*(1), 27–35. https://doi.org/10.1177/1045159519854547

National Academies of Sciences, Engineering, and Medicine. (NASEM, 2018). *Graduate STEM education for the 21st century*. The National Academies Press. https://doi.org/10.17226/25038

National Academies of Sciences, Engineering, and Medicine. (NASEM, 2020). *Promising practices for addressing the underrepresentation of women in science, engineering, and medicine: Opening doors.* The National Academies Press. https://doi.org/10.17226/25585

National Center for Education Statistics. (2018). *Fast facts: Distance learning*. U.S. Department of Education, Institute of Education Sciences. https://nces.ed.gov/fastfacts/display.asp?id=80

National Research Council. (NRC, 2012). *A framework for K-12 science education: Practices, crosscutting concepts, and core ideas*. Committee on a Conceptual Framework for New K-12 Science Education Standards, Board on Science Education, Division of Behavioral and Social Sciences and Education. The National Academies Press. https://www.nationalacademies.org/read/13165

National Science Board. (2018). *Science and engineering indicators 2018.* National Science Foundation. https://www.nsf.gov/statistics/2018/nsb20181/assets/nsb20181.pdf

National Science Foundation, National Center for Science and Engineering Statistics. (NSF, 2023). *Diversity and STEM: Women, minorities, and persons with disabilities 2023* (NSF 23–315). https://www.nsf.gov/reports/statistics/diversity-stem-women-minorities-persons-disabilities-2023

Picciano, A. G. (2017). Theories and frameworks for online education: Seeking an integrated model. *Online Learning, 21*(3), 166–190. https://doi.org/10.24059/olj.v21i3.1225

Ramlo, S. (2017). Student views regarding online freshmen physics courses. *Research in Science & Technological Education*, *35*(4), 461–476. https://doi.org/10.1080/02635143.2017.1353961

Reid, J., & Wilkes, J. (2016). Developing and applying quantitative skills maps for STEM curricula, with a focus on different modes of learning. *International Journal of Mathematical Education in Science and Technology*, *47*(6), 837–852. https://doi.org/10.1080/0020739X.2016.1144814

Rennar-Potacco, D., & Orellana, A. (2018). Academically supporting STEM students from a distance through videoconferencing: Lessons learned. *American Journal of Distance Education*, *32*(2), 131–149. https://doi.org/10.1080/08923647.2018.1446121

Rennar-Potacco, D., Orellana, A., Chen, P., & Salazar, A. (2019). Rethinking academic support: Improving the academic outcomes of students in high-risk STEM courses with synchronous videoconferencing. *Journal of College Student Retention: Research, Theory & Practice, 20*(4), 455–474. https://eric.ed.gov/?id=EJ1201691

Rozek, C. S., Ramirez, G., Fine, R. D., & Beilock, S. L. (2019). Reducing socioeconomic disparities in the STEM pipeline through student emotion regulation. *Proceedings of the*

National Academy of Sciences, *116*(5), 1553–1558. https://doi.org/10.1073/pnas.1808589116

Sanders, M. (2009). STEM, STEM education, STEMmania. *The Technology Teacher*, *68*(4), 20–26. https://eric.ed.gov/?id=EJ821633

Sanga, C., Magesa, M. M., Chingonikaya, E., & Kayunze, K. A. (2013). Can e-learning promote participation of female students in STEM disciplines in higher learning institutions of Tanzania? *International Journal of Education and Development Using Information and Communication Technology, 9*(3), 86–102. https://eric.ed.gov/?id=EJ1071373

Schwartz, R. S., & Lederman, N. G. (2002). "It's the nature of the beast": The influence of knowledge and intentions on learning and teaching nature of science. *Journal of Research in Science Teaching, 39*(3), 205–236. https://doi.org/10.1002/tea.10021

Seaman, J. E., Allen, I. E., & Seaman, J. (2018). *Grade increase: Tracking distance education in the United States*. Babson Survey Research Group. https://onlinelearningsurvey.com/reports/gradeincrease.pdf

Seymour, E., & Hunter, A.-B. (Eds.). (2019). *Talking about leaving revisited: Persistence, relocation, and loss in undergraduate STEM education.* Springer. https://doi.org/10.1007/978-3-030-25304-2

Sgro, C. M., Bobowski, T., & Oliveira, A. W. (2020). Current praxis and conceptualization of STEM education: A call for greater clarity in integrated curriculum development. In V. L. Akerson & G. A. Buck (Eds.), *Critical questions in STEM education* (Vol. 51, pp. 185–210). Springer. https://doi.org/10.1007/978-3-030-57646-2_11

Shea, P., & Bidjerano, T. (2010). Learning presence: Towards a theory of self-efficacy, self-regulation, and the development of a communities of inquiry in online and blended learning environments. *Computers & Education, 55*(4), 1721–1731. https://doi.org/10.1016/j.compedu.2010.07.017

Singh, V., & Thurman, A. (2019). How many ways can we define online learning? A systematic literature review of definitions of online learning (1988–2018). *American Journal of Distance Education, 33*(4), 289–306. https://doi.org/10.1080/08923647.2019.1663082

Spaniol-Mathews, P., Letourneau, L. E., & Rice, E. (2016). The impact of online supplemental instruction on academic performance and persistence in undergraduate STEM courses. *Supplemental Instruction Journal*, *2*(1), 19–32. https://eric.ed.gov/?id=ED600833

State University of New York [SUNY]. (2025). *Online learning data definitions*. https://online.suny.edu/wp-content/uploads/2025/06/Online-Learning-Definitions-June-2025.pdf

Sun, A., & Chen, X. (2016). Online education and its effective practice: A research review. *Journal of Information Technology Education: Research, 15,* 157–190. https://doi.org/10.28945/3502

Swan, K., Shea, P., Fredericksen, E., Pickett, A., Pelz, W., & Maher, G. (2000). Building knowledge-building communities: Consistency, contact, and communication in the virtual classroom. *Journal of Educational Computing Research, 23*(4), 359–383. https://doi.org/10.2190/W4G6-HY52-57P1-PPNE

Tinto, V. (1975). Dropout from higher education: A theoretical synthesis of recent research. *Review of Educational Research*, *45*(1), 89–125. https://doi.org/10.3102/00346543045001089

Tinto, V. (2012). *Completing college: Rethinking institutional action.* University of Chicago Press.

Vakil, S., McKinney de Royston, M., Suad Nasir, N., & Kirshner, B. (2016). Rethinking race and power in design-based research: Reflections from the field. *Cognition and Instruction*, *34*(3), 194–209. https://doi.org/10.1080/07370008.2016.1169817

van Dorresteijn, C., Fajardo-Tovar, D., Pareja Roblin, N., Cornelissen, F., Meij, M., Voogt, J., & Volman, M. (2025). What factors contribute to effective online higher education? A meta-review. *Technology, Knowledge and Learning, 30*, 171–202. https://doi.org/10.1007/s10758-024-09750-5

Wallace, R. M. (2003). Online learning in higher education: A review of research on interactions among teachers and students. *Education, Communication & Information*, *3*(2), 241–280. https://doi.org/10.1080/14636310303143

Wenger, E. (1998). *Communities of practice: Learning, meaning, and identity.* Cambridge University Press. https://doi.org/10.1017/CBO9780511803932

Whittemore, R., & Knafl, K. (2005). The integrative review: Updated methodology. *Journal of Advanced Nursing*, *52*(5), 546–553. https://doi.org/10.1111/j.1365-2648.2005.03621.x

Wladis, C., Conway, K. M., & Hachey, A. C. (2015). The online STEM classroom—Who succeeds? An exploration of the impact of ethnicity, gender, and non-traditional student characteristics in the community college context. *Community College Review*, *43*(2), 142–164. https://doi.org/10.1177/0091552115571729

Wladis, C., Hachey, A. C., & Conway, K. M. (2014). An investigation of course-level factors as predictors of online STEM course outcomes. *Computers & Education*, *77*, 145–150. https://doi.org/10.1016/j.compedu.2014.04.015

Wladis, C., Hachey, A. C., & Conway, K. M. (2015). The representation of minority, female, and non-traditional STEM majors in the online environment at community colleges: A nationally representative study. *Community College Review*, *43*(1), 89–114. https://doi.org/10.1177/0091552114555904

Woodley, X., Hernández, C., Parra, J., & Negash, B. (2017). Celebrating difference: Best practices in culturally responsive teaching online. *TechTrends*, *61*(5), 470–478. https://doi.org/10.1007/s11528-017-0207-z

Wu, B., Hu, Y., & Wang, M. (2019). Scaffolding design thinking in online STEM preservice teacher training. *British Journal of Educational Technology, 50*(5), 2271–2287. https://doi.org/10.1111/bjet.12873

Yang, D., & Baldwin, S. J. (2020). Using technology to support student learning in an integrated STEM learning environment. *International Journal of Technology in Education and Science (IJTES), 4*(1), 1–11. https://ijtes.net/index.php/ijtes/article/view/1592