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Blueprint for the 21st century online learning environment in stem education through a systematic review and qualitative synthesis

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Abstract: This study explores the critical role of STEM education in equipping students for the challenges of the 21st century and examines the effectiveness of Online Learning Environments (OLEs) in delivering such education. The purpose of this research is to identify the essential characteristics of effective OLEs and provide a comprehensive blueprint for their development. Utilizing a systematic review and qualitative synthesis of 228 peer-reviewed articles published between 2000 and 2023, the study adopts a rigorous methodological approach following PRISMA guidelines to analyze key trends, themes, and actionable insights. Findings reveal 46 essential features of optimal OLEs, categorized into ten themes: future-proofing, brain-based approaches, diverse learning mechanisms, high-fidelity implementation, instructional design perspectives, advanced technologies, online learning objects, pedagogical approaches, psychological considerations, and usability factors. These findings emphasize the integration of innovative technologies and pedagogical strategies to create engaging, inclusive, and adaptive learning environments tailored to diverse learner needs. The study concludes with a comprehensive blueprint designed to guide educators, policymakers, and technology developers in creating OLEs that enhance engagement and learning outcomes in STEM education. Practical implications include actionable recommendations for integrating emerging technologies, fostering professional development, and addressing accessibility challenges to democratize STEM education and prepare learners for the digital economy.

Keywords: *21st century skills, Educational technology, Online learning environments, STEM education, Systematic review.*

1. Introduction

1.1. Background

STEM (Science, Technology, Engineering, and Mathematics) education has become increasingly vital in equipping students with the skills necessary for thriving in the rapidly evolving 21st-century workforce. However, traditional approaches to STEM education often fail to accommodate the diverse needs of learners, particularly as technology reshapes the educational landscape. Online Learning Environments (OLEs) have emerged as powerful tools for delivering STEM education, offering flexibility, scalability, and access to advanced technological resources. The COVID-19 pandemic underscored the necessity of robust OLEs, which proved essential for ensuring educational continuity and fostering innovation during global disruptions.

Despite the growing prevalence of OLEs in STEM education, the field lacks a comprehensive, evidence-based framework that identifies and organizes the essential characteristics of effective OLEs. Previous studies have highlighted the role of individual technologies or pedagogical strategies but fall short of presenting an integrated blueprint that bridges the gap between research and practice. This void underscores the need for a systematic analysis of the literature to identify actionable insights and guide educators, policymakers, and developers in creating impactful and adaptable online STEM learning environments.

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1.2. Research Gap and Importance

Existing literature on OLEs in STEM education often focuses on isolated aspects such as specific technologies, pedagogical methods, or theoretical frameworks. While valuable, these fragmented perspectives fail to provide a holistic understanding of how OLEs can be optimized to address the diverse challenges of STEM education. Furthermore, as educational demands evolve in response to technological advancements and societal changes, it is imperative to identify features that ensure OLEs remain adaptable, inclusive, and future-proof.

This study addresses these gaps by conducting a systematic review and qualitative synthesis of 228 peer-reviewed articles, aiming to consolidate current knowledge into a comprehensive framework. By identifying 46 essential features organized into ten thematic categories, this research provides actionable insights that transcend disciplinary silos, offering a practical guide for the development of next-generation OLEs in STEM education.

1.3. Objectives and Research Questions

This study seeks to reimagine the design of OLEs in STEM education by addressing the following research questions:

- **Key Characteristics:** What are the critical features that define effective OLEs in STEM education?
- **Technology Integration:** How can advanced technologies be integrated into OLEs to enhance learning experiences and outcomes?
- **Diverse Learning Mechanisms:** What instructional strategies and design principles best support diverse learners and foster engagement in online STEM education?

1.4. Scope and Contributions

Through an extensive qualitative synthesis, this study presents a "Blueprint for the 21st Century Online Learning Environment in STEM Education," detailing essential features and providing practical recommendations for educators, policymakers, and technology developers. By integrating advanced technologies such as artificial intelligence, virtual reality, and blockchain with innovative pedagogical approaches, this research aims to set the standard for future research and practice in STEM education.

2. Theoretical Framework

The Technological Pedagogical Content Knowledge (TPACK) framework stands as a pivotal theoretical model for amalgamating technological knowledge (TK), pedagogical knowledge (PK), and content knowledge (CK), offering educators a robust guide for the effective integration of technology in teaching, particularly within online STEM education contexts. This framework accentuates the crucial interplay among these domains, facilitating the crafting of superior instructional strategies and the enhancement of student learning experiences in STEM disciplines. Research by Zhang et al. [1] underscores the utility of TPACK in dissecting and supporting online teachers' knowledge within professional learning communities, thus evidencing its applicability in online pedagogical analysis and teacher support. Doering et al. [2] further illuminate the TPACK's versatility in OLE design and educator professional development, emphasizing its significance in instructional design and the framework's evolution to meet the specific needs of online STEM education. Valtonen et al. [3] demonstrate its efficacy in evaluating and fostering the twenty-first-century skills of pre-service teachers, highlighting TPACK's role in enhancing educators' competencies for the digital era. Additionally, Umutlu [4] explores the TPACK framework's application in reengineering online courses for STEM pre-service teachers, showcasing the imperative of intertwining pedagogical strategies with technological proficiency. Collectively, these studies affirm the TPACK framework's comprehensive capability to empower educators in navigating the complexities of technology integration, thereby sAignificantly enriching STEM education in virtual settings. Therefore, this study is primarily guided by the TPACK framework.

3. Methodology

The methodology for this systematic review strictly adhered to PRISMA guidelines, focusing on the eligibility of studies, data extraction, and synthesis of findings to ensure a rigorous analysis.

3.1. Eligibility Criteria

Studies were included if they were peer-reviewed articles published between 2000 and 2023, centered on STEM education in online learning environments (OLEs), and contributed to understanding technology integration in STEM. Non-peer-reviewed articles, studies unrelated to STEM or OLEs, and those not significantly contributing to core themes were excluded.

3.2. Information Sources, Search Strategy and Selection Process

An exhaustive search was conducted across prominent academic databases, including PubMed, ERIC, Web of Science, and Scopus. The search strategy involved a combination of keywords such as "STEM education," "online learning," "technology integration," and "pedagogical innovations." Boolean operators were used to refine the search results, capturing a broad range of relevant articles. Several other sources were also included in the initial pool of studies identified. The selection process began with an initial screening of titles and abstracts to eliminate irrelevant studies. Full-text articles were then assessed for eligibility based on the inclusion and exclusion criteria. This selection resulted in a dataset of 228 resources (please see Figure 1.)

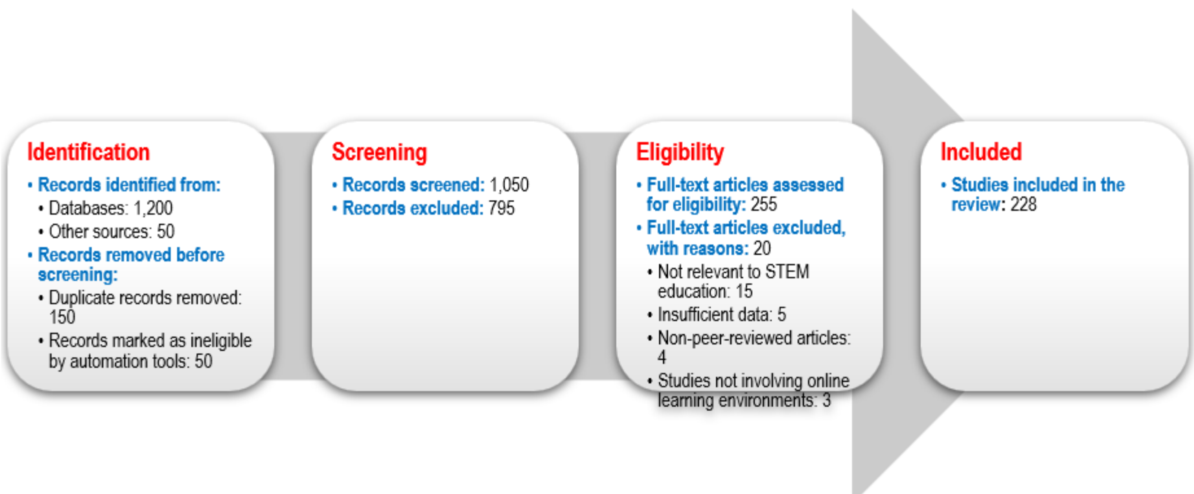

Figure 1.
PRISMA flow diagram that describes the selection process for the studies included.

3.3. Data Collection Process

Data extraction was performed using a standardized form, collecting details on publication year, research methodologies, theoretical frameworks, key findings, and technologies discussed. Data were meticulously organized in spreadsheets to facilitate preliminary analysis and the identification of overarching patterns and themes.

3.4. Data Items

Data items extracted from included studies were as follows:

- ***Publication Details***: Title of the study, authors, year of publication, journal or source.
- ***Study Characteristics***: Type of study (e.g., qualitative, quantitative, mixed-methods), study design (e.g., case study, experimental, survey), sample size and demographics, context or setting of the study (e.g., educational level, geographic location).

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- ***Methodology***: Data collection methods (e.g., surveys, interviews, observations), data analysis techniques (e.g., thematic analysis, statistical analysis).
- ***Key Findings***: Main results or outcomes, identified themes or patterns, implications for online learning environments in stem education.
- ***Technological Integration***: Types of technologies used (e.g., VR, ar, ai), purpose and effectiveness of technology integration, challenges and benefits reported.
- ***Pedagogical Methods***: Instructional strategies employed (e.g., problem-based learning, gamification), effectiveness of these methods, impact on student engagement and learning outcomes.
- ***Psychological And Usability Factors***: Psychological considerations (e.g., motivation, mental health), usability aspects (e.g., accessibility, user-friendliness), student and teacher feedback on these factors.
- ***Limitations And Bias***: Identified limitations of the studies, potential sources of bias.
- ***Recommendations And Future Directions***: Recommendations provided by the authors suggestions for future research.

The data extracted are stored in a repository (Author, 2024). These data items ensure a comprehensive extraction of relevant information to identify essential features and create a robust blueprint for effective online STEM education environments.

3.5. Risk of Bias in Individual Studies

The risk of bias was assessed using established tools, including the Cochrane Risk of Bias tool for randomized studies and the Newcastle-Ottawa Scale for observational studies. Each study was evaluated for potential sources of bias. The risk of bias within individual studies was generally low, with most studies providing clear methodologies and robust data analysis. However, some studies lacked detailed descriptions of their sampling methods, which may have introduced selection bias.

3.6. Qualitative Analysis and Coding

The literature synthesis was conducted following these steps:

- ***Initial Code Extraction:*** The initial set of codes was directly derived from the objectives and critical topics of the research.
- ***Generation of Sub-Codes:*** Sub-codes were generated as the analysis progressed, and more nuanced themes emerged from the data. These sub-codes helped categorize the data more precisely and facilitate a deeper analysis.
- ***Iterative Coding Process:*** As coding proceeded, new themes emerged that were not initially anticipated. This iterative process involved revisiting the data with these new themes in mind, leading to the creation of additional codes and continuous refinement of existing codes and sub-codes to better capture the nuances of the data.
- ***Thematic Grouping:*** After extensive coding, related codes and sub-codes were grouped into larger themes representing significant literature patterns. This step enabled synthesizing the findings and drawing conclusions from the literature review.
- ***Identification of Patterns:*** Connections between themes were visually represented, and the coding framework was dynamically adjusted as the analysis evolved. Patterns were identified, and codes were reorganized into hierarchical structures reflected by the data.

3.7. Thematic Synthesis

The thematic synthesis revealed several key themes, codes and sub-codes, reflecting the rich landscape of STEM education research in online contexts. The systematic approach to literature selection and detailed qualitative analysis has enabled a comprehensive exploration of the field, identifying current trends, challenges, and opportunities. This methodology aimed to create a rigorous literature review offering a foundational basis for future research directions and practical applications in online STEM education.

4. Findings

The qualitative analysis and the resulting thematic synthesis of the research literature yielded 46 essential features of the ideal OLE for STEM education, grouped under 10 themes. Please see Table 1 for the results of this process.

Table 1.
The themes and essential features with the number of references and actual references consulted for each essential feature of the 21st century online learning environment in STEM education.

Theme	Essential feature	Number of references consulted	References consulted
Being future proof	New and useful educational technologies	5	[5–9]
	New and useful instructional paradigms	6	[10–15]
Brain based approaches	Emotional learning	7	[16–22]
	Schema theory	5	[23–27]
	Multiple intelligences	6	[28–33]
	Neuroscientific research and neuroplasticity	6	[34–39]
	Metacognition	6	[40–45]
Diversity in learning mechanisms	Customizable, adaptive, and personalized instruction	5	[46–50]
	Multimodal resources and instruction	5	[51–55]
	Different types of learning experiences	7	[48, 56–61]
High fidelity implementation	Educational standards and guidelines	5	[62–66]
	Professional development modules	5	[67–71]
	High fidelity implementation guidelines	5	[72–76]
Instructional design perspectives	A streamlined content library	5	[56, 66, 77–79]
	Live learner support	5	[80–84]
	Seamless communication with learning management systems (LMS)	8	[71, 73, 85–90]
	Video conferencing	5	[91–95]
	Virtual classrooms	4	[96–99]
Integration of advanced technologies	Virtual Reality (VR) and augmented reality (AR)	7	[100–106]
	Artificial intelligence	6	[107–112]
	Big data and learning analytics	5	[58, 113–116]
	Blockchain technology	7	[117–123]
	Metaverse	6	[124–129]
	Web3 compatibility	5	[17, 130–133]
Online learning objects	Computer and video tutorials	4	[134–137]
	Gamification	5	[138–142]
	Online and virtual labs	4	[143–146]
	Online learning activities	5	[147–151]
	Online learning objects	4	[152–155]
	Online sketching, graphing, and	7	[156–162]

	calculator software		
Pedagogical approaches	Learner reflection	6	[163–168]
	Regular practice, online quizzes, and immediate feedback	3	[169–171]
	Problem-based learning	4	[172–175]
	Project-based learning	4	[176–179]
	Active learning	8	[179–185]
	Regular repetition and review	4	[186–189]
	Scaffolding	5	[58, 190–192]
Psychological approaches	Cooperative learning	6	[193–198]
	Positive attitudes in learners	5	[199–203]
	Social learning	6	[59, 204–207]
	Mental health and well-being	5	[208–212]
Usability	Accessibility and flexibility	7	[63, 68, 71, 73, 213–215]
	Flexibility in hybrid learning	4	[216–219]
	Platform independence	3	[220–222]
	Time zone adaptability	3	[71, 223, 224]
	User-friendliness	3	[225, 226]

Please see Figure 2 below for the visual representation of these themes and the essential features listed under each theme:

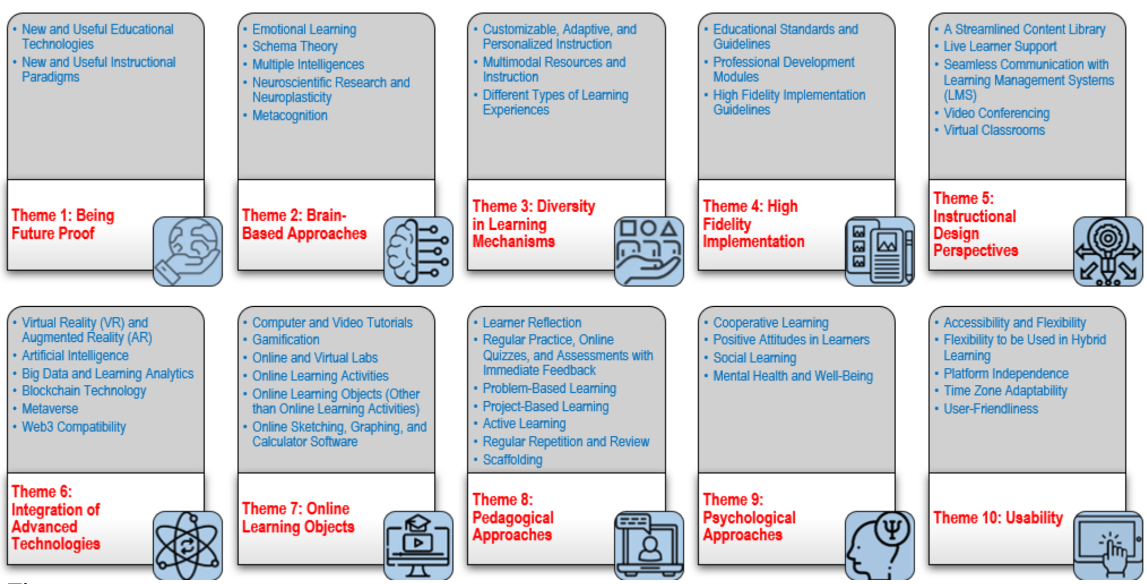

Figure 2.
The 46 essential features listed under 10 themes.

5. Results

5.1. Theme 1: Being Future Proof

Integrating new educational technologies and instructional paradigms in online STEM education is essential for preparing students for the digital economy and enhancing learning environments. Emphasizing learner-centered and adaptive approaches aligns teaching methods with technological advancements and diverse learner needs. The COVID-19 pandemic accelerated this shift, highlighting the importance of innovative practices for educational continuity and effectiveness.

- ***New and Useful Educational Technologies:*** Integrating new educational technologies into online STEM education is crucial for adapting to the digital economy and enhancing learning environments. This process, driven by both intrinsic and extrinsic factors, involves adopting innovative instructional technologies to prepare students for digitally skilled careers, aligning with the global shift towards digital education [5]. Technologies such as big data offer flexibility and connectedness, enhancing the quality of online discourse through thoughtful instructional design [6]. Fostering interactive learning environments is essential for effective outcomes, promoting active engagement among students [7]. The COVID-19 pandemic further accelerated the adoption of these technologies to maintain educational continuity [8, 9].
- ***New and Useful Instructional Paradigms:*** Integrating new instructional paradigms in STEM education is vital for aligning teaching methods with technological advancements and meeting diverse learner needs. Emphasizing learner-centered, flexible, and adaptive paradigms, Reigeluth [10] underscores the necessity of instructional theories for the post-industrial age. Nadelson et al. [11] highlight the importance of fostering an innovative educational culture, while Sudha and Amutha [12] discuss adapting to rapid changes in online education. Collaboration in developing new instructional methods is crucial for their practicality and sustained integration [13]. Landrum et al. [14] emphasize assessing the instructional climate to evaluate active learning approaches, and Khatri et al. [15] advocate for the sustained adoption of innovative practices to enhance STEM education fully.

5.2. Theme 2: Brain-Based Approaches

Incorporating brain-based approaches in online STEM education, including emotional learning, schema theory, and multiple intelligences, significantly enhances student engagement and understanding. Emotional learning fosters a supportive environment by recognizing the role of emotions in success and satisfaction, while schema theory aids in organizing knowledge for better retention. Additionally, integrating neuroscientific insights, neuroplasticity, and metacognition tailors learning experiences to individual needs, improving cognitive development and fostering critical thinking skills.

- ***Emotional Learning:*** Incorporating emotional learning in online STEM education enhances engagement, success, and satisfaction by acknowledging emotions' impact on learning. Emotional presence, including emotional intelligence and self-efficacy, humanizes online environments, making them more engaging and effective [16, 17]. Emotional engagement facilitates interactions and supports persistence [18]. Positive emotional experiences improve outcomes [19], and academic emotions significantly affect learning performance and satisfaction [20]. Emotional learning analytics improve engagement and outcomes by analyzing emotional and cognitive states [21], and social-emotional learning principles enhance online education [22].
- ***Schema Theory:*** Schema theory highlights the role of organized knowledge in enhancing learning and memory, suggesting that individuals create schemas to understand and interpret new information [23, 24]. In online STEM education, schema theory aids memory retention, especially for complex concepts, and knowledge construction is facilitated through integrating new information with existing knowledge, promoting deeper understanding [25]. Effective strategies include knowledge maps, integrative learning activities, collaborative learning, multimedia resources, and schema-based assessments to improve outcomes [26, 27].
- ***Multiple Intelligences:*** Howard Gardner's theory of multiple intelligences suggests individuals possess varied cognitive abilities across domains like linguistic and logical-mathematical intelligence [28]. Recognizing these intelligences in online STEM education allows for personalized and engaging learning experiences that leverage students' strengths [29]. Multimodal learning analytics enhance education by matching learning experiences to dominant intelligences [30]. Stimulating various intelligences deepens understanding and addresses motivation by aligning activities with cognitive strengths [31]. The multimodality of online

education supports multi-literacy and accommodates different learning mechanisms [32]. Artificial intelligence in learning models during challenges like COVID-19 highlights the importance of incorporating multiple intelligences [33].

- ***Neuroscientific Research and Neuroplasticity:*** Integrating neuroscientific research and neuroplasticity principles into STEM education enhances learning environments. Insights from neuroplasticity, such as those from tDCS studies [34], inform strategies aligning with the brain's natural processes, potentially improving STEM competence [35]. Customizing learning experiences to individual needs, along with digital tools and interdisciplinary connections [36–38], supports making educational practices more brain-friendly [39]. These approaches enhance comprehension, stimulate interest, and facilitate cognitive development.
- ***Metacognition:*** Integrating metacognition in online STEM education enhances learning by fostering awareness and control over learning processes. Metacognition enables students to understand their own learning mechanisms, identify improvement areas, and implement strategies [40]. Tailoring instruction based on metacognitive skills assessments optimizes learning experiences [41]. During the COVID-19 pandemic, metacognitive strategies like planning and self-evaluation were crucial for effective learning management [42]. In STEM disciplines, these strategies enhance analytical skills, deeper engagement, and critical thinking [43]. Educators' understanding of metacognitive principles impacts learning, emphasizing the need for teacher training in metacognitive strategies [44], supporting academic success and preparation for future challenges [45].

5.3. Theme 3: Diversity in Learning Mechanisms

An optimal OLE integrates customizable, adaptive, and personalized instruction, addressing diverse learner needs through tailored content and methodologies. This environment leverages multimodal resources, incorporating visual, auditory, and kinesthetic elements to enhance engagement and comprehension, particularly in STEM education. Additionally, fostering varied learning experiences that support social, cognitive, and teaching presence is essential to accommodate different learning mechanisms and promote self-regulated learning.

- ***Customizable, Adaptive, and Personalized Instruction:*** An ideal OLE includes customizable, adaptive, and personalized instruction to meet diverse learner needs. This approach tailors content and methodologies to individual styles and goals, optimizing the experience [46]. Effective course design with organized development models supports self-regulated learning [47, 48]. The integration of technology and understanding of student individualities by instructors is crucial for effective online learning [49]. Understanding learner characteristics and fostering self-efficacy are essential for adaptive learning and improved performance [50].
- ***Multimodal Resources and Instruction:*** Integrating multimodal resources in online STEM education enhances outcomes by leveraging visual, auditory, and kinesthetic modes. This approach deepens engagement and understanding of complex concepts, critical in STEM disciplines [51]. Multimodal resources simulate real-world scenarios, fostering meaningful learning and aiding in theory application [52]. They support the development of teamwork and communication skills, preparing students for collaborative environments [53]. These resources also develop critical viewing and communication skills, aligning with contemporary digital literacy practices [54, 55].
- ***Different Types of Learning Experiences:*** Creating ideal OLEs involves supporting diverse experiences, fostering social, cognitive, and teaching presence tailored to learner needs. Rapanta et al. [56] and Ramlee et al. [57] stress designing settings that accommodate different styles. Korkmaz and Toraman [58] highlight the importance of presence for robust communities and self-directed learners. Students' characteristics and self-regulated learning impact effectiveness [48]. Social learning and engagement are crucial, with Lagat and Concepcion [59] emphasizing social interactions. Kim and Yim [60] explore customer learning processes' impact in

commercial settings, while Osler and Wright [61] advocate for incorporating neuroeducation principles in online interfaces.

5.4. Theme 4: High Fidelity Implementation

High fidelity implementation in online STEM education ensures rigorous adherence to educational standards and guidelines, enhancing the quality and accessibility of learning experiences. Integrating professional development modules strengthens educators' skills, enabling them to effectively use new technologies and address diverse student needs. This precise approach improves educational outcomes, fostering student self-efficacy and engagement while maximizing the benefits of STEM education.

- ***Educational Standards and Guidelines:*** Adhering to educational standards is crucial for developing effective online STEM education, ensuring alignment with criteria set by authorities, thus providing rigorous and comprehensive learning [62]. Integrating these standards allows platforms to democratize access to quality STEM education [63]. Including engineering in science standards fosters a holistic approach, enriching students' understanding through discipline integration [64]. Continuous evaluation through standards and checklists promotes enhancement, ensuring alignment with benchmarks [65]. Leveraging technologies like cloud computing and multimedia interfaces enhances learning experiences [66].
- ***Professional Development Modules:*** Incorporating professional development modules is essential for advancing STEM education by enhancing educators' pedagogical skills and integrating new technologies [67]. Tailored modules address Open Educational Resources (OER), interactive environments, and self-efficacy, ensuring educators meet diverse student needs [68]. These modules also support personalized learning and foster a cohesive STEM teacher identity [69, 70]. The COVID-19 pandemic highlighted the importance of professional development in navigating online challenges, equipping educators with effective tools and strategies [71].
- ***High Fidelity Implementation Guidelines:*** High-fidelity implementation in online STEM education emphasizes precise program execution, enhancing educational outcomes and consistency [72, 73]. This approach improves student self-efficacy, computational thinking, and engagement [74]. Achieving high fidelity requires comprehensive training and ongoing support [75]. Fidelity in course development expands access to STEM education, maximizing benefits [76].

5.5. Theme 5: Instructional Design Perspectives

Instructional design perspectives in online STEM education emphasize the importance of a streamlined content library, live learner support, and seamless communication through Learning Management Systems (LMS). These components enhance accessibility, personalize learning experiences, and foster real-time interactions, crucial for problem-solving and engagement. Integrating video conferencing and virtual classrooms further enriches learning, offering interactive and dynamic platforms that support critical skills and educational continuity.

- ***A Streamlined Content Library:*** Creating a streamlined content library is vital for enhancing STEM education in online environments, supporting diverse and inclusive educational materials. It aligns with pedagogical content knowledge (PCK), enhancing accessibility and learning effectiveness [77]. Integrating technologies like Virtual Reality (VR) enriches experiences, helping students grasp complex concepts interactively [78]. This strategic curation positively impacts students' attitudes toward STEM, encouraging exploration and potential careers [79]. Leveraging natural language processing (NLP) techniques enhances content alignment with educational standards [56]. Streamlined libraries have been critical during the COVID-19 pandemic, offering adaptable strategies for educational continuity [56].
- ***Live Learner Support:*** Live learner support optimizes STEM education by providing personalized assistance, enhancing the learning experience across online platforms [80, 81]. Personalization addresses individual needs, promoting self-regulation and study skills [81].

Learner-centered approaches like heutagogy empower students, fostering autonomy and engagement [82]. Community and mentorship increase interest in STEM, providing academic and emotional support [83]. Technological advancements enhance accessibility and personalization, supporting interactive learning strategies [80]. Ensuring access to resources and technology supports learner autonomy and improves outcomes [84].

- ***Seamless Communication with Learning Management Systems (LMS):*** Seamless communication within LMS is essential for advancing online STEM education, enhancing collaborative learning and interactions. Effective communication supports real-time feedback and resource sharing, critical for developing problem-solving skills [85, 86]. It also improves online mentoring quality by facilitating meaningful interactions [73]. LMS platforms incorporate diverse tools and resources, catering to various learning needs [87]. Integration of LMS with an OLEsstreamlines grading, enhancing efficiency and consistency (Leal and Queirós [88]; Alfadly, A. 2013). During the COVID-19 pandemic, LMS maintained continuous student support and educational integrity [71], promoting online research and global connectivity [90].
- ***Video Conferencing:*** Video conferencing technology in online STEM education enhances learning by offering interactive experiences for educators and students. It enables synchronous interactions, fostering real-time engagement and participation [91], and builds a sense of community [92]. This technology positively impacts motivation, outcomes, and satisfaction [93] and supports classroom discipline [94]. Addressing security and privacy is essential, with the pandemic underscoring the need for effective implementation and training [95].
- ***Virtual Classrooms:*** Virtual classrooms revolutionize STEM education by creating dynamic platforms that enrich learning. They facilitate real-time interactions, enhancing communication and engagement [96]. These platforms enable virtual simulations, offering hands-on experiences that deepen understanding of complex concepts [97]. Virtual classrooms support the development of critical skills such as creativity and problem-solving, essential for success in STEM fields [98]. During the pandemic, they maintained educational continuity and supported underrepresented groups [99].

5.6. Theme 6: Integration of Advanced Technologies

Integrating advanced technologies in online STEM education, including VR, AR, and AI, enhances engagement and personalizes learning experiences. These technologies enable immersive and interactive environments, improving understanding and motivation. Additionally, the use of big data, blockchain, and Web3 fosters secure, customized learning, while the metaverse revolutionizes accessibility and collaboration in education.

- ***Virtual Reality (VR) and Augmented Reality (AR):*** Integrating VR and AR into online STEM education transforms learning by enhancing engagement and understanding through immersive experiences. VR enables exploration of complex concepts in virtual environments, increasing motivation [100]. AR merges virtual elements with reality, making abstract concepts tangible [101]. These technologies improve outcomes across various fields [102] and offer innovative practical experiences in areas like dental education and ergonomics [103, 104]. Mixed-reality environments further revolutionize STEM education by combining VR and AR elements, enhancing teaching possibilities [105, 106].
- ***Artificial Intelligence:*** Integrating AI into online STEM education enables personalized learning experiences by tailoring content to individual needs [107, 108]. AI analyzes learning behaviors, creating customized pathways and providing insights into student performance for targeted support [109]. Adaptive systems adjust content based on progress, optimizing learning [110] and supporting transdisciplinary problem-solving skills [110]. AI technologies, such as educational robots, cater to diverse learning mechanisms [111]. However, ethical considerations regarding potential biases highlight the need for careful implementation [112].

- ***Big Data and Learning Analytics:*** Integrating big data and learning analytics in online STEM education enhances learning outcomes by offering insights into student behaviors. Big Data Analytics enables content customization, providing individualized pathways for success [113]. Learning analytics improve instructional support by decoding learning behaviors [114, 115], facilitating personalization [116]; intelligent learning environments leverage analytics for personalized recommendations and real-time feedback, optimizing experiences. Big Data Analytics also aids evidence-based decision-making, enhancing academic quality [58].
- ***Blockchain Technology:*** Blockchain technology in online STEM education enhances security and transparency. It maintains immutable records of qualifications, ensuring credential integrity [117, 118]. Blockchain secures assessments and protects intellectual property rights, promoting collaboration [119, 120]. It also enhances data security, protecting sensitive information [121]. Blockchain enables decentralized learning management systems and secure platforms, innovating educational processes [122, 123].
- ***Metaverse:*** The metaverse revolutionizes online STEM education by integrating virtual and real worlds, offering immersive environments that transcend physical limitations [124]. It provides unlimited resources, global accessibility, and personalized learning experiences, addressing traditional challenges [125, 126]. The metaverse increases engagement through interactive simulations and fosters collaboration [127, 128]. It enables practical application of theoretical knowledge, crucial for STEM education [129].
- ***Web3 Compatibility:*** Web3, emphasizing user control over data and enhanced privacy, shifts online interactions towards decentralization [17]. In education, Web3 fosters a democratized environment, allowing control over content and data, enhancing participation [130]. It ensures secure, verifiable records, improving trust in certifications [131]. Web3 introduces tokenization and incentivization, revolutionizing engagement and funding for educational initiatives [132]. In STEM education, Web3 supports collaborative learning, providing access to tools and resources for problem-solving [133].

5.7. Theme 7: Online Learning Objects

Integrating diverse online learning objects in STEM education, such as computer tutorials, gamification, and virtual labs, significantly enhances student engagement and understanding. These tools provide interactive and personalized learning experiences that clarify complex topics and foster critical skills. Additionally, multimedia elements and online sketching software enrich the educational environment, promoting active learning and improving outcomes.

- ***Computer and Video Tutorials:*** Integrating computer and video tutorials in online STEM education enhances learning by providing visual, interactive resources that clarify complex topics and cater to various learning mechanisms, increasing engagement and retention [134]. These tutorials address motivational factors, mitigate boredom, and boost achievement, encouraging persistence in STEM courses [135]. They also support skill development, such as APA-style citations, through visual demonstrations and interactive exercises, contributing to academic success [136]. Incorporating emotional elements further enhances engagement, making learning more enjoyable and memorable [137].
- ***Gamification:*** Gamification in online STEM education incorporates game design elements to engage and motivate students, facilitating deeper understanding of complex subjects. It leverages intrinsic motivation through rewards and challenges, creating an achievement-driven environment [138]. This approach makes STEM subjects more interactive, aligns with sustainable education goals, and enhances lesson quality [139, 140]. Gamification supports self-regulated learning by encouraging goal-setting and progress monitoring, increasing student success by improving engagement and interest [141, 142].
- ***Online and Virtual Labs:*** Online and virtual labs in STEM education bridge theoretical knowledge with practical application, offering interactive, inquiry-based experiences. They allow remote experimentation, enabling repeated trials for mastering concepts and safely

conducting dangerous experiments [143]. Although they may not replicate all aspects of physical labs, they complement traditional labs by providing additional exploration opportunities [144]. Virtual labs promote active learning and are cost-effective alternatives, especially highlighted during the COVID-19 pandemic for maintaining education continuity [145, 146].

- ***Online Learning Activities:*** Diverse online learning activities are crucial for creating an effective STEM learning environment, fostering engagement and improved outcomes. Incorporating readings, videos, and interactive tasks caters to different learning mechanisms, making the process dynamic [147]. Metacognitive strategies and motivational scaffolding, especially through pedagogical agents, enhance self-regulation and engagement [148]. Collaboration and problem-based learning prepare students for professional practice, while authentic activities develop critical thinking and problem-solving skills [149, 150]. Designing activities requires consideration of self-regulated learning and learner characteristics for inclusivity [151].
- ***Online Learning Objects:*** Integrating online learning objects like multimedia elements, simulations, and virtual manipulatives enhances STEM education by fostering engagement and improving concept retention. Multimedia elements make learning enjoyable, catering to various styles and increasing accessibility [152]. Simulations offer hands-on experiences, enhancing understanding of scientific principles in a safe environment [153]. Virtual manipulatives promote active learning and problem-solving, aiding conceptual understanding [154]. Effective design and organization of these materials maximize their educational benefits [155].
- ***Online Sketching, Graphing, and Calculator Software:*** Integrating online sketching, graphing, and calculator software in STEM education enhances understanding of complex concepts through visualization and analysis, fostering active learning [156–158]. These tools support project-based learning and the development of critical thinking skills [159, 160]. They also address diminishing sketching skills, providing a platform for refinement and enhancing evidence-based education research [161, 162]. These technologies improve learning outcomes and student engagement [227].

5.8. Theme 8: Pedagogical Approaches

Incorporating diverse pedagogical approaches in online STEM education enhances learning by fostering critical thinking, engagement, and autonomy. Strategies like learner reflection, problem-based learning, and scaffolding promote deeper understanding and effective decision-making. Regular practice, active learning, and structured feedback further support student mastery and self-regulation, creating a dynamic and supportive learning environment.

- ***Learner Reflection:*** Facilitating learner reflection in online STEM education enhances understanding and cognitive growth. Reflective practices bridge experiences and learning, enabling critical analysis and informed decision-making [163]. Students often need structured support for effective reflective thinking [164]. Educators play a key role in fostering reflection, with facilitation and collaboration enhancing reflective thinking [165]. Structured roles in discussions, like moderators and summarizers, support knowledge construction [166]. Educators' reflective practices influence their STEM identity and teaching approach, impacting student outcomes [167]. The COVID-19 pandemic emphasized the importance of reflection in adapting to new learning environments [168].
- ***Regular Practice, Online Quizzes, and Immediate Feedback:*** Regular practice, online quizzes, and immediate feedback are crucial in online STEM education, enhancing engagement and understanding. Quizzes allow students to gauge mastery, with feedback guiding targeted learning [169]. This approach promotes autonomous learning, enabling students to adjust strategies in real-time [170]. Adaptive quizzes increase engagement and identify students needing support [228]. Considering students' perceptions of assessments can inform quiz design for better engagement and learning [171].

- ***Problem-Based Learning:*** Problem-based learning (PBL) in online STEM education enhances performance and addresses attrition. By engaging students in real-world problems, PBL fosters deep engagement and increases retention in STEM [172]. Integrating technology with PBL prepares students for future demands [173]. This approach develops critical thinking and problem-solving skills, influencing learning perceptions [174]. PBL encourages multidisciplinary knowledge, enhancing problem-solving abilities and promoting STEM literacy [175].
- ***Project-Based Learning:*** Project-based learning (PjBL) in online STEM education enhances outcomes, promotes teamwork, and increases engagement. This approach, involving student-centered projects, connects theoretical knowledge with practical applications, improving critical thinking [176]. Digital platforms facilitate teamwork, allowing efficient collaboration [177]. PjBL maintains interest through relevant projects and supports integrated learning by exploring scientific concepts' interconnectedness [178]. Effective project management equips students with essential skills [179].
- ***Active Learning:*** Active learning in online STEM education improves engagement and outcomes. Incorporating active learning strategies and assessments significantly increases involvement [180]. Educational technologies and flexible models boost engagement [181]. Key factors include meaningful communication and project management for remote learning [179]. Emotions and self-efficacy are vital in virtual experiences [182]. Despite challenges in online learning, active learning principles motivate student engagement [183]. Approaches like narrative-based and game-based learning enhance critical thinking [184]. Instructor professional development ensures inclusive, high-quality instruction [185].
- ***Regular Repetition and Review:*** Incorporating regular repetition and review in online learning enhances experiences, emphasizing engagement with materials. Flexible opportunities for repetition promote autonomy and satisfaction [186]. Regular presentations enhance learning outcomes by improving pattern recognition [187]. Peer feedback reinforces understanding [188]. Repetition and review facilitate online planning, developing nuanced understanding [189].
- ***Scaffolding:*** Scaffolding in online STEM education enhances understanding and autonomy. It significantly impacts learning outcomes, aiding mastery of complex concepts [190]. Scaffolding promotes self-regulated learning, reducing reliance on direct support [191]. Various scaffolding types—metacognitive, motivational, procedural, and strategic—foster autonomy [192]. Scaffolding creates supportive environments with high social, cognitive, and teaching presence [58].

5.9. Theme 9: Psychological Approaches

Incorporating psychological approaches in online STEM education enhances engagement, motivation, and well-being. Cooperative learning and fostering positive attitudes promote teamwork and critical thinking, preparing students for success. Emphasizing social learning and mental health creates a supportive environment, essential for meaningful engagement and academic achievement.

- ***Cooperative Learning:*** Cooperative learning in STEM education enhances engagement, motivation, and academic achievement through collaborative work. It fosters social interdependence, shared responsibility, and individual accountability, promoting mastery of complex subjects [193, 194]. This approach develops essential skills like problem-solving, critical thinking, and teamwork, preparing students for success [195]. It also promotes inclusivity and a positive classroom culture [196], cultivating cooperation and teamwork for a productive learning environment [197, 198].
- ***Positive Attitudes in Learners:*** Fostering positive attitudes in STEM education enhances engagement and achievement, especially in online environments. The transition to online learning presents challenges but also promotes inquiry learning and online lab skills [199]. Educators play a key role in nurturing positive attitudes, emphasizing professional development

in online pedagogical strategies [200]. Positive STEM attitudes are linked to computational thinking and 21st-century skills, influenced by socioeconomic backgrounds [201]. Online readiness among educators correlates with their pedagogical competence [202]. A boundary-crossing pedagogical framework addresses diverse learner needs in STEM [203].

- ***Social Learning:*** Social learning in online STEM education enhances experiences by fostering collaboration, group activities, and community engagement, creating a sense of belonging and effective knowledge sharing [59]. Social presence contributes to community connectedness and improves satisfaction [204, 205]. From a constructionist perspective, learning is collaborative, co-creating identities and knowledge through social interactions [206]. Online presence and social web technologies capture interactions, offering insights into student behaviors [207]. Social interactions are vital for meaningful engagement, with student readiness crucial for successful platform use [59].
- ***Mental Health and Well-Being:*** Integrating mental health and well-being in online STEM education is critical for a positive learning experience. Mental health significantly impacts learning success, emphasizing the need for supportive strategies [208]. The transition to online education has raised concerns about increased stress, highlighting the importance of mental health considerations [209]. A respectful, inclusive environment enhances well-being and learning [210]. Interventions focusing on positive psychology improve happiness and well-being [211]. Innovative teaching methods and tools contribute to motivation and mental health in online learning [212].

5.10. Theme 10: Usability

Usability in online STEM education focuses on accessibility, flexibility, and user-friendliness to enhance learning experiences for diverse students. Ensuring platform independence and time zone adaptability supports global engagement and independent learning. By fostering inclusive and adaptable environments, educators can cater to varied needs, promoting effective and satisfying educational experiences.

- ***Accessibility and Flexibility:*** Accessibility and flexibility are crucial in online STEM education, ensuring inclusivity and adaptability for diverse students, thereby enhancing effectiveness [71]. Accessible communication channels are vital for mentoring and support in online programs [73]. Scalable platforms make STEM education more accessible, especially for underrepresented groups, offering equivalent outcomes at lower costs [63]. Inclusive STEM schools emphasize flexible structures to support engagement [213]. The shift to a knowledge-based economy requires accessible STEM education for growth and innovation, particularly in regions like the GCC [214]. EU initiatives focus on accessible technology and digital skills, underscoring these characteristics' importance [215]. Customizing environments to meet diverse needs and ensuring early access to technology in rural areas are critical [68].
- ***Flexibility in Hybrid Learning:*** Flexibility in hybrid learning models is essential for addressing diverse needs and integrating STEM disciplines. Adaptable environments benefit students with autism spectrum disorder by accommodating individual needs [216]. Flexibility-based training minimizes gender gaps, enhancing problem-solving skills in girls [217]. Flexible teaching approaches foster collaboration and equity, enabling educators to cater to diverse needs [218]. An integrated STEM approach requires flexibility to blend disciplines and promote holistic understanding [219].
- ***Platform Independence:*** Platform independence ensures accessibility and quality in online STEM education, allowing content access across various devices and platforms. Benefits include reducing cognitive load, enhancing interactivity, bridging learning contexts, and supporting independent learning [220, 221]. Seamless access to resources modernizes STEM content and improves independent learning [222].
- ***Time Zone Adaptability:*** Addressing time zone adaptability in online STEM education fosters inclusivity for a global student body. Innovative scheduling and course design accommodate

diverse schedules and connectivity issues, maintaining engagement [71]. E-learning platforms reduce costs and provide accessibility across time zones, making STEM opportunities widely available [223]. Asynchronous and synchronous activities offer flexibility, enabling engagement according to local schedules [224].

- ***User-Friendliness:*** User-friendliness in online STEM education impacts perceptions, engagement, and learning experiences. Practicality and operability in STEM disciplines highlight the need for user-friendly interfaces [225]. Long-term platform use depends on perceived usefulness, satisfaction, and switching costs, emphasizing the importance of user satisfaction [226].

6. Discussion

6.1. Discussion of Findings

The findings of this systematic review provide a comprehensive blueprint for developing effective online learning environments in STEM education. By incorporating the identified features, educators and developers will create engaging, adaptable, and future-proof educational experiences. Here are the 46 essential features identified for effective online learning environments (OLEs) in STEM education, grouped under ten themes:

Theme 1: Being Future Proof: Integrating innovative educational technologies into online STEM education is essential for preparing students for the digital economy and ensuring continuity during crises like COVID-19. Adopting new instructional paradigms fosters an adaptive, learner-centered environment that aligns teaching methods with technological advancements, meeting diverse needs and supporting innovative educational practices.

1. ***New and Useful Educational Technologies***: Integrating innovative educational technologies into online STEM education is crucial for preparing students for the digital economy, enhancing digital learning environments, and ensuring continuity during crises like COVID-19.
2. ***New and Useful Instructional Paradigms***: Adopting new instructional paradigms in STEM education aligns teaching methods with technological advancements, fostering an adaptive, learner-centered environment that meets diverse needs and supports innovative educational practices.

Theme 2: Brain-Based Approaches: Incorporating emotional learning in online STEM education enhances student engagement and satisfaction by acknowledging the impact of emotions on learning. Schema theory, multiple intelligences, and principles of neuroplasticity optimize learning environments by emphasizing organized knowledge, diverse cognitive abilities, and natural learning processes. Metacognitive strategies improve learning experiences by fostering students' awareness and control over their learning processes.

3. ***Emotional Learning***: Incorporating emotional learning in online STEM education enhances student engagement, success, and satisfaction by acknowledging the significant impact of emotions on learning processes.
4. ***Schema Theory***: Schema theory emphasizes the importance of organized knowledge in enhancing learning and memory, aiding in the retention and understanding of complex concepts in online STEM education through structured mental frameworks.
5. ***Multiple Intelligences***: Howard Gardner's theory of multiple intelligences highlights the need to recognize and cater to diverse cognitive abilities in educational practices, creating personalized and engaging learning experiences in online STEM education.
6. ***Neuroscientific Research and Neuroplasticity***: Integrating neuroscientific research and neuroplasticity principles into STEM education enhances learning environments, optimizing them for student achievement and cognitive development by aligning with natural learning processes.
7. ***Metacognition***: Incorporating metacognitive strategies in online STEM education improves learning experiences by fostering students' awareness and control over their learning processes, enhancing analytical skills and critical thinking.

Theme 3: Diversity in Learning Mechanisms: Customizable and adaptive instruction leverages technology for personalized experiences, while multimodal resources and various learning experiences create inclusive and engaging environments that support digital literacy and practical application.

8. ***Customizable, Adaptive, and Personalized Instruction:*** *An ideal OLE requires customizable and adaptive instruction to meet diverse learner needs, leveraging technology and instructor characteristics for personalized learning experiences.*
9. ***Multimodal Resources and Instruction:*** *Integrating multimodal resources in online STEM education enhances engagement and understanding by leveraging visual, auditory, and kinesthetic modes to simulate real-world scenarios and support digital literacy.*
10. ***Different Types of Learning Experiences:*** *Supporting diverse learning experiences in online education involves fostering social, cognitive, and teaching presence, enhancing engagement, and tailoring environments to various learner needs.*

Theme 4: High Fidelity Implementation: Adhering to educational standards and incorporating professional development modules ensure quality and effectiveness in online STEM education. High-fidelity implementation guidelines maintain consistent delivery, enhancing student engagement and outcomes by aligning instructional strategies with expert criteria.

11. ***Educational Standards and Guidelines***: Adhering to educational standards and guidelines ensures the quality and effectiveness of online STEM education, aligning instructional strategies with expert criteria to democratize opportunities for diverse learners.
12. ***Professional Development Modules***: Incorporating professional development modules into online STEM education equips educators with the skills to integrate new technologies and pedagogical methods, enhancing student learning outcomes.
13. ***High Fidelity Implementation Guidelines***: Ensuring high-fidelity implementation in online STEM education improves student engagement and outcomes by maintaining consistent and accurate delivery of educational programs as planned.

Theme 5: Instructional Design Perspectives: A streamlined content library and live learner support optimize online STEM education by providing diverse, accessible materials and personalized assistance. Seamless communication within LMS platforms, video conferencing, and virtual classrooms enhance interactive and collaborative learning experiences, facilitating real-time participation and skill development.

14. ***A Streamlined Content Library***: Creating a streamlined content library enhances online STEM education by providing diverse, inclusive, and accessible educational materials, enriched with advanced technologies for immersive learning experiences.
15. ***Live Learner Support***: Live learner support is crucial for optimizing online STEM education, offering personalized and interactive assistance to bridge educational gaps and enhance learning experiences across various platforms.
16. ***Seamless Communication with Learning Management Systems (LMS)***: Effective communication within LMS platforms enhances collaborative learning, teacher-student interactions, and the grading process, significantly improving online STEM education.
17. ***Video Conferencing***: Integrating video conferencing in online STEM education enhances interactive and engaging learning experiences, fostering real-time participation and community building within virtual classrooms.
18. ***Virtual Classrooms***: Virtual classrooms revolutionize STEM education by providing dynamic and interactive platforms that facilitate real-time interactions, practical experiments, and the development of essential skills.

Theme 6: Integration of Advanced Technologies: Integrating VR, AR, AI, and learning analytics into online STEM education provides immersive and personalized learning experiences. Blockchain technology ensures secure academic processes, while the metaverse and Web3 foster decentralized and interactive environments, enhancing engagement and data control.

19. ***Virtual Reality (VR) and Augmented Reality (AR)***: Integrating VR and AR into online STEM education transforms learning by providing immersive and interactive experiences that enhance student engagement and understanding.

20. ***Artificial Intelligence***: AI integration in online STEM education personalizes learning experiences, providing tailored educational content and insights into student performance to enhance engagement and efficacy.
21. ***Big Data and Learning Analytics***: The use of big data and learning analytics in online STEM education offers deep insights into student behaviors, enabling personalized learning pathways and targeted interventions to improve outcomes.
22. ***Blockchain Technology***: Blockchain technology enhances online STEM education by ensuring secure, transparent, and decentralized processes for academic record-keeping, assessments, and content distribution.
23. ***Metaverse***: The metaverse revolutionizes online STEM education by providing immersive and interconnected environments that enhance engagement, collaboration, and practical application of theoretical knowledge.
24. ***Web3 Compatibility***: Web3 technology fosters a decentralized and democratic educational environment, enhancing data control, security, and personalized learning experiences in online STEM education.

Theme 7: Online Learning Objects: Computer and video tutorials, gamification, and virtual labs enhance online STEM education by providing interactive and engaging resources. Diverse online learning activities and multimedia elements support dynamic learning environments, while sketching, graphing, and calculator software facilitate visualization and critical thinking.

25. ***Computer and Video Tutorials***: Integrating computer and video tutorials in online STEM education enhances learning by providing visual and interactive resources that increase engagement, retention, and skill development.
26. ***Gamification***: Gamification in online STEM education leverages game design elements to engage and motivate students, facilitating deeper understanding and retention of complex subjects.
27. ***Online and Virtual Labs***: Online and virtual labs provide interactive and inquiry-based learning experiences that bridge theoretical knowledge with practical application in STEM education.
28. ***Online Learning Activities***: Diverse and engaging online learning activities foster dynamic and effective learning environments in STEM disciplines, enhancing student engagement, motivation, and outcomes.
29. ***Online Learning Objects (Other than Online Learning Activities)***: Integrating interactive multimedia elements, simulations, and virtual manipulatives enhances STEM education by fostering engagement, understanding, and retention of complex concepts.
30. ***Online Sketching, Graphing, and Calculator Software***: These tools enhance STEM education by facilitating visualization and analysis, supporting active learning, and fostering critical and creative thinking skills.

Theme 8: Pedagogical Approaches: Facilitating learner reflection and incorporating regular practice, online quizzes, and immediate feedback improve understanding and outcomes in online STEM education. Problem-based and project-based learning connect theoretical knowledge with practical applications, while active learning and scaffolding enhance engagement and self-regulation through interactive activities and support.

31. ***Learner Reflection***: Facilitating learner reflection in online STEM education enhances understanding, self-awareness, and cognitive growth through critical analysis and structured support.
32. ***Regular Practice, Online Quizzes, and Assessments with Immediate Feedback***: These elements enhance online STEM education by providing continuous assessment and immediate feedback, promoting autonomous learning and improving outcomes.
33. ***Problem-Based Learning***: Problem-based learning in online STEM education enhances student performance and retention by engaging students in real-world problems, fostering critical thinking and multidisciplinary knowledge.

34. ***Project-Based Learning***: Project-based learning improves outcomes, teamwork, engagement, and integrated learning in online STEM education by connecting theoretical knowledge with practical applications.
35. ***Active Learning***: Active learning strategies in online STEM education improve engagement and outcomes by incorporating interactive activities, robust assessments, and effective use of educational technologies.
36. ***Regular Repetition and Review***: Incorporating regular repetition and review in online learning enhances learning experiences by improving retention and understanding through consistent engagement with content.
37. ***Scaffolding***: Scaffolding supports online STEM education by enhancing understanding, self-regulation, and autonomy, facilitating deeper learning of complex concepts.

Theme 9: Psychological Approaches: Cooperative learning and fostering positive attitudes in learners enhance engagement and achievement in online STEM education. Social learning fosters collaborative interactions and community engagement, while integrating mental health and well-being ensures a supportive learning experience crucial for student success.

38. ***Cooperative Learning***: Cooperative learning enhances STEM education by fostering collaboration, engagement, and academic achievement through group work and shared responsibility.
39. ***Positive Attitudes in Learners***: Fostering positive attitudes in learners enhances engagement and achievement in online STEM education, supported by educators' professional development and tailored pedagogical strategies.
40. ***Social Learning***: Social learning enhances online STEM education by fostering collaborative interactions, group activities, and community engagement, creating a sense of belonging and effective knowledge sharing.
41. ***Mental Health and Well-Being***: Integrating mental health and well-being into online STEM education ensures a positive and supportive learning experience, crucial for student success and engagement.

Theme 10: Usability: Ensuring accessibility and flexibility in online STEM education democratizes learning by broadening reach and tailoring experiences. Flexibility in hybrid learning models and platform independence address diverse needs and ensure high-quality learning across devices. Time zone adaptability and user-friendliness enhance engagement and continuous learning.

42. ***Accessibility and Flexibility***: Ensuring accessibility and flexibility in online STEM education democratizes learning by broadening reach and tailoring experiences to individual needs.
43. ***Flexibility to be Used in Hybrid Learning***: Flexibility in hybrid learning models addresses diverse needs, empowers educators, and effectively integrates STEM disciplines.
44. ***Platform Independence***: Platform independence in online STEM education ensures accessibility, flexibility, and high-quality learning experiences across various devices and platforms.
45. ***Time Zone Adaptability***: Addressing time zone adaptability in online STEM education fosters inclusivity and effectiveness by accommodating diverse schedules and ensuring continuous engagement.
46. ***User-Friendliness***: User-friendly OLEs enhance engagement and learning outcomes in STEM education by providing accessible, comfortable, and well-designed platforms.

6.2. Suggestions for Policy and Practice in STEM Education

To translate the findings of this study into actionable policies and practices, a series of comprehensive recommendations is provided. These suggestions aim to guide policymakers, educators, and developers in creating effective online learning environments (OLEs) for STEM education.

6.3. Policy Recommendations

- ***Integration of Emerging Technologies:*** Governments and educational authorities should prioritize investments in cutting-edge technologies like artificial intelligence (AI), virtual reality

(VR), and blockchain to enhance online STEM learning. National policies should allocate funding for technological infrastructure and research to implement these technologies in diverse educational settings.

- ***Standardization and Accreditation Frameworks;*** Develop standardized frameworks for online STEM education that align with global best practices, such as the use of blockchain for secure credentialing and Web3-compatible platforms. Accreditation policies should validate innovative pedagogical practices and ensure quality assurance across institutions.
- ***Equitable Access to Resources:*** Ensure universal access to high-quality internet, devices, and digital tools in underserved and rural areas. Public-private partnerships can help bridge the digital divide, making STEM education inclusive and accessible for all students.
- ***Data-Driven Decision-Making:*** Encourage the use of big data analytics to monitor and improve educational outcomes. Policymakers should create ethical guidelines for data collection, storage, and analysis to maintain privacy while optimizing personalized learning.
- ***Incentives for Professional Development:*** Offer financial incentives, scholarships, and grants for educators to participate in professional development programs that enhance their technological and pedagogical competencies, focusing on frameworks like TPACK.

6.4. Practice Recommendations

- ***Curriculum Design and Development***
    - ***Future-Proofing***: Incorporate flexibility in curricula to adapt to technological advancements, such as virtual labs and simulations for STEM subjects. Emphasize skills like computational thinking, problem-solving, and critical analysis.
    - ***Customization***: Use adaptive learning platforms that personalize content to individual student needs, ensuring tailored support for diverse learning mechanisms.
- ***Pedagogical Innovations***
    - Implement problem-based and project-based learning to foster real-world applications of STEM concepts.
    - Utilize gamification and active learning strategies to boost engagement, particularly for complex STEM topics.
    - Incorporate regular reflection and scaffolding to support critical thinking and self-regulated learning.
- ***Teacher Training and Support***
    - Provide continuous professional development opportunities focused on integrating advanced technologies like AI and VR into instruction.
    - Establish communities of practice for educators to share successful strategies and challenges in online STEM education.
    - Equip teachers with tools and resources to effectively manage hybrid and online classrooms, emphasizing user-friendly technologies.
- ***Student-Centric Practices***
    - Foster cooperative and social learning opportunities to build teamwork and communication skills.
    - Address mental health and well-being by incorporating supportive practices, including flexible deadlines and mindfulness exercises.
    - Design user-friendly platforms with intuitive navigation, ensuring accessibility for students with diverse needs.
- ***Technological Enhancements***
    - Develop and deploy platform-independent learning management systems (LMS) that enable seamless integration of multimodal resources.
    - Incorporate secure and decentralized systems using blockchain for student records and certifications.

    - Leverage the metaverse for immersive learning environments that simulate real-world STEM applications.
- ***Parental and Community Engagement***
    - Involve parents and community members in understanding and supporting online STEM education.
    - Create awareness programs to highlight the benefits and functionalities of OLEs.
    - Collaborate with local businesses to provide real-world problem-solving opportunities for students.

6.5. Monitoring and Evaluation

- ***Performance Metrics:*** Establish measurable outcomes for OLEs, including student engagement, retention, and performance in STEM disciplines. Regularly update metrics to reflect the evolving educational landscape.
- ***Feedback Loops:*** Incorporate continuous feedback mechanisms from students, educators, and stakeholders to refine practices and policies. Employ learning analytics to identify and address gaps in student understanding.
- ***Scalability and Sustainability:*** Pilot innovative practices in select schools or regions before scaling them nationwide. Ensure long-term sustainability by integrating eco-friendly technologies and reducing dependency on outdated systems.

6.6. Gaps Identified in the Research Literature and Future Research Directions

The systematic review highlights several gaps in the existing research on Online Learning Environments (OLEs) in STEM education. These gaps provide a basis for future investigations aimed at advancing the field and addressing the complex challenges of integrating technology and pedagogy in STEM disciplines.

One prominent gap lies in the limited empirical studies that evaluate the long-term impact of specific technologies on student learning outcomes in STEM OLEs. While many studies explore the immediate effects of tools like artificial intelligence (AI), virtual reality (VR), and gamification, there is insufficient research on how these technologies influence students' retention, problem-solving abilities, and career readiness over time. Future research should prioritize longitudinal studies that assess these long-term impacts and identify best practices for sustainable implementation.

The existing literature also lacks comprehensive analyses of the interplay between advanced technologies and pedagogical strategies. While frameworks such as TPACK emphasize the integration of technological, pedagogical, and content knowledge, few studies examine how these components interact dynamically in online STEM settings. Future research could explore how specific pedagogical approaches, such as scaffolding or project-based learning, align with technologies like blockchain or the metaverse to enhance STEM learning experiences.

Equity and access remain underexplored areas in the context of STEM OLEs. Although some studies acknowledge the importance of accessibility, they often fail to address systemic barriers such as the digital divide, socio-economic disparities, and cultural biases that impact learners' engagement with online platforms. Further research should investigate targeted interventions to reduce these inequities, including policies and practices that expand access to high-quality internet, devices, and teacher training in underserved communities.

Another critical gap is the limited focus on the psychological and social dimensions of online learning. While the reviewed literature touches on topics like mental health, social learning, and cooperative activities, there is a need for more nuanced studies that explore how these factors interact with STEM education in OLEs. Future research could examine the role of social presence, community building, and mental health support in fostering student engagement and resilience in digital learning environments.

The rapid pace of technological advancement also poses a challenge for existing research. Many studies are unable to keep pace with emerging technologies such as Web3 and decentralized learning systems, resulting in a lack of theoretical and practical guidance for integrating these innovations into OLEs. Future investigations should focus on understanding the pedagogical implications of these technologies and developing adaptive frameworks that remain relevant in an evolving educational landscape.

Lastly, there is a notable scarcity of cross-disciplinary research that bridges STEM education with fields such as cognitive neuroscience, design thinking, and ethics. For example, insights from neuroscience could inform the development of brain-based learning strategies, while ethical frameworks could guide the responsible use of data analytics and AI in education. Future research should adopt interdisciplinary approaches to address the multifaceted challenges of STEM OLEs.

In summary, future research should focus on longitudinal studies of technological impacts, deeper exploration of technology-pedagogy interactions, strategies to address equity and access, the psychological and social dimensions of online learning, the integration of emerging technologies, and interdisciplinary collaborations. Addressing these gaps will contribute to the development of more effective, inclusive, and innovative OLEs that meet the diverse needs of STEM learners in the 21st century.

7. Conclusion

7.1. Summary of Key Findings

This study establishes a robust framework for the design and implementation of effective Online Learning Environments (OLEs) in STEM education, addressing the critical challenges of inclusivity, adaptability, and technological integration in the 21st-century educational landscape. Through a systematic review and qualitative synthesis of 228 peer-reviewed articles, the research identifies 46 essential features of optimal OLEs, organized into ten thematic categories. These findings offer actionable insights into creating adaptable, engaging, and future-proof STEM learning environments that respond to the evolving needs of students, educators, and policymakers.

The blueprint proposed in this research highlights the transformative potential of emerging technologies, such as artificial intelligence, virtual and augmented reality, blockchain, and learning analytics, in fostering immersive and personalized educational experiences. By integrating these technologies with advanced pedagogical strategies, including problem-based learning, scaffolding, and gamification, OLEs can transcend traditional barriers to STEM education, ensuring equitable access and enhanced learning outcomes for diverse learner populations.

Moreover, the study emphasizes the importance of professional development and institutional support in equipping educators with the skills and tools necessary to leverage the full potential of OLEs. Tailored professional development modules and the integration of frameworks such as TPACK ensure that educators can effectively align technological, pedagogical, and content knowledge to meet the demands of STEM disciplines. The findings also underscore the significance of psychological and usability factors, advocating for inclusive, user-friendly designs that prioritize accessibility, mental health, and social learning.

This research contributes to the global discourse on educational innovation by presenting a comprehensive and evidence-based framework that bridges the gap between theory and practice in STEM education. It offers policymakers a roadmap for integrating cutting-edge technologies into national curricula while maintaining high educational standards and addressing diverse learner needs. For practitioners, it provides a guide to implementing pedagogically sound and technologically advanced approaches that enhance student engagement and achievement.

As the digital economy continues to evolve, the role of STEM education in preparing students for the challenges and opportunities of the future cannot be overstated. This study serves as a foundational resource for stakeholders seeking to design and implement effective OLEs that not only meet current educational needs but also anticipate and adapt to the demands of tomorrow's learners. By embracing the principles outlined in this blueprint, educational institutions can foster a generation of innovative, resilient, and globally competent STEM professionals.

7.2. Limitations

This study presents a comprehensive blueprint for Online Learning Environments (OLEs) in STEM education, yet several limitations should be acknowledged to contextualize the findings. The research is based on a systematic review of 228 peer-reviewed articles published between 2000 and 2023. While this range captures significant developments in the field, it may exclude insights from earlier studies or more recent works published after the review process was concluded. Furthermore, the study excludes gray literature, such as reports and unpublished studies, which could provide valuable perspectives that complement the findings derived from peer-reviewed sources.

The global scope of the review introduces variability, as it synthesizes studies conducted across diverse educational and cultural contexts. While this enhances the generalizability of the proposed framework, it also means that the findings may not fully account for regional or institutional differences in technological infrastructure, socio-economic conditions, or pedagogical practices. These contextual disparities could impact the feasibility and effectiveness of implementing the identified features in specific settings.

The qualitative synthesis employed in this study relies on thematic analysis, which is inherently interpretive. Although rigorous procedures were followed to ensure reliability, the process remains subject to researcher bias in the coding and theme generation stages. This limitation underscores the absence of a quantitative meta-analysis, which could have provided statistical validation of the themes and strengthened the overall robustness of the findings.

The study's focus on STEM education, while deliberate, constrains the applicability of its findings to other disciplines. Features identified as essential for STEM learning environments may not be directly transferable to areas such as the humanities or social sciences, which often prioritize different pedagogical and technological approaches. Moreover, the research proposes a theoretical framework without empirically validating its application in real-world educational settings. As a result, the practical effectiveness of the blueprint remains speculative, pending further studies that implement and evaluate its features in diverse learning environments.

Technological advancement presents another limitation, as the rapid pace of innovation could render some of the technologies discussed in the reviewed studies obsolete or overshadowed by newer tools. This necessitates periodic updates to the framework to maintain its relevance and alignment with emerging trends in educational technology.

While the study emphasizes accessibility and equity, it does not delve deeply into systemic barriers such as digital divides, funding disparities, or cultural obstacles that may hinder the widespread adoption of OLEs in underserved communities. Addressing these challenges requires targeted research and policy development beyond the scope of this work.

Finally, the reliance on secondary data imposes constraints on the study, as the quality and consistency of the original studies vary. Differences in methodologies, sample sizes, and theoretical frameworks across the reviewed literature may introduce inconsistencies that affect the reliability of the synthesized findings. These limitations suggest avenues for future research, including empirical validation of the proposed framework, exploration of cross-disciplinary applications, and ongoing refinement to accommodate technological and educational developments.

Data Availability Statement: The data that support the findings of this study are made openly available at: Meylani, R. (2024). *Data extracted from the studies included in the systematic review of online learning environments in STEM education.* (ResearchGate) [Data set].
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N/A. The following text is copied and pasted from PROSPERO website: "PROSPERO does not accept scoping reviews, literature reviews or mapping reviews. This should not stop you from submitting your full protocol or completed review for publication in a journal."

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