A systematic review of Self-Directed Learning: empirical evidence from STEM teaching and learning

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Abstract

Amid the burgeoning interest in self-directed learning (SDL) and its implications, particularly in science, technology, engineering, and mathematics teaching and learning (STEM-TL), our systematic review meticulously examined 50 articles. Extracting data from the Web of Science (WoS) and Scopus databases spanning the recent five years, the review canvassed a diverse set of parameters encompassing study characteristics, methodological approaches, underlying learning theories, strategic pedagogies, technological integrations, perceptible impacts, encountered challenges, and potential research trajectories concerning SDL within STEM-TL. The accumulated evidence testifies to SDL's multifaceted application within STEM-TL, underpinning its salience in equipping students with quintessential 21st-century competencies. Notably, while a vast swathe of the literature accentuates the positive outcomes of SDL, a limited subset critically evaluates potential pitfalls, encompassing premature SDL induction, potential erosion of student ethics, unchecked technological advancement, and the ambiguity of prospective educational landscapes. This review, therefore, serves as a synthesized repository, offering invaluable insights to inform and shape pedagogical frameworks and curricula in STEM-TL for educators, institutional policymakers, and other stakeholders.

Keywords

Self-directed learning (SDL), STEM teaching and learning (STEM-TL), systematic literature review

Résumé

Face à l'intérêt croissant pour l'apprentissage auto-dirigé (SDL) et ses implications, en particulier dans l'enseignement et l'apprentissage des sciences, de la technologie, de l'ingénierie et des mathématiques (STEM-TL), notre revue systématique a minutieusement examiné 50 articles. En extrayant des données des bases de données Web of Science (WoS) et Scopus couvrant les cinq dernières années, la revue a exploré un ensemble diversifié de paramètres englobant les caractéristiques des études, les approches méthodologiques, les théories d'apprentissage sous-jacentes, les pédagogies stratégiques, les intégrations technologiques, les impacts perceptibles, les défis rencontrés, et les trajectoires de recherche potentielles concernant le SDL au sein de STEM-TL. Les preuves accumulées témoignent de l'application multifacette du SDL au sein de STEM-TL, soulignant son importance pour doter les étudiants de compétences essentielles du 21ème siècle. Notamment, alors qu'une grande partie de la littérature met en évidence les résultats positifs du SDL, un sous-ensemble limité évalue de manière critique les éventuels écueils, englobant l'introduction prématurée du SDL, l'érosion potentielle de l'éthique des étudiants, l'avancement technologique non contrôlé, et l'ambiguïté des paysages éducatifs à venir. Cette revue sert donc de répertoire synthétisé, offrant des perspectives inestimables pour informer et façonner les cadres pédagogiques et les programmes d'études en STEM-TL pour les éducateurs, les décideurs institutionnels et les autres parties prenantes.

Mots-clés

Apprentissage auto-dirigé (SDL), Enseignement et apprentissage STEM (STEM-TL), revue de la littérature systématique

Cite this article

Asyhari, A., Sunyono, S., Haenilah, E.Y., & Hariri, H. (2023). A systematic review of Self-Directed Learning: Empirical evidence from STEM teaching and learning. *Review of Science, Mathematics and ICT Education*, *17*(2), 47-74. https://doi.org/10.26220/rev.4501

Introduction

In the twenty-first century, the global educational landscape has faced myriad challenges, catalyzing shifts in teaching and learning paradigms. The burgeoning interest in self-directed learning (SDL) is central to these shifts. Notably, the Covid-19 pandemic accelerated the transition from teacher-directed to student-directed learning (Jeong, 2022; Khodaei et al., 2022; Schweder & Raufelder, 2022; Ziegler et al., 2021). Despite the growing emphasis on SDL, there remains a dearth of comprehensive research documentation detailing its effects on skills, learning outcomes, and contributory factors. This gap is particularly pronounced in science, technology, engineering, and mathematics teaching and learning (STEM-TL).

STEM, characterized by its multidisciplinary nature, prioritizes real-world problem-solving, student-centeredness, collaborative communication, diverse solution pathways, and transforming failures into learning opportunities (Arztmann et al., 2023; Aydin Gunbatar et al., 2022). As a field, STEM demands a diverse array of competencies, such as critical thinking, data analysis, and visualization (Arztmann et al., 2023; Wright & Waxman, 2022). The evolving nature of lifelong learning competencies in today's era brings forth challenges in enhancing the quality of STEM education (Liu et al., 2022; Melton et al., 2022). As a response, STEM scholars seek to construct a robust theoretical model to fathom STEM's cognitive and affective dimensions and learner engagement (Pollard et al., 2018).

SDL is Central to this discourse, a digital age competency to foster lifelong learning (Boyer et al., 2014; Morris, 2019). SDL empowers students to take ownership of their learning processes, from identifying needs and setting goals to utilizing resources and evaluating outcomes (Knowles, 1975). This autonomy is complemented by the ability to leverage online resources, manage their learning, and effectively tackle academic challenges (Palaniappan & Noor, 2022; Zhu & Doo, 2022). While SDL emphasizes macro-level constructs like goal setting and decision-making, it closely aligns with self-regulated learning (SRL) at the micro-level (Higgins et al., 2021; Kayacan & Ektem, 2019; Lin et al., 2019).

There have been various endeavors to embed SDL within STEM contexts. Researchers have explored diverse SDL methodologies, from theoretical learning frameworks (Alotaibi & Alanazi, 2021; Bishara, 2021; Geng et al., 2019) and learning strategies (Al Mamun et al., 2020; Gerard et al., 2022; Gozzard & Zadnik, 2021) to the integration of modern technologies (Onah et al., 2021; Palaniappan & Noor, 2022; Toh & Kirschner, 2020) However, tangible data outlining the implications of these methodologies remain scant.

In light of this, our systematic literature review, based on 50 studies from 2018 to 2022, seeks to delve into the prevailing SDL research trends in the STEM-TL landscape. This comprehensive analysis evaluates the SDL impact across various dimensions.

Therefore, the purpose of this study's analysis is to answer the following research questions (RQ):

RQ1. What are the data characteristics of articles investigating SDL in the context of STEM teaching and learning (trend, country, objective, and education level)?

RQ2. What research methods are used to investigate SDL in STEM teaching and learning?

RQ3. What theories and approaches are used by researchers to use SDL in STEM teaching and learning?

RQ4. How have learning technology platforms been used to connect SDL with STEM teaching and learning?

RQ5. How does the relationship between SDL and STEM teaching and learning benefit students?

RQ6. What challenges do researchers face in implementing SDL in STEM learning?

Methodology

Research Design

The content analysis examined journal articles cited in SDL research from 2018 to 2022. Content analysis is a method that allows qualitative data collected in a study to be analyzed systematically and reliably so that generalizations about the categories of interest to the researcher can be made (Haggarty, 1996). Stemler (2015) states that the content analysis methodological approach is one of the most influential research tools in the "big data" era. Their adaptability—textual, visual, and audio—can all benefit from content analysis. Elo and Kyngas (2008) say that the process of analyzing data in content analysis is to prepare, organize, and report.

Content analysis in this study is appropriate because it can describe and judge things systematically and objectively (Downe-Wamboldt, 1992; Krippendorff, 2004). Another reason could be linking related data and analysis themes that readers can read quickly and efficiently to get information, new ideas, a clear picture of the facts, and actionable advice. It can also be used as a reference by other researchers (Krippendorff, 2004; Weber, 1990) for their work. Several academics who work in education have added to what is known about content analysis through their research. Zainuddin et al. (2019) conducted a study investigating current trends in Flipped Classrooms. They looked at 48 scientific research articles from 17 professional journals published by the Social Sciences Citation Index (SSCI) to determine how flipped classrooms positively affect learning outcomes, motivation or engagement, self-efficacy, and social interaction. They also investigated the difficulties associated with flipped classroom implementation. Lin et al. (2018) did another content analysis in which they looked at 1088 papers from 2013 to 2017 about research trends in Science Education. This study looked at which nations publish the most, variances in research article kinds, differences in research themes, the top ten most referenced articles, research trends in country contribution, research types, research topics, and the top ten most cited papers.

Search Strategy

A search technique was developed for this systematic review to locate relevant literature on SDL in the STEM sector. This systematic review investigation used the Scopus and Web of Science databases. We looked for articles containing three primary phrases and their synonyms: (1) SDL, (2) STEM or Mathematics, Physics, Chemistry, Biology, Technology, or Science, and (3) teaching and learning. The original search yielded 2,678 articles, 1,482 WoS searches, and 1,196 Scopus searches.

Selection Criteria

The following inclusion and exclusion criteria were then used to screen research publications:

- Inclusion Criteria:
- Articles in English.
- Empirical studies in the STEM domain.
- Journal articles published between January 2018 and October 2022.
- Addressing the application of SDL in education.
- Discussing the tangible effects of SDL on educational outcomes, including academic, behavioral, and affective dimensions.

Exclusion Criteria:

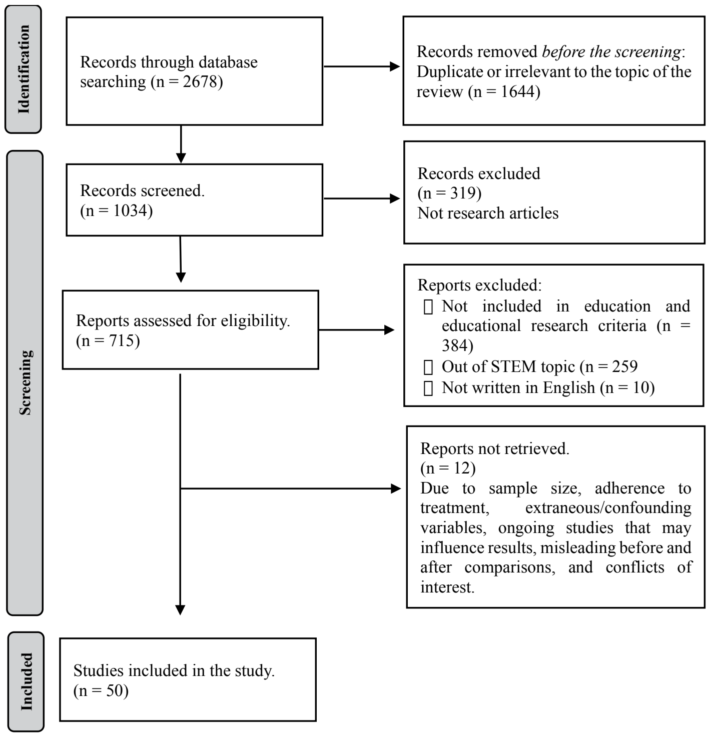
- Duplicates and non-original content.
- Non-research-based content such as opinion pieces, technical reports, and presentations.
- Articles did not strictly adhere to the STEM domain (like those oriented towards medical or arts disciplines).
- Content not in English.
- Articles that lacked clarity in outcome evaluation or presented without quantifiable results.

Three assessors reviewed a random sample of articles to ensure they fit specific criteria. From the initial 2,678 articles, 62 were shortlisted based on strict inclusion and exclusion rules. Here is a breakdown of why 2,616 articles were excluded:

- 1,544 were not research focused.
- 319 were not genuine articles.
- 384 did not fall under the "Education: Educational Research" category.
- 259 were unrelated to STEM (they were on topics like medicine, music, etc.).
- 10 were not in English.
- 96 were duplicates.
- 4 were literature reviews.

Further checks for research validity led to 12 more articles being dropped, leaving 50 articles. These underwent quality assessment. Figure 1 provides a visual summary of this process.

FIGURE 1



Study selection chart PRISMA 2020 framework adapted from Page et al. (2021)

TABLE 1

List of the 50 selected articles reviewed in this study

ID	Year	Title	Author	Journal
1	2018	Transforming self-driven learning using action research	Newman & Farren	Journal of Work-Applied Management
2	2018	Mastery goals, positive emotions, and learning behavior in self-directed vs. teacher-directed learning	Schweder	European Journal of Psychology of Education
3	2018	Enhancing theoretical understanding of a practical biology course using active and self-directed learning strategies	Scott et al.	Journal of Biological Education

Table 1

ID	Year	Title	Author	Journal
4	2018	Motivating engineering students learning via monitoring in personalized learning environment with tagging system	Balakrishnan	Computer Applications in Engineering Education
5	2018	An Examination of High School Students' Online Engagement in Mathematics Problems	Lim et al.	International Journal of Web-Based Learning and Teaching Technologies
6	2018	The impact of cooperative learning on self-directed learning abilities in the computer applications technology class	Mentz & Van Zyl	International Journal of Lifelong Education
7	2018	Factors related to college students' self-directed learning with technology	Sumuer	Australasian Journal of Educational Technology
8	2018	Cognitive loading due to self-directed learning, complex questions, and tasks in the zone of proximal development of students	Zulu et al.	Problems of Education in the 21st Century
9	2019	The Effects of Biology Laboratory Practices Supported with Self-regulated Learning Strategies on Students' Self-directed Learning Readiness and Their Attitudes Towards Science Experiments	Kayacan & Ektem	European Journal of Educational Research
10	2019	The Impact of Android-Based Assessment for Learning System Toward Students Self-Directed Learning Ability on Thermodynamic Matter	Prasetio et al.	Journal of Science Education
11	2019	STEM education supported by virtual laboratory incorporated in self-directed learning process	Truchly et al.	Journal of Electrical Engineering-Elektrotechnicky Casopis
12	2019	Virtual reality to improve group work skill and selfdirected learning in problembased learning narratives	Abdullah et al.	Virtual Reality
13	2019	Investigating self-directed learning and technology readiness in blending learning environment	Geng et al.	International Journal of Educational Technology in Higher Education
14	2019	An exploration of primary school students' perceived learning practices and associated self-efficacies regarding mobile-assisted seamless science learning	Lin et al.	International Journal of Science Education
15	2019	Fostering teachers' autonomous motivation during professional learning: a self-determination theory perspective	Power & Goodnough	Teaching Education
16	2019	Designing MOOCs to Facilitate Participant Self-Monitoring for Self-Directed Learning	Zhu & Bonk	Online Learning Journal

Table 1

ID	Year	Title	Author	Journal
17	2020	A Self-Directed Workshop for Developing Advanced Data Processing and Analysis Skills in Chemistry Using Microsoft Excel	Campbell et al.	Journal of Chemical Education
18	2020	"Monkey See, Monkey Do, That's Not Going to Actually Teach You": Becoming a Self-Directed Learner in Enabling Mathematics Units	Mann & Willans	Student Success
19	2020	Effect of Concept Attainment Models and Self-Directed Learning (SDL) on Mathematics Learning Outcomes	Sukarjo & Salam	International Journal of Instruction
20	2020	Self-directed learning in video games, affordances and pedagogical implications for teaching and learning	Toh & Kirschner	Computers & Education
21	2020	The New Generation Self-Directed Teaching Materials of Natural Science in Elementary Schools Validity Tests	Budiastra et al.	International Journal of Instruction
22	2020	Teaching and Instructional Design Approaches to Enhance Student's Self-Directed Learning in Blended Learning Environments	Adinda & Mohib	Electronic Journal of E-Learning
23	2020	Instructional design of scaffolded online learning modules for self-directed and inquiry-based learning environments	Al Mamun et al.	Computers & Education
24	2020	University-school initiative for a career in engineering: development of self-directed learning when solving mathematics problems	Jordaan & Havenga	World Transactions on Engineering and Technology Education
25	2020	Patterns of Computational Thinking Development while Solving Unplugged Coding Activities Coupled with the 3S Approach for Self-Directed Learning	Threekunprapa & Yasri	European Journal of Educational Research
26	2021	Massive Open Online Courses Model with Self-directed Learning to Enhance Digital Literacy Skills	Chatwattana	International Journal of Engineering Pedagogy
27	2021	Investigating the Effect of Using Web 2.0 Tools on 7th -Grade Students' Academic Achievements in Science and Self-Directed Learning with Technology	Kırıkkaya & Yıldırım	Journal of Turkish Science Education
28	2021	Differences in Self-Directed Learning: Middle-School Students' Autonomous Outdoor Studying	Uus et al.	Frontiers in Education

Table 1

ID	Year	Title	Author	Journal
29	2021	The influences of conceptions of mathematics and self-directed learning skills on university students' achievement in mathematics	Alotaibi & Alanazi	European Journal of Education
30	2021	The cultivation of self-directed learning in teaching mathematics	Bishara	World Journal on Educational Technology: Current Issues
31	2021	How kids manage self-directed programming projects: Strategies and structures	Brennan	Journal of the Learning Sciences
32	2021	The dynamic mix of heutagogy and technology: Preparing learners for lifelong learning	Blaschke	British Journal of Educational Technology
33	2021	Contribution of self-directed, naked-eye observations to students' conceptual understanding and attitudes toward astronomy	Gozzard & Zadnik	Physical Review Physics Education Research
34	2021	Goal-oriented active learning (GOAL) system to promote reading engagement, self-directed learning behavior, and motivation in extensive reading	Li et al.	Computers & Education
35	2021	An innovative MOOC platform: the implications of self-directed learning abilities to improve motivation in learning and to support self-regulation	Onah et al.	International Journal of Information and Learning Technology
36	2021	Did Self-Directed Learning Curriculum Guidelines Change Taiwanese High-School Students' Self-Directed Learning Readiness?	Chen et al.	The Asia-Pacific Education Researcher
37	2022	Supporting Teachers to Customize Curriculum for Self-Directed Learning	Gerard et al.	Journal of Science Education and Technology
38	2022	The Influence of Affective Feedback Adaptive Learning System on Learning Engagement and Self-Directed Learning	Liu et al.	Frontiers in Psychology
39	2022	Gamification Strategy to Support Self-Directed Learning in an Online Learning Environment	Palaniappan & Noor	International Journal of Emerging Technologies in Learning
40	2022	The Effect of Self-Directed Learning on Students' Digital Literacy Levels in Online Learning	Rini et al.	International Journal of Instruction
41	2022	Self-directed learning: A case study of school students scientific knowledge construction outdoors	Uus et al.	Cogent Education

TABLE 1

ID	Year	Title	Author	Journal
42	2022	Enhancing Self-directed Learning Readiness at Elementary Level; a Study from American Schools	Alwadaeen & Piller	Journal of Curriculum and Teaching
43	2022	Relationship between Technology Acceptance and Self-Directed Learning: Mediation Role of Positive Emotions and Technological Self-Efficacy	An et al.	Sustainability
44	2022	Exploration of learner-content interactions and learning approaches: The role of guided inquiry in the self-directed online environments	Al Mamun et al.	Computers & Education
45	2022	Mapping the Relationships between Self-Directed Learning and Design Thinking in Pre-Service Science and Technology Teachers	Avsec & Savec	Sustainability
46	2022	Atomic Physics Teaching Materials in Blended Learning to Improve Self-Directed Learning Skills in Distance Education	Erlina et al.	Turkish Online Journal of Distance Education
47	2022	Using the Online Self-Directed Learning Environment to Promote Creativity Performance for University Students	Jin et al.	Educational Technology & Society
48	2022	Learning through technology in middle school classrooms: Students' perceptions of their self-directed and collaborative learning with and without technology	Labonté & Smith	Education and Information Technologies
49	2022	Metacognition and the development of self-directed learning in a problem-based engineering curriculum	Marra et al.	Journal of engineering education
50	2022	Self-directed learners' perceptions and experiences of learning computer science through MIT open courseware	Zhu & Kadirova	Open Learning: The Journal of Open, Distance and e-Learning

FINDINGS AND DISCUSSION

A comprehensive literature review with content analysis was conducted on 50 publications published between 2018 and 2022 within educational research focused on SDL related to STEM teaching and learning. This serves as the foundation for answering research questions.

Research Question 1. What are the data characteristics of articles investigating SDL in the context of STEM teaching and learning (trend, country, objective, and education level)?

Trend

Upon examining Table 1, which enumerates 50 selected articles centered on SDL within STEM education, several distinct trends become apparent across the specified time-frame. The chronological distribution reveals a burgeoning academic interest in SDL, as evidenced by the uptick in published articles over the years. This escalation in scholarly attention suggests that SDL is becoming progressively more integral to educational strategies, particularly within STEM disciplines.

Methodologically, a notable evolution can be observed. Earlier papers from 2018 tend to employ more traditional quantitative approaches—often focusing on metrics such as learning outcomes or academic achievement. However, as we progress to the latest articles in 2021 and 2022, there is an evident shift towards employing more qualitative and mixed-method approaches. These methodologies offer a more prosperous, multi-dimensional understanding of SDL, capturing not just the 'what' but also the 'why' and 'how' of self-directed practices in STEM education.

Regarding subject focus, earlier articles (2018–2019) are often more generalized, exploring SDL primarily in the context of either a single STEM subject or STEM as a broad category. In contrast, later articles from 2021 and 2022 demonstrate a tendency to investigate SDL in more specific sub-domains within STEM, such as computational thinking, data processing in chemistry, and digital literacy, among others.

Moreover, the thematic concentration of these articles shows a transition over time. Initial articles focus predominantly on the individual attributes of learners—such as mastery goals, positive emotions, and attitudes. By contrast, later publications increasingly explore the systemic factors that support SDL, including technological tools like MOOCs, VR, and adaptive learning systems. These indicate a shift from a micro-level focus on individual learners to a macro-level focus on educational systems and technologies.

Furthermore, the context in which SDL is studied also seems to diversify with time. Earlier articles are more geared towards traditional classroom settings, while more recent works consider various learning environments, such as online, blended, and even outdoor educational settings, reflecting the broadening landscape of where and how SDL can be effective.

In summary, the analysis of these 50 articles presents a dynamic picture of the evolving trends in SDL research within STEM education. The shifts in methodological approaches, thematic focus, subject specificity, and educational contexts offer a comprehensive overview of how the field matures, making it apparent that SDL in STEM is a multifaceted and ever-evolving area of scholarly inquiry.

Country

Table 2 showcases the distribution of 50 publications from 21 nations investigating SDL in STEM contexts. The United States is the primary contributor, with eight articles indicating a significant emphasis on SDL in its STEM research landscape. Notably, both Australia and Indonesia follow closely with five articles each. This prominence underscores SDL's universal appeal and importance in STEM across varied educational and cultural settings.

Several nations, such as Malaysia, China, South Africa, the United Kingdom, and Turkey, have presented three research articles each. Meanwhile, many countries, including Canada, Thailand, Taiwan, and Estonia, have twice ventured into this research domain. Singular contributions come from countries spanning Europe to Asia, such as Slovenia, Spain, Japan, Saudi Arabia, Ireland, Germany, Singapore, and Slovakia.

TABLE 2

Distribution of countries that frequently investigate SDL in STEM contexts

Countries	Paper ID from Table 1	Frequencies
USA	42, 30, 31, 37, 5, 49, 50, 16	8
Australia	23, 44, 13, 33, 18	5
Indonesia	21, 46, 10, 40, 19	5
Malaysia	12, 4, 39	3
China	43, 47, 14	3
South Africa	24, 6, 8	3
United Kingdom	17, 35, 3	3
Turkey	9, 27, 7	3
Canada	48, 15	2
Thailand	26, 25	2
Taiwan	36, 38	2
Estonia	28, 41	2
French	22	1
Slovenia	45	1
Spain	32	1
Japan	34	1
Saudi Arabia	29	1
Ireland	1	1
Germany	2	1
Singapore	20	1
Slovakia	11	1

The commitment to SDL in STEM often reflects a nation's educational orientation and priorities. Countries renowned for their robust educational frameworks, like the United States (Alwadaeen & Piller, 2022; Marra et al., 2022), Canada (Labonte & Smith, 2022), and various European nations (Newman & Farren, 2018; Onah et al., 2021), have integrated SDL strategies to stay abreast with the swift technological advancements characterizing contemporary education.

Similarly, some Asian countries, recognized for their rigorous academic settings, such as those cited by Alotaibi and Alanazi (2021) and Chen et al. (2022), have leveraged SDL to cater to evolving technological challenges. In contrast, nations on the path of educational development have recognized SDL's potential as a catalyst. By adopting SDL, these nations aim to enhance educational practices, thereby elevating academic standards (Erlina et al., 2022; Sukardjo & Salam, 2020).

As the twenty-first century unfolds, marked by rapid transformations across diverse sectors, the emphasis on SDL as an indispensable skill intensifies. Countries with a visionary perspective on education swiftly adapt their curricula to incorporate SDL (Chen et al., 2022). Beyond equipping learners with contemporary skills, the overarching objective remains to foster an educational environment where learners are nurtured to think independently, engage with curiosity, and take ownership of their learning journey.

Objective

Table 3 portrays various objectives across the 50 scrutinized articles. The most prevalent objective underscores the integration of technology in STEM-TL and its interplay with SDL. Studies such as Onah et al. (2021) deploy cutting-edge platforms like MOOCs to probe their influence on SDL proficiencies. Central to their findings is the revelation that aspects like time management, learning goal setting, and assignment strategies are critical determinants of successful learning. Intriguingly, the mere introduction of technology is not the panacea; instead, it is the preparedness of both educators and learners that capitalizes on its potential.

Adjacent to the technological objective, a significant cluster of articles delves into the nexus between SDL and learning outcomes within the STEM-TL domain. Emblematic research, such as that by Scott et al. (2018), posits that in demanding subjects such as biology, the marriage of active SDL strategies can elevate the learning experience. It is underscored that passive participation is insufficient; active and autonomous engagement emerges as the key.

A further layer of investigation traces SDL's ramifications across multifaceted tiers, spanning individual learners to expansive educational systems. Within this scope, insights from Gozzard and Zadnik (2021) illuminate the transformative power of reflective practices, such as diary-keeping, in fostering deeper student engagement.

In reflection of this breadth of exploration, we observe another objective that characterizes the SDL implementation across diverse STEM-TL contexts. Studies exemplified by Adinda and Mohib (2020) advocate for innovative pedagogical designs tailored to nurture SDL competencies, especially in hybrid learning scenarios.

While less dominant, there is a discernible thrust toward devising tools that measure SDL efficacy. In this realm, pioneering works like Budiastra et al. (2020) and Prasetio et al. (2019) offer a glimpse into novel SDL evaluation instruments, hinting at their viability as alternative assessment avenues in specific regions like Indonesia.

Cumulatively, these nuanced objectives underscore the multifaceted role of SDL in the STEM-TL landscape, cementing its centrality in shaping the educational trajectories of the future.

TABLE 3

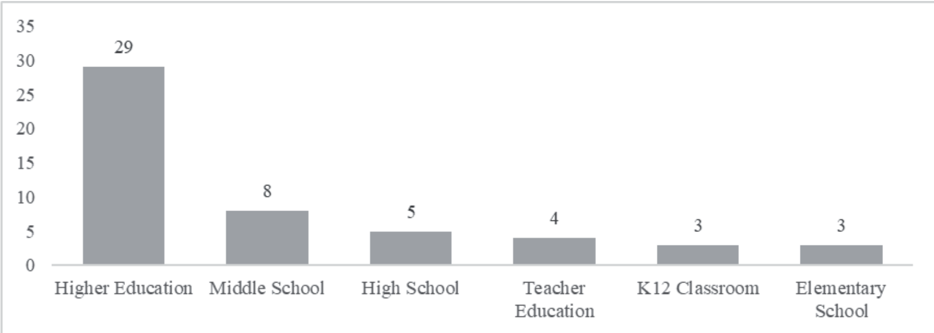
The objectives SDL in the STEM-TL research

Objectives	Paper ID from Table 1	Frequencies
Researching the use of technology in STEM Teaching and Learning and its relationship with SDL	4, 26, 37, 27, 48, 34, 5, 14, 38, 6, 1, 35, 39, 10, 40, 3, 7, 25, 20, 50, 16	21
Investigate the relationship between SDL and student or teacher learning outcomes in the context of STEM Teaching and Learning	45, 30, 17, 13, 37, 47, 9, 27, 38, 49, 39, 15, 40, 2, 3, 19	16
Examines the extent of SDL as a variable at the student, teacher, class, school, or country level	44, 29, 42, 31, 33, 18, 49, 1, 2, 11, 28, 41, 8	13
Investigate SDL in STEM Teaching and Learning activities across classrooms, schools, or countries	12, 22, 23, 43, 32, 36, 46, 24, 49, 19, 20, 28	12
Investigate SDL as a variable that can be measured by developing learning evaluation instruments	21, 10	2

Education Level

As shown in Figure 2, the distribution of articles predominantly centers on higher education, with 29 papers dedicated to this segment. This pronounced inclination towards tertiary levels is juxtaposed with fewer explorations at the middle school, high school, teacher education, K–12 classrooms, and elementary school levels, signaling a potential research opportunity for scholars. Intriguingly, this data suggests that primary and secondary schools remain underexplored regarding SDL practices within the STEM context. This underrepresentation reiterates the significance of understanding students' perceptions of SDL proficiency, especially in an era increasingly permeated by technology (Labonte & Smith, 2022).

FIGURE 2



Distribution of SDL in STEM contexts across educational levels

Delving deeper, the emphasis on SDL across various educational strata is not merely a function of age or academic rigor. It aligns with the evolution of cognitive maturity and diverse learning environments encountered at each phase. Notably, while cognitive maturity often intertwines with age, compelling insights from Heo and Han (2017) underscore that SDL aptitudes extend beyond these conventional metrics, encompassing educational echelons.

Mirroring these findings, Schweder and Raufelder (2019) illuminate the pivotal role of educators in bolstering SDL, irrespective of the student's age or gender. Their research accentuates the symbiotic relationship between educators and learners. Educators can offer targeted feedback by facilitating tools such as learning diaries, ensuring learners remain anchored to their SDL trajectories. Such interventions empower learners to periodically introspect, refine, and adapt their SDL strategies, emphasizing the significance of continuous guidance in cultivating SDL expertise.

In summation, while presently skewed towards higher education, exploring SDL in the STEM landscape underscores a compelling need to expand horizons. Embracing the manifold intricacies of diverse educational levels can catalyze a more holistic and enriched understanding of SDL in STEM pedagogies.

Research Question 2: What research methods are used to investigate SDL in STEM teaching and learning?

An exploration into the methodologies adopted to study SDL's intricacies in STEM pedagogies uncovers a range of research designs, as described by Fraenkel et al. (2011). The quantitative approach, employed in 27 studies, emerges as a prominent choice, underscoring the drive for empirical precision. Researchers utilizing this method aim to capture, measure, and analyze the prevalence and impact of SDL in STEM environments through structured numerical data.

In contrast, the qualitative design, manifested in 13 studies, provides a deeper, more nuanced understanding. By delving into human experiences, perceptions, and interpretations, this method unravels the intricacies of SDL's application in STEM classrooms, gleaning insights from the rich tapestry of human narratives.

Ten studies, blending the empirical rigor of quantitative methods with the depth of qualitative research, opted for a mixed-methods design. This dual approach amalgamates the strengths of both methodologies, offering a comprehensive, multifaceted lens into the SDL phenomenon within the STEM context.

In essence, these varied research designs mirror the multifaceted nature of SDL in STEM education, each providing distinct yet invaluable insights into its understanding and application.

Research Question 3: What theories and approaches are used by researchers to use SDL in STEM teaching and learning?

A meticulous examination of empirical studies on SDL in STEM teaching and learning reveals the foundational learning theories and pedagogical strategies that anchor their research endeavors. The diversity and breadth of these theories and strategies, as presented in Tables 4 and 5, speak to the multifaceted nature of SDL and the complexity inherent in STEM education.

A profound understanding of instructional pedagogy is essential for research to be efficacious and make a notable contribution. Delving deeper into the instructional design principles and marrying theory with practice can illuminate how learners navigate their educational journey. By scrutinizing these techniques, researchers can discern the evolution and application of SDL skills within the STEM domain.

It is imperative to ground research in sound learning theories, coupled with the practical application of instructional design concepts. Without such a theoretical scaffold, the edifice of instructional design risks being perceived as incomplete or flawed. Echoing Bruner (1966) insights, influential instructional theories are marked by four critical elements: a stimulus that kindles the desire to learn, clarity in conceptualizing the learning set, strategic sequencing of instructional content, and apt calibration of reinforcements and feedback. This perspective, while being prescriptive, and prioritizing the optimization of learning pathways, also bears a normative essence, emphasizing goal setting.

TABLE 4

Distribution of underlying theories in SDL research

Theories	Paper ID from Table I	Frequencies
Behaviorism	12, 22, 42, 43, 31, 17, 26, 36, 13, 33, 48, 34, 38, 49, 1, 35, 39, 2, 3, 19, 7, 20, 11, 28, 41	25
Social Cognitive	22, 42, 43, 45, 4, 31, 17, 26, 33, 9, 27, 34, 38, 18, 39, 40, 2, 3, 20, 11, 28	21
Social constructivism	12, 29, 42, 43, 30, 32, 36, 46, 13, 37, 24, 48, 14, 6, 1, 19, 7, 41	18
Engagement	12, 43, 32, 17, 26, 37, 33, 27, 38, 39, 10, 40, 3, 20, 11	15
Constructivism	23, 29, 30, 46, 13, 48, 5, 49, 35, 25, 50, 8	12
Self-theory	32, 47, 5, 14, 1, 15, 2, 20, 16	9
Malone and Lepper's taxonomy of motivation	29, 42, 30, 17, 2	5
Cognitive stage	21, 10, 19, 28	4
Zone of proximal development (ZPD)	31, 3, 8	3
Online collaborative learning	26, 27	2
Meaningful learning	44, 31	2
Control-value	43	1

An overarching observation from the analyzed studies is their collective endeavor to realize effective SDL grounded in robust learning principles tailored to their specific research objectives. Key insights include the realization that a learner's prior knowledge can be a double-edged sword, facilitating or impeding the learning process. The motivation underpinning a student's academic pursuits is pivotal in shaping their learning trajectory. The structural organization of a student's knowledge profoundly influences their learning dynamics and application. Mastery in SDL is an iterative process, necessitating the assimilation of skill components, their integration through practice, and discernment in their application. Well-defined, goal-oriented tasks complemented with bespoke feedback are catalysts for student learning. The milieu of a student's socio-emotional and intellectual environment significantly modulates their autonomous learning pursuits. Lastly, for students to truly become autonomous learners, they need self-awareness, monitoring, and fine-tuning their learning strategies.

TABLE 5

The strategies used in combining SDL in STEM-TL

Strategies	Paper ID from Table 1	Frequencies
Self-directed learning strategy	42, 4, 30, 17, 26, 33, 47, 24, 48, 34, 5, 14, 15, 3, 7, 16, 8	17
Online-Based Learning	23, 44, 32, 47, 27, 10, 40, 50, 16	9
Problem-based learning	12, 18, 49, 2, 25	5
Game-based learning	38, 39, 20, 11	4
Blended learning	22, 46, 13, 35	4
Inquiry-based learning	23, 44, 37	3
Design-based learning	28, 41	2
Project-based learning	32, 19	2
Collaborative learning	48, 14	2
Research-based learning	1	1
Cooperative learning	6	1

Research Question 4: How have learning technology platforms been used to connect SDL with STEM teaching and learning?

In the modern education landscape, the centrality of technology in fostering and nurturing students' SDL skills stands uncontested, as evidenced by the studies we analyzed. As SDL technology gains traction, it manifests as leveraging information and communication technology to orchestrate learning activities. These activities, in turn, empower students to streamline, act, and critically reflect upon their learning journeys.

In their research, Toh and Kirschner (2020) delve deeper into the untapped potential of video games as potent tools in the SDL arsenal. Far from being mere entertainment vessels, video games encompass intrinsic attributes conducive to fostering independent study. Paramount among these is the provision of a risk-free space and the simulation of authentic learning milieus, both pivotal for cultivating students' autonomous learning capacities. The study demystifies the SDL-enabling mechanisms inherent in video games by meticulously analyzing player interactions through user experience methodologies, such as in-depth interviews and real-time 'think-aloud' protocols.

Three pivotal axes emerge from this exploration:

1. Meta-behavioral Dimensions: Students' SDL journeys in video games are punctuated by iterative processes of trial and error, keen observation, emulation of models, and learning reinforced by feedback.
2. Meta-cognitive Facets: As students navigate the virtual realms, they engage in interconnected learning, indulge in reflective practices, sharpen their logical and analytical prowess, embark on inquiry-driven quests, and engage in the synthesis of information.
3. Meta-emotional Aspects: The emotional roller-coaster intrinsic to gameplay, oscillating between moments of dissatisfaction, bursts of anger, pangs of curiosity, and the elation of satisfaction, forms an integral part of the SDL narrative in gaming.

The implications of these findings are multifold. Game designers and pedagogues can harness these insights to gauge the educative potential of video games, ensuring they align with the overarching objective of bolstering students' autonomous learning propensities. Furthermore, educators and scholars can glean empirical evidence by operationalizing the self-learning strategy framework delineated in the study as a coding template in user experience research. Such evidence can shed light on the games best suited for different learning contexts, be it formal classroom settings or informal learning environments. These coding frameworks pave the way for a deeper understanding of how foundational self-learning strategies can be instrumental in lifelong learning trajectories.

TABLE 6

Technology Platforms in SDL Research in STEM-TL

Technology		Paper ID from Table 1	Frequencies
Platforms	**Types**		
Computer-supported	Web-based	23, 44, 42, 45, 4, 32, 46, 37, 47, 27, 48, 5, 7	13
	Learning management system	22, 46, 13, 48, 34, 38, 40	7
	MOOCs	32, 26, 36, 35, 50, 16	6
	Youtube	32, 5, 3, 50	4
	Computer applications	43, 31, 6, 25	4
	Microsoft Excel	17	1
	Video game	20	1
	Virtual laboratory	39	1
Mobile Based	Mobile gaming	39	1
	Virtual reality	12	1
	Mobile application	10	1
	Mobile-assisted seamless science learning	14	1

Research Question 5: How does the relationship between SDL and STEM teaching and learning benefit students?

In the landscape of education, learning outcomes serve as crucial guideposts. These outcomes highlight what educators should emphasize and provide insights into how learners can transfer their newfound knowledge and skills into real-world contexts. Birtwistle et al. (2016) define learning outcomes as clear articulations that depict what learners should comprehend, internalize, or be capable of post their educational engagement. They encapsulate the anticipated cognitive, affective, and psychomotor metamorphoses in students.

TABLE 7

Distribution of SDL and STEM-TL on learning outcomes

Learning Outcomes	Paper ID from Table 1	Frequencies
Self-Directed Learning Skills	22, 23, 44, 32, 46, 13, 47, 24, 49, 6, 1, 35, 10, 11, 16	15
Achievement in knowledge	23, 44, 29, 30, 46, 13, 33, 47, 27, 39, 3, 19, 11, 41	14
Motivation	4, 13, 5, 35, 39, 15, 2	7
Attitude	30, 33, 9, 38, 18, 28	6
Self-directed Learning Readiness	42, 36, 9, 7	4
Digital Literacy Skills	26, 5, 40, 7	4
Students' perception	48, 34, 50	3
Problem-solving skills	17, 5	2
Self-efficacy	14, 7	2
Creativity	47	1
Critical thinking	47	1
Curiosity	44	1
Group work skill	12	1
Science process skills	9	1
Design Thinking Ability	45	1
Awareness	45	1
Interpersonal Skills	45	1
Metacognition	49	1
Computational thinking	25	1
Cognitive loading	8	1

A thorough examination of the current empirical literature reveals a deep-seated impact of SDL within the context of STEM-TL. Our analysis categorizes these findings into three overarching categories:

1. Intellectual Skills: These represent the realm of applied knowledge, encompassing the ability to understand and operationalize learning. As Donald (1985) and Rancourt (2012) expound, intellectual skills transcend rote memorization, leaning into the application of understanding. Jin et al. (2022) presented a potent case with their exploration of online SDL environments (OSDLE). These environments push students beyond passive reception, nudging them to seek out and engage with optimal learning resources actively. Such engagements naturally spur heightened creative capacities. The iterative feedback loop, rich with inputs from peers and educators within OSDLE, further compounds this by nurturing reflection and fostering a culture of ideation.
2. Cognitive Strategies: Distinct from intellectual skills, cognitive strategies bring forth specialized modes of thinking that align with specific fields or vocations, as explicated by Dinsmore and Fryer (2019). It is about synthesizing prior knowledge with new information. Standout research by Kayacan and Ektem (2019) underscored this. Within a biology practical environment enriched with SDL approaches, students became more prepared for autonomous learning and displayed an enhanced affinity towards science projects. This transformation can be attributed to the SDL's capacity to instill a sense of ownership, making students active stewards of their educational journey.
3. Attitudinal Impacts: These delve into internal change, capturing the nuances of how new learning experiences reshape a student's intrinsic disposition. Albarracin and Johnson (2019) elucidate that attitudes reflect the internal transformation post-new learning experiences. One poignant study in this vein is by Gozzard and Zadnik (2021), centered around astronomy lectures. Their findings indicate that SDL tools, exemplified by daily observation books, can significantly recalibrate students' perceptions about a subject. The shift towards a more positive outlook was especially pronounced among those disenchanted with traditional assessment mechanisms.

Integrating SDL within STEM-TL has fostered numerous positive outcomes, from enhanced intellectual skills to transformed attitudes. Such findings underscore the pivotal role of SDL methodologies in enriching the educational landscape and catalyzing student growth.

Research Question 6: What challenges do researchers face in implementing SDL in STEM learning?

SDL might be entrenched in educational paradigms, yet its integration within STEM-TL brings forth distinctive challenges. The extensive analysis of fifty pertinent publications elucidates these hurdles, offering a richer understanding of the nuances at play.

Foremost among these is the provision of an optimal educational environment. This aspect is not merely about physical spaces but extends to the essence of a curriculum's operational framework, enveloping all facets of a learner's ecosystem. Bahrami et al. (2022) expounded that a profound synergy exists between the learning milieu and student behavior, with both elements synergistically influencing motivation in SDL's purview. Consequently, Kim et al. (2014) emphasize the pivotal role of this environment, suggesting its direct bearing on student accomplishments.

The double-edged sword of technology presents the next major challenge. While technology indisputably amplifies the efficacy of SDL — with tools like PCs and smartphones acting as invaluable aids — they concurrently usher in potential distractions. These distractions can derail a student's trajectory unless mitigated by heightened self-awareness or external interventions. Cheong et al. (2016) posit an intriguing perspective, emphasizing the educators' role in asserting authority via diverse communication modalities, including codified norms and strategic deflective tactics.

The core principle of SDL, learner autonomy, further exacerbates challenges when grappling with intricate subjects like mathematics. Alotaibi and Alanazi (2021) underscore the pivotal nature of methodological adoption in SDL for digesting complex mathematical constructs. Dolmans et al. (2015) offer an illuminating strategy framework, juxtaposing surface learning (rooted in rote memorization) with more profound learning, emphasizing comprehensive comprehension, integrative thinking, and critical evaluations.

Amplified by the globalized nature of online resources, communication barriers further compound these challenges. There is an evident trend of learners from countries with evolving educational systems accessing resources outside their native languages. This linguistic disconnect necessitates additional strides in comprehension. Experiences like those relayed by Kırıkkaya and Yıldırım (2021) and Erlina et al. (2022) underscore the imperativeness of language inclusivity in Web 2.0 tools and bespoke SDL resources.

Temporal constraints, exacerbated by the expansive nature of SDL, often result in student procrastination. The SDL paradigm's temporal elasticity might, paradoxically, foster a sense of complacency. Coupled with this is the prevalent challenge of information deluge, necessitating sharp digital literacy skills to navigate and curate optimal resources. The dearth of collaborative acumen among students, as spotlighted by Abdullah et al. (2019), further complicates this dynamic. They champion the potential of virtual environments as a remedy, underscoring their efficacy in nurturing group work capabilities.

The finale in this litany of challenges revolves around mentorship. It is not enough to merely champion the SDL ethos; educational institutions bear the onus of providing sustained guidance. In the SDL milieu, abandoning students to their devices is not the solution; consistent guidance and mentorship are paramount.

In summary, while SDL's integration within STEM-TL is a promising paradigm, it comes interspersed with multifaceted challenges that necessitate strategic interventions for optimal outcomes.

Table 8

The challenges in implementing SDL in the STEM-TL domain

Challenges	Paper ID from Table 1	Frequencies
Educational environment	22, 44, 42, 45, 4, 32, 26, 36, 46, 33, 47, 24, 9, 27, 48, 38, 6, 1, 35, 39, 2, 3, 7, 20, 11, 28, 41, 16	28
Distraction due to technology	12, 23, 42, 43, 4, 26, 13, 27, 48, 5, 14, 6, 35, 39, 10, 40, 7, 25, 20, 11, 50, 16	22
Difficulty in learning complex concepts	29, 42, 30, 17, 46, 33, 24, 18, 3, 19, 25, 28, 50, 8	14
Communication barriers	44, 46, 27, 48, 14, 49, 40, 7, 50	9
Time constraints	29, 31, 5, 49, 15	5
Lack of organizational skills	12, 31, 33, 34, 5	5
Information overload	23, 42, 43, 34, 40	5
Faculty guidance	37	1

Conclusion and recommendations

In this systematic review, a comprehensive analysis was undertaken of empirical studies on SDL within the STEM domain, spanning a period of five years from 2018 to 2022. The review canvassed 50 selected articles, probing into various dimensions, from data characteristics such as research provenance, trends, objectives, and educational levels to research techniques, underlying theories, technological tools, impacts, challenges, and the future potential of SDL within STEM.

Our analysis elucidates that SDL's adoption in STEM-TL has garnered global traction, prominently underpinned by research contributions from American and European contexts. A discernible trend emerges in the preferred research methodologies, which predominantly hinge on investigating the symbiotic relationship between SDL and technological interventions across diverse educational strata. Interestingly, the prevailing inclination for SDL application within STEM appears skewed toward higher education. This observation underscores a gap in nurturing an independent learning ethos among younger students and presents an intriguing avenue for future researchers. The criticality of SDL skills for 21st-century learners and its apparent under-representation at the secondary educational tier further emphasize this point.

The surveyed literature exhibited a predilection towards specific theories, pedagogical strategies, and technological platforms. However, a glaring oversight persists in failing to adequately account for pre-existing learner attributes, ranging from self-concept and intrinsic motivation to technological proficiency and foundational conceptions of specific learning subjects. Such insights can be invaluable for future scholars, allowing them to anticipate potential impediments that could influence SDL's seamless incorporation within STEM-TL.

While a sizeable portion of the scrutinized literature praises the benefits of integrating SDL in STEM-TL concerning learning outcomes, most studies disproportionately focus on the cognitive sphere. Such focus neglects the equally pivotal affective and psychomotor facets of learning. Given that holistic learning encompasses these three intertwined domains, these findings highlight a pressing need for future research to explore the impact of SDL on the affective and psychomotor aspects of STEM-TL.

Lastly, the overarching narrative across the articles unequivocally touched upon the inherent challenges and prospects of integrating SDL within STEM-TL. These explicit and subtle insights are seminal for stakeholders, from educators and institutional policymakers to curriculum developers. Such understandings are instrumental in shaping cogent SDL-centric curricula and can serve as beacon guides for subsequent scholars venturing into SDL research within the STEM-TL milieu.

As the educational landscape continually evolves, so must our strategies, tools, and methodologies. This systematic review sheds light on pivotal areas, underscoring the imperativeness of a more holistic and nuanced approach to SDL within STEM. The recommendations and insights gleaned herein pave the way for future research, curriculum design, and pedagogical strategies, fostering a more inclusive and effective STEM-TL environment.

References

Abdullah, J., Mohd-Isa, W. N., & Samsudin, M. A. (2019). Virtual reality to improve group work skill and self-directed learning in problem-based learning narratives. *Virtual Reality, 23*(4), 461-471.

Adinda, D., & Mohib, N. (2020). Teaching and instructional design approaches to enhance student's self-directed learning in blended learning environments. *Electronic Journal of E-Learning, 18*(2), 162-174.

Al Mamun, M. A., Lawrie, G., & Wright, T. (2020). Instructional design of scaffolded online learning modules for self-directed and inquiry-based learning environments. *Computers & Education, 144*, Article 103695. https://doi.org/10.1016/j.compedu.2019.103695

Albarracin, D., & Johnson, B. T. (2019). *The handbook of attitudes: Basic principles* (Second ed.). Routledge.

Alotaibi, K., & Alanazi, S. (2021). The influences of conceptions of mathematics and self-directed learning skills on university students' achievement in mathematics. *European Journal of Education, 56*(1), 117-132.

Alwadaeen, N. B., & Piller, B. (2022). Enhancing self-directed learning readiness at elementary level; a study from American schools. *Journal of Curriculum and Teaching, 11*(4), 24-38.

Arztmann, M., Hornstra, L., Jeuring, J., & Kester, L. (2023). Effects of games in STEM education: A meta-analysis on the moderating role of student background characteristics. *Studies in Science Education, 59*(1), 109-145.

Aydin Gunbatar, S., Ekiz Kiran, B., Boz, Y., & Roehrig, G. H. (2022). A closer examination of the STEM characteristics of the STEM activities published in NSTA journals. *Research in Science & Technological Education*, 1-26. https://doi.org/10.1080/02635143.2022.2121692.

Birtwistle, T., Brown, C., & Wagenaar, R. (2016). A long way to go. A study on the implementation of the learning-outcomes based approach in the EU. *Higher Education, 3*(2), 429-463.

Bishara, S. (2021). The cultivation of self-directed learning in teaching mathematics [Article]. *World Journal on Educational Technology: Current Issues, 13*(1), 82-95.

Boyer, S. L., Edmondson, D. R., Artis, A. B., & Fleming, D. (2014). Self-directed learning: A tool for lifelong learning. *Journal of Marketing Education, 36*(1), 20-32.

Bruner, J. S. (1966). *Toward a theory of instruction*. Belknap Press of Harvard University.

Budiastra, A. A. K., Wicaksono, I., & Sanjaya, I. G. M. (2020). The new generation self-directed teaching materials of natural science in elementary schools validity tests. *International Journal of Instruction, 13*(4), 763-780.

Chen, C.-H., Chen, K.-Z., & Tsai, H.-F. (2022). Did self-directed learning curriculum guidelines change Taiwanese high-school students' self-directed learning readiness? *The Asia-Pacific Education Researcher, 31*(4), 409-426.

Cheong, P. H., Shuter, R., & Suwinyattichaiporn, T. (2016). Managing student digital distractions and hyperconnectivity: Communication strategies and challenges for professorial authority. *Communication Education, 65*(3), 272-289.

Dinsmore, D. L., & Fryer, L. K. (2019). Developing learners' cognitive strategies and the motivation to use them: Rethinking education policy. *Policy Insights from the Behavioral and Brain Sciences, 6*(2), 107-114.

Dolmans, D. H. J. M., Loyens, S. M. M., Marcq, H., & Gijbels, D. (2015). Deep and surface learning in problem-based learning: A review of the literature. *Advances in Health Sciences Education, 21*(5), 1087-1112.

Donald, J. G. (1985). Intellectual skills in higher education. *Canadian Journal of Higher Education, 15*(1), 52-68.

Downe-Wamboldt, B. (1992). Content analysis: Method, applications, and issues. *Health Care Women International, 13*(3), 313-321.

Elo, S., & Kyngas, H. (2008). The qualitative content analysis process. *Journal of Advanced Nursing, 62*(1), 107-115.

Erlina, N., Prayekti, & Wicaksono, I. (2022). Atomic Physics teaching materials in blended learning to improve self-directed learning skills in distance education. *Turkish Online Journal of Distance Education*, *23*(4), Article 2. https://www.scopus.com/inward/record.uri?eid=2-s2.0-85140038234&partnerID=40&m d5=2a62d6a91c9c91d8a09502801fe56fce.

Fraenkel, J., Wallen, N., & Hyun, H. (2011). *How to design and evaluate research in education*. McGraw-Hill.

Geng, S., Law, K. M. Y., & Niu, B. (2019). Investigating self-directed learning and technology readiness in blending learning environment. *International Journal of Educational Technology in Higher Education*, *16*, Article 17. https://doi.org/10.1186/s41239-019-0147-0.

Gerard, L., Bradford, A., & Linn, M. C. (2022). Supporting teachers to customize curriculum for self-directed learning. *Journal of Science Education and Technology, 31*(5), 660-679.

Gozzard, D. R., & Zadnik, M. G. (2021). Contribution of self-directed, naked-eye observations to students' conceptual understanding and attitudes towards astronomy. *Physical Review Physics Education Research*, *17*(1), 010134. https://journals.aps.org/prper/abstract/10.1103/PhysRevPhysEducRes.17.010134.

Haggarty, L. (1996). What is ... content analysis? *Medical Teacher, 18*(2), 99-101.

Heo, J., & Han, S. (2017). Effects of motivation, academic stress and age in predicting self-directed learning readiness (SDLR): Focused on online college students. *Education and Information Technologies, 23*(1), 61-71.

Higgins, N. L., Frankland, S., & Rathner, J. A. (2021). Self-regulated learning in undergraduate science. *International Journal of Innovation in Science and Mathematics Education, 29*(1), 58-70.

Jeong, K.-O. (2022). Facilitating sustainable self-directed learning experience with the use of mobile-assisted language learning. *Sustainability, 14*(5), 13, 2894. https://doi.org/10.3390/su14052894.

Jin, X. Q., Jiang, Q., Xiong, W. Y., Pan, X. Z., & Zhao, W. (2022). Using the online self-directed learning environment to promote creativity performance for university students. *Educational Technology & Society, 25*(2), 130-147.

Kayacan, K., & Ektem, I. S. (2019). The effects of biology laboratory practices supported with self-regulated learning strategies on students' self-directed learning readiness and their attitudes towards science experiments. *European Journal of Educational Research, 8*(1), 313-323.

Khodaei, S., Hasanvand, S., Gholami, M., Mokhayeri, Y., & Amini, M. (2022). The effect of the online flipped classroom on self-directed learning readiness and metacognitive awareness in nursing students during the COVID-19 pandemic. *BMC Nursing*, *21*, 22. https://doi.org/10.1186/s12912-022-00804-6

Kim, R., Olfman, L., Ryan, T., & Eryilmaz, E. (2014). Leveraging a personalized system to improve self-directed learning in online educational environments. *Computers and Education*, *70*, 150-160.

Kırıkkaya, E. B., & Yıldırım, İ. (2021). Investigating the effect of using Web 2.0 Tools on 7th-grade students' academic achievements in Science and self-directed learning with technology. *Journal of Turkish Science Education, 18*(3), 439-460.

Knowles, M. S. (1975). *Self-directed learning: A guide for learners and teachers*. Association Press.

Krippendorff, K. (2004). *Content Analysis: An introduction to its methodology*. Sage Publications.

Labonte, C., & Smith, V. R. (2022). Learning through technology in middle school classrooms: Students' perceptions of their self-directed and collaborative learning with and without technology. *Education and Information Technologies, 27*(5), 6317-6332.

Lin, T.-J., Lin, T.-C., Potvin, P., & Tsai, C.-C. (2018). Research trends in science education from 2013 to 2017: A systematic content analysis of publications in selected journals. *International Journal of Science Education, 41*(3), 367-387.

Lin, X. F., Tang, D., Lin, X., Liang, Z. M., & Tsai, C. C. (2019). An exploration of primary school students' perceived learning practices and associated self-efficacies regarding mobile-assisted seamless science learning. *International Journal of Science Education, 41*(18), 2675-2695.

Liu, A., Shapiro, C., Gregg, J., Levis-Fitzgerald, M., Sanders O'Leary, E., & Kennison, R. L. (2022). Scaling up a life sciences college career exploration course to foster STEM confidence and career self-efficacy. *Research in Science & Technological Education*, 1-17. https://doi.org/10.1080/02635143.2022.2083599.

Marra, R. M., Hacker, D. J., & Plumb, C. (2022). Metacognition and the development of self-directed learning in a problem-based engineering curriculum. *Journal of Engineering Education, 111*(1), 137-161.

Melton, J. W., Ali Saiful, J., & Pat Shein, P. (2022). Interdisciplinary STEM program on authentic aerosol science research and students' systems thinking approach in problem-solving. *International Journal of Science Education, 44*(9), 1419-1439.

Morris, T. H. (2019). Self-directed learning: A fundamental competence in a rapidly changing world. *International Review of Education, 65*(4), 633-653.

Newman, E., & Farren, M. (2018). Transforming self-driven learning using action research. *Journal of Work-Applied Management, 10*(1), 4-18.

Onah, D. F. O., Pang, E. L. L., Sinclair, J. E., & Uhomoibhi, J. (2021). An innovative MOOC platform: the implications of self-directed learning abilities to improve motivation in learning and to support self-regulation. *International Journal of Information and Learning Technology, 38*(3), 283-298.

Page, M. J., McKenzie, J. E., Bossuyt, P. M., Boutron, I., Hoffmann, T. C., Mulrow, C. D., Shamseer, L., Tetzlaff, J. M., Akl, E. A., Brennan, S. E., Chou, R., Glanville, J., Grimshaw, J. M., Hrobjartsson, A., Lalu, M. M., Li, T., Loder, E. W., Mayo-Wilson, E., McDonald, S., . . . Moher, D. (2021). The PRISMA 2020 statement: An updated guideline for reporting systematic reviews. *BMJ, 372*, n71. https://doi.org/10.1136/bmj.n71.

Palaniappan, K., & Noor, N. M. (2022). Gamification strategy to support self-directed learning in an online learning environment. *International Journal of Emerging Technologies in Learning, 17*(3), 104-116.

Pollard, V., Hains-Wesson, R., & Young, K. (2018). Creative teaching in STEM. *Teaching in Higher Education, 23*(2), 178-193.

Prasetio, H., Rosidin, U., & Suyatna, A. (2019). The impact of android based assessment for learning system toward students self-directed learning ability on thermodynamic matter. *Journal of Science Education, 20*(2), 16-19.

Rancourt, A. M. (2012). Assessing academic/intellectual skills in Keene State College's integrative studies program. *The Journal of Assessment and Institutional Effectiveness, 2*(2), 211-262.

Schweder, S., & Raufelder, D. (2019). Positive emotions, learning behavior and teacher support in self-directed learning during adolescence: Do age and gender matter? *Journal of Adolescence, 73*(1), 73-84.

Schweder, S., & Raufelder, D. (2022). Adolescents' expectancy-value profiles in school context: The impact of self-directed learning intervals. *Journal of Adolescence*, *94*(4), 569-586.

Scott, P. H., Veitch, N. J., Gadegaard, H., Mughal, M., Norman, G., & Welsh, M. (2018). Enhancing theoretical understanding of a practical biology course using active and self-directed learning strategies. *Journal of Biological Education, 52*(2), 184-195.

Stemler, S. E. (2015). *Content Analysis*. John Wiley & Sons, Inc.

Sukardjo, M., & Salam, M. (2020). Effect of concept attainment models and self-directed learning (SDL) on mathematics learning outcomes. *International Journal of Instruction, 13*(3), 275-292.

Toh, W., & Kirschner, D. (2020). Self-directed learning in video games, affordances and pedagogical implications for teaching and learning. *Computers & Education*, *154*. https://doi.org/10.1016/j.compedu.2020.103912.

Weber, R. P. (1990). *Basic Content Analysis: Quantitative Applications in the Social Sciences*. Sage Publications, Inc.

Wright, K., & Waxman, H. C. (2022). A multilevel analysis of malleable school and teacher factors contributing to middle grades' teachers use of effective STEM practices. *Educational Studies*, 1-21. https://doi.org/10.1080/03055698.2021.2023474.

Zainuddin, Z., Haruna, H., Li, X., Zhang, Y., & Chu, S. K. W. (2019). A systematic review of flipped classroom empirical evidence from different fields: What are the gaps and future trends? *On the Horizon, 27*(2), 72-86.

Zhu, M. N., & Doo, M. Y. (2022). The relationship among motivation, self-monitoring, self-management, and learning strategies of MOOC learners. *Journal of Computing in Higher Education, 34*(2), 321-342.

Ziegler, E., Edelsbrunner, P. A., & Stern, E. (2021). The benefit of combining teacher-direction with contrasted presentation of algebra principles. *European Journal of Psychology of Education, 36*(1), 187-218.

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