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Self-Directed Learning in STEM Teaching and Learning: A Systematic Review of Empirical Evidence

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ABSTRACT

Despite the growing popularity of self-directed learning (SDL) research, the impacts of this approach on science, technology, engineering, and mathematics teaching and learning (STEM-TL) still need to be well documented. To address this issue, this systematic review analysed and synthesised content from 50 published articles in the form of study characteristics, research methods, learning theories and strategies, technology platforms, impacts, challenges, and research opportunities related to the application of SDL in STEM-TL retrieved from the Web of Science (WoS) database and Scopus within the last five years. The studies examined reveal evidence that the use of SDL in STEM-TL has been quite diverse and holds promise for student success in acquiring and mastering 21st-century skills. Unfortunately, only some studies anticipate other potential concerns, such as early SDL application, student character degeneration, uncontrolled technological progress, and an unknown future educational environment. This systematic review gives a summary of what was found, which can be used to build a framework that teachers, schools, and policymakers can use in current and future STEM-TL settings and curricula.

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

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INTRODUCTION

In response to the problems of the twenty-first century, research on self-directed learning (SDL) is expanding. Especially after the Covid-19 pandemic, which shifted the learning paradigm (Chau et al., 2021; Jeong, 2022; Khodaei et al., 2022; Shao et al., 2022; Sun et al., 2022) from teacher-directed to student-directed learning (Altillo et al., 2021; Schweder & Raufelder, 2021, 2022; Shah et al., 2020; Ziegler et al., 2021).

Nonetheless, many studies on SDL have yet to be well documented, especially to see how SDL influences skills and learning outcomes, what factors give rise to SDL, and how SDL research affects science, technology, engineering, and mathematics teaching and learning (STEM-TL).

STEM has long been characterised as having a close connection with actual problems, student-centred, teamwork-based communication, guidelines in designing processes, and prioritising various correct answer choices to rebuild a failure into meaningful learning (Allen et al., 2016; Arztmann et al., 2022; Aydin Gunbatar et al., 2022; Galoyan & Songer, 2022; LeBeau et al., 2012). It is a multidisciplinary field that necessitates the capacity to think, visualize, imagine, analyse, abstract, and integrate concepts (Arztmann et al., 2022; Fang et al., 2022; Wright & Waxman, 2022; Zoechling et al., 2022). Requirements for problem-solving, critical thinking, and data analysis skills as lifelong learning competencies have altered the demands of STEM in today's modern-day (A. Liu et al., 2022; Melton et al., 2022), posing significant challenges to increasing the quality of teaching and learning. As a result, STEM researchers and authors are now attempting to construct a solid theoretical model of the cognitive and affective parts of STEM to gain a better understanding of how learners engage with their learning environment (Pollard et al., 2018).

SDL is a necessary skill that can be used to increase students' lifelong learning abilities, especially in today's digital age (Boyer et al., 2014; Morris, 2019; Nicoll & Fejes, 2011). According to Tekkol and Demirel (2018), self-directed learning skills are marginally associated with lifelong learning habits and workplace skills such as creativity, communication, and cooperation. Instead of being taught, students should learn how to construct metacognitive learning strategies independently. Self-directed learning is a process in which students take the initiative, with or without the assistance of others, to determine what they need to learn, set learning goals, locate human and material resources for learning, select and apply appropriate learning strategies, and assess how well they learn (Knowles, 1975). Gibbons (2002) believes that Self-directed learning is any self-made increase in knowledge, skill, achievement, or pmersonal growth achieved by any method, in any setting, at any time. Self-directed learning in a pedagogical environment means that students take on most of the tasks that teachers usually do until they plan and do their own learning activities.

SDL also refers to students' mental processes to learn new things and solve their difficulties (Long, 1994). Independent learners often look at online learning resources, do their classwork, and plan and evaluate how they are doing with their learning. Self-management at a high level is essential in SDL, and learners must employ several techniques to deal with various challenges (Palaniappan & Noor, 2022; Zhu & Doo, 2022). SDL is related to self-regulated learning in that it focuses on goal-setting and decision-making, both of which are necessary for students to learn together (Lin et al., 2019). The required skills for each differ between SDL and self-regulated learning (SRL). The required skills for each differ between SDL and self-regulated learning

(SRL). SDL constructions are at the macro level, whereas SRL constructions are at the micro level (Higgins et al., 2021; Kayacan & Ektem, 2019).

Many researchers have used the idea of SDL to try to help students learn on their own in STEM contexts, for example, by using a learning theory approach (Alotaibi & Alanazi, 2021; Bishara, 2021; Geng et al., 2019; Labonte & Smith, 2022), learning strategies (Adinda & Mohib, 2020; Al Mamun et al., 2020; Gerard et al., 2022; Gozzard & Zadnik, 2021), and technologies (Abdullah et al., 2019; Onah et al., 2021; Palaniappan & Noor, 2022; Toh & Kirschner, 2020; Zhu & Bonk, 2019) to assist students in learning independently. However, there is a need for more actual data on the effects of implementing this concept. Based on 50 recently published studies from 2018 to 2022, this systematic literature review assessed and analysed SDL research trends and content to determine the best suggestions for their application to the STEM-TL domain. An analysis was carried out based on the impact of SDL in various areas.

The main goal of this study is to examine empirical evidence regarding the effectiveness of Self-directed learning in teaching Science through systematic review. Specifically, it seeks to answer the following:

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

RQ2 What research methods are commonly 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?

RQ7 What are the future opportunities for SDL research in the context of STEM teaching and learning?

RESEARCH METHODOLOGY

Research Design

Content analysis was used to examine journal articles cited in self-directed learning research from 2018 to 2022. Content analysis is a method that allows qualitative data collected in a study to be analysed systematically and reliably so that generalisations 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 analysing data in content analysis is to prepare, organize, and report.

The use of content analysis in this study is appropriate because it can be used to 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 to investigate 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 figure out how flipped classroom affects learning outcomes, motivation or engagement, self-efficacy, and social interaction in a positive way. 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.

Preparation

Search Strategy

A search technique was developed for this systematic review to locate relevant literature on Self-Directed Learning 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) Self-Directed Learning, (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.

Organization

Selection Criteria

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

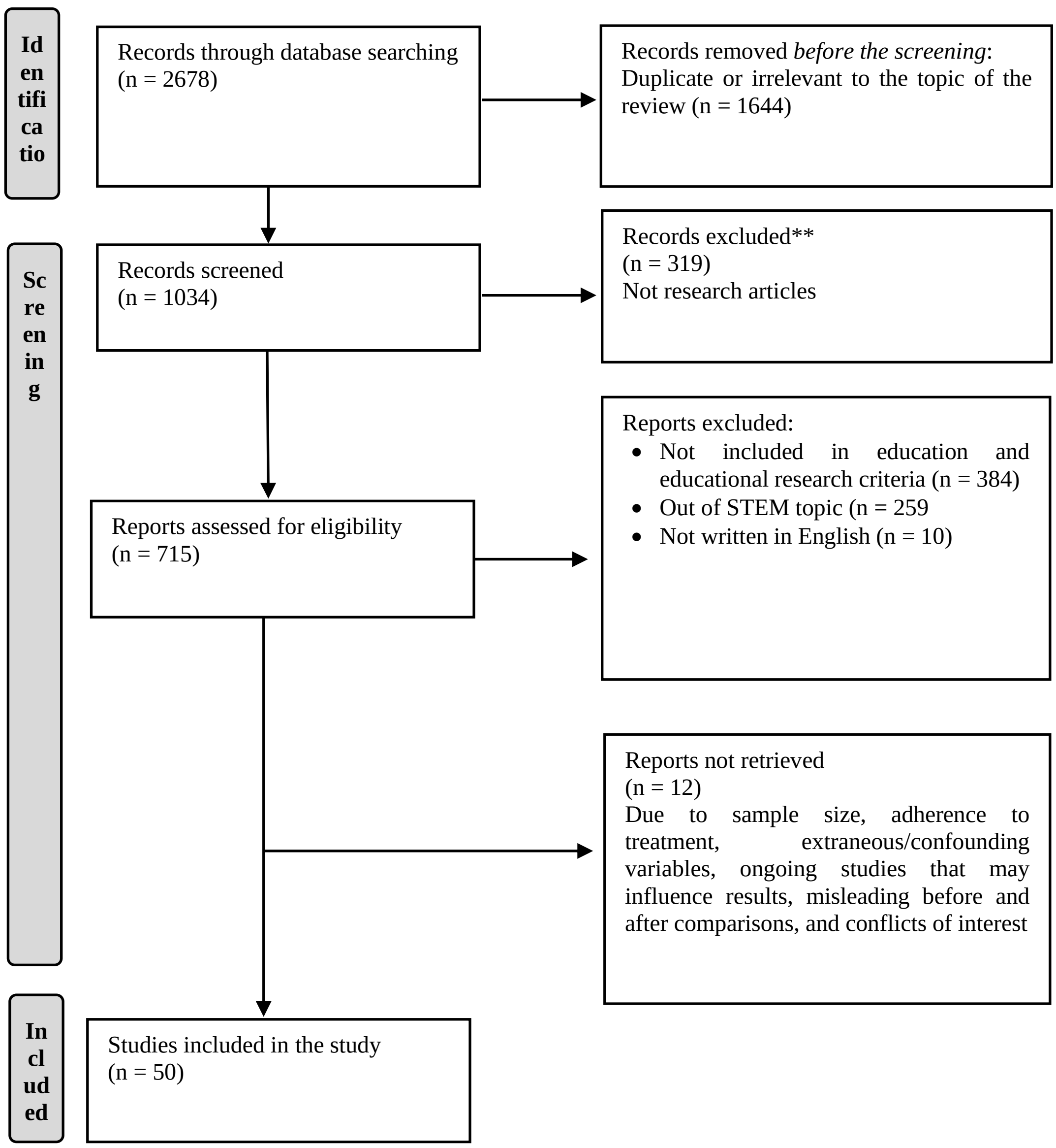
Inclusion Criteria:

- Reported in English.
- Empirical research in the STEM field.
- Journal articles.
- Published between January 2018 and October 2022.
- Regarding the use of SDL in education.
- On the use of SDL, which impacts outcomes (e.g., test scores), and behavioural and affective outcomes (e.g., motivation, attitudes and behaviour, and self-confidence).

Exclusion Criteria:

- Duplicate.
- Constituting a proceeding paper, review article, early access article, editorial material, meeting abstract, book chapter, and letter.
- Available in book chapters, conferences, and grey literature (opinion pieces, technical reports, blogs, presentations, etc.).
- Not a research report at all.
- Description of the intervention and how the intervention could (theoretically) improve outcomes without evaluating outcomes.
- Studies that do not have a precise outcome evaluation.
- Studies with no tangible or measurable results.
- Ethnography, opinion pieces, guide summaries, or manuals.

Figure 1. Study Selection Chart PRISMA 2020 Framework Adapted from Page et al. (2021)



A pre-set sample of articles was then randomly selected and assessed by three assessors to ensure consistency in applying inclusion and exclusion criteria. Inclusion and exclusion criteria were used, and 62 studies were saved (out of 2678) for data extraction. The following factors contributed to the removal of 2616 articles from 2018 to 2022:

- 1544 articles were removed for non-research reasons.
- 319 articles were eliminated because they were not articles.
- 384 publications were eliminated because they were not included in the Education: Educational Research category.
- 259 articles were eliminated because they were not STEM-related (for example, medical, nursing, music, and medicine).
- 10 articles were removed because they were not in English.
- 96 were removed because they were duplicates.
- 4 articles were omitted because it was a literature review.

During the criteria selection phase, study components that may impair or strengthen the internal and external validity of the research were also examined. The details included sample size, treatment adherence, extraneous or confounding variables, ongoing research that could influence the results, misleading before-and-after comparisons, and conflicts of interest, resulting in the omission of 12 articles after the final selection. Finally, 50 articles were archived, and their quality was assessed. The flowchart in Figure 1 shows the number of studies at each stage, from identification and screening to data extraction.

RESULT AND DISCUSSION

A comprehensive literature review with content analysis was conducted on 50 publications published between 2018 and 2022 within the scope of educational research focused on self-directed learning 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 (country, objective, and education level)?

Country

Table 1 depicts the 21 nations identified from the 50 publications examined. With eight articles, the United States has the most SDL investigations in STEM fields, followed by Australia and Indonesia with five, Malaysia, China, South Africa, the United Kingdom, and Turkey with three, Canada, Thailand, Taiwan, and Estonia with two, Slovenia, Spain, Japan, Saudi Arabia, Ireland, Germany, Singapore, and Slovakia with one.

Table 1. Countries that Frequently Investigate SDL in STEM Contexts

Countries	References	Frequencies
USA	(Alwadaeen & Piller, 2022; Bishara, 2021; Brennan, 2021; Gerard et al., 2022; Lim et al., 2018; Marra et al., 2022; Zhu & Kadirova, 2022; Zhu & Bonk, 2019)	8
Australia	(Al Mamun et al., 2020, 2022; Geng et al., 2019; Gozzard & Zadnik, 2021; Mann & Willans, 2020)	5
Indonesia	(Budiastra et al., 2020; Erlina et al., 2022; Prasetio et al., 2019; Rini et al., 2022; Sukardjo & Salam, 2020)	5
Malaysia	(Abdullah et al., 2019; Balakrishnan, 2018; Palaniappan & Noor, 2022)	3
China	(An et al., 2022; Jin et al., 2022; Lin et al., 2019)	3
South Africa	(Jordaan & Havenga, 2020; Mentz & Van Zyl, 2018; Zulu et al., 2018)	3
United Kingdom	(Campbell et al., 2020; Onah et al., 2021; Scott et al., 2018)	3
Turkey	(Kayacan & Ektem, 2019; Kırıkkaya & Yıldırım, 2021; Sumuer, 2018)	3
Canada	(Labonte & Smith, 2022; Power & Goodnough, 2019)	2
Thailand	(Chatwattana, 2021; Threekunprapa & Yasri, 2020)	2
Taiwan	(Chen et al., 2021; H. L. Liu et al., 2022)	2
Estonia	(Uus et al., 2022; Uus et al., 2021)	2
French	(Adinda & Mohib, 2020)	1
Slovenia	(Avsec & Ferk Savec, 2022)	1
Spain	(Blaschke, 2021)	1
Japan	(Li et al., 2021)	1

Saudi Arabia	(Alotaibi & Alanazi, 2021)	1
Ireland	(Newman & Farren, 2018)	1
Germany	(Schweder, 2019)	1
Singapore	(Toh & Kirschner, 2020)	1
Slovakia	(Truchly et al., 2019)	1

The country's educational quality is the crucial factor influencing SDL implementation in various nations in the context of STEM-TL. Countries with excellent educational institutions, such as the United States (Alwadaeen & Piller, 2022; Lim et al., 2018; Marra et al., 2022), Canada (Labonte & Smith, 2022), European countries (Newman & Farren, 2018; Onah et al., 2021), and some Asian countries (Alotaibi & Alanazi, 2021; Chen et al., 2021; Toh & Kirschner, 2020), commonly used SDL to address the needs of ever-increasingly rapid technological developments. Meanwhile, countries with developing educational quality seek to adopt SDL to increase education and academic quality (Erlina et al., 2022; Sukardjo & Salam, 2020).

The twenty-first century brings rapid changes and progress in many areas of life; SDL is frequently cited as a critical skill for surviving in this century. As a result, countries that are sensitive to this modify their education policies swiftly (Chen et al., 2021). The other goal of adapting SDL is to teach the next generation of learners how to think for themselves, ask questions, try again, and be responsible for their own learning.

Objective

Table 2 illustrates five types of objectives that often appear in the 50 papers we examined. The first category contains 21 papers investigating technology use in STEM-TL and its link with SDL. In the second category, 16 articles were discovered that sought to study the relationship between SDL and student or teacher outcomes in the STEM-TL environment. The 13 articles in the third category are intended to investigate the extent to which SDL is a variable at the student, teacher, class, school, or country level. The fourth category contains 12 articles exploring SDL in STEM-TL activities across classrooms, schools, or countries. In the fifth category, two articles were found. Two publications were chosen to study SDL as a variable that can be measured by making learning evaluation instruments.

Table 2. The Objectives SDL in the STEM-TL Research

Objectives	References	Frequencies
Researching the use of technology in STEM Teaching and Learning	(Balakrishnan, 2018; Chatwattana, 2021; Gerard et al., 2022; Kırıkkaya & Yıldırım, 2021; Labonte & Smith, 2022; Li et al., 2021; Lim et al., 2018;	21

and its relationship with SDL	Lin et al., 2019; H. L. Liu et al., 2022; Mentz & Van Zyl, 2018; Newman & Farren, 2018; Onah et al., 2021; Palaniappan & Noor, 2022; Prasetio et al., 2019; Rini et al., 2022; Scott et al., 2018; Sumuer, 2018; Threekunprapa & Yasri, 2020; Toh & Kirschner, 2020; Zhu & Kadirova, 2022; Zhu & Bonk, 2019)	
Investigate the relationship between SDL and student or teacher learning outcomes in the context of STEM Teaching and Learning	(Avsec & Ferk Savec, 2022; Bishara, 2021; Campbell et al., 2020; Geng et al., 2019; Gerard et al., 2022; Jin et al., 2022; Kayacan & Ektem, 2019; Kırıkkaya & Yıldırım, 2021; H. L. Liu et al., 2022; Marra et al., 2022; Palaniappan & Noor, 2022; Power & Goodnough, 2019; Rini et al., 2022; Schweder, 2019; Scott et al., 2018; Sukardjo & Salam, 2020)	16
Examines the extent of SDL as a variable at the student, teacher, class, school, or country level	(Al Mamun et al., 2022; Alotaibi & Alanazi, 2021; Alwadaeen & Piller, 2022; Brennan, 2021; Gozzard & Zadnik, 2021; Mann & Willans, 2020; Marra et al., 2022; Newman & Farren, 2018; Schweder, 2019; Truchly et al., 2019; Uus et al., 2022; Uus et al., 2021; Zulu et al., 2018)	13
Investigate SDL in STEM Teaching and Learning activities across classrooms, schools, or countries	(Abdullah et al., 2019; Adinda & Mohib, 2020; Al Mamun et al., 2020; An et al., 2022; Blaschke, 2021; Chen et al., 2021; Erlina et al., 2022; Jordaan & Havenga, 2020; Marra et al., 2022; Sukardjo & Salam, 2020; Toh & Kirschner, 2020; Uus et al., 2021)	12
Investigate SDL as a variable that can be measured by developing learning evaluation instruments	(Budiastra et al., 2020; Prasetio et al., 2019)	2

This set of objectives serves as the foundation for developing and implementing SDL in the STEM-TL context through problem-solving. For example, in the first category of objectives, Onah et al. (2021) used a more innovative MOOC as a technology to assess its impact on SDL capabilities. Using mixed methods as an exploratory case study, they found that time management, setting learning goals, and techniques for completing assignments when using MOOCs were highly valued variables that could affect individual learning achievement.

Most studies on the impact of STEM-TL technology on SDL imply that teachers and students are not quickly pulled into the intricacies and efficacy of the technology, but that preparedness is more crucial. Alwadaeen and Piller (2022) say that researchers can use three groups of components (physical classroom setting, instruction, diagnostics and evaluation, and social and emotional environment) as a framework to study the factors that affect SDL preparedness.

In terms of the second category of objectives, namely investigating the relationship between SDL and student or teacher learning outcomes in STEM-TL contexts, most research addresses pedagogical techniques to achieve meaningful learning in SDL, i.e., students need to do more than sit and take notes if they want to learn something of value. They must actively participate in autonomous learning. Scott et al. (2018) employed SDL's active technique to improve theoretical comprehension in biology practice. This study found that putting active SDL strategies into challenging biology classes can help students learn much more.

The third category's goal is to investigate the extent to which SDL is a variable at the student, teacher, class, school, or country levels. SDL as a variable contributing to student learning processes can be explored in research focusing on the third group of objectives. For example, Gozzard and Zadnik (2021) discovered that writing down the whole experience of autonomously studying at university in a diary for one semester might create a pleasant learning experience that impacts students' more profound interest in astronomy.

The fourth category examines SDL in STEM-TL activities across classrooms, schools, or countries. Most codified articles fall into this category to disseminate information, transmit structured knowledge, and promote understanding and conceptual change or intellectual development using the teacher's approach model as an SDL instructor in STEM-TL activities. For example, Adinda and Mohib (2020) made a teaching and instructional design method to help students improve their SDL skills in a mixed-learning setting.

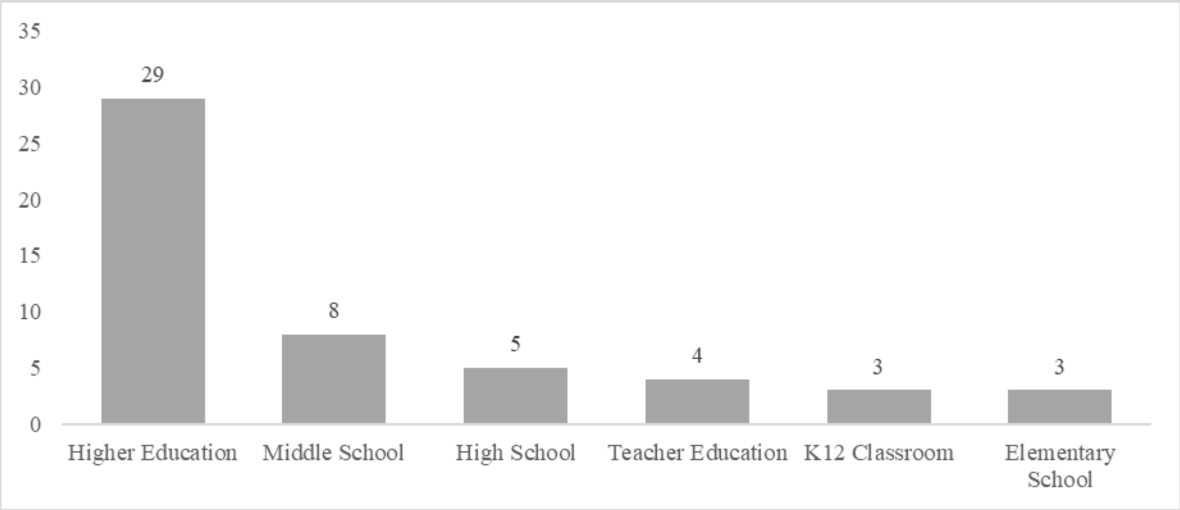
The fifth category aims to explore SDL as a variable that can be quantified by creating learning evaluation instruments. Only two of the 50 papers fall into this category: studies on the validity of new-generation SDL learning devices in elementary science (Budiastra et al., 2020) and studies on the effects of mobile-based evaluations on SDL in physics (Prasetio et al., 2019). Based on how people learn in some countries, like Indonesia, these studies can be used as an alternative way to measure learning.

Education Level

The educational levels found in the STEM-TL SDL study were 29 in higher education, 8 in middle school, 5 in high school, 4 in teacher education, 3 in K–12 classrooms, and 3 in elementary school. Figure 2 also explains that SDL investigations in schools appear to be of little interest when compared to higher education and adults.

This gap can motivate researchers to build SDL competencies in primary and secondary education STEM classrooms because there is a need to understand students' perceptions of their abilities to engage in SDL, both with and without technology (Labonte & Smith, 2022). Morris and Rohs (2021) say that pedagogical techniques that encourage SDL in the classroom can be built on and improved by looking at how much SDL students use in elementary and secondary school in different settings.

Figure 2. Identification of Educational Levels from 50 Articles



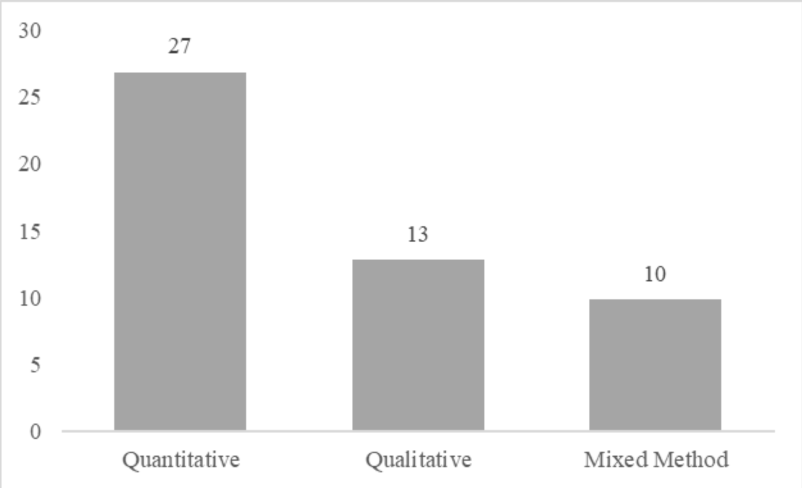
Education levels correlate not only with differing levels of human mental maturity but also with learning. Although thinking maturity is frequently associated with age and gender, studies by Heo and Han (2017) and Schweder and Raufelder (2019) show that SDL skills are also related to education level. Also, at each level, the learning environment is different, which adds depth and helps develop SDL skills.

In their study, Heo and Han (2017) discovered that, whereas age determines education level, it does not significantly correspond with SDL level. Nonetheless, according to this study, the function of the teacher at each educational level will enable all students to continue to lead themselves and have positive control over their learning decisions. This finding is supported by Schweder and Raufelder (2019) discovery that students, regardless of gender or age, gain from instructor support in SDL. Instructors, for example, can look up the learning diaries that students must keep and refer to personally established learning goals, learning actions, learning outcomes, and other indicators to provide guidance and assistance as needed while assisting students with SDL. It also acts as a foundation for both good feedback and criticism. Teachers can also help students think about the SDL process often and either keep going with a clear mind or change the process as needed.

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

Figure 3 depicts an analysis of the types of research methodologies utilised in the examined papers, as classified by Fraenkel et al. (2011). A quantitative research approach was employed in 27 studies to describe and understand how SDL is used in STEM classes. The most prevalent research method was the qualitative research design in 13 studies. This strategy focuses on learning more about how SDL is used in STEM classes by using unstructured and non-numerical data. A mixed methods research design with ten studies is the last and most popular method. This method uses both quantitative and qualitative research to give the researcher a full picture of the problem being studied.

Figure 3. The Distribution of Articles based on Research Methods



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

The empirical studies assessed provide explicit and implicit information regarding the learning theories that underpin their research and the learning strategies they employ when applying SDL to STEM-TL in their studies. Tables 3 and 4 present various learning theories and strategies.

Researchers must comprehend instructional pedagogy and incorporate instructional design concepts, theory, and practice to significantly contribute to their study. To provide the best learning experience for students, researchers must examine the many techniques used by students for learning in their research results. By doing so, researchers can determine how SDL skills can grow in STEM-TL practice.

In addition, good research must be based on learning theory and implemented using instructional design concepts. The learning process will be perceived as defective if the instructional design is not based on learning theory. According to Bruner (1966), a theory of instruction must include four key components that describe the following: 1) experiences that instil in students a desire to learn; 2) how the learning set is to be understood; 3) the most efficient order of material to be presented and studied, and 4) the nature and speed of rewards and punishments in the learning process. A pedagogical perspective like this is authoritarian because it is related to selecting the most effective way to achieve learning goals. It is also normative because it requires setting.

Table 3. Underlying Theories in SDL Research

Theories	**References**	**Frequencies**
Behaviourism	(Abdullah et al., 2019; Adinda & Mohib, 2020; Alwadaeen & Piller, 2022; An et al., 2022; Brennan, 2021; Campbell et al., 2020; Chatwattana, 2021; Chen et al., 2021; Geng et al., 2019; Gozzard & Zadnik, 2021; Labonte & Smith, 2022; Li et al., 2021; H. L. Liu et al., 2022; Marra et al., 2022; Newman & Farren, 2018; Onah et al., 2021; Palaniappan & Noor, 2022; Schweder, 2019; Scott et al., 2018; Sukardjo & Salam, 2020; Sumuer, 2018; Toh & Kirschner, 2020; Truchly et al., 2019; Uus et al., 2022; Uus et al., 2021)	25
Social Cognitive	(Adinda & Mohib, 2020; Alwadaeen & Piller, 2022; An et al., 2022; Avsec & Ferk Savec, 2022; Balakrishnan, 2018; Brennan, 2021; Campbell et al., 2020; Chatwattana, 2021; Gozzard & Zadnik, 2021; Kayacan & Ektem, 2019; Kırıkkaya & Yıldırım, 2021; Li et al., 2021; H. L. Liu et al., 2022; Mann & Willans, 2020; Palaniappan & Noor, 2022; Rini et al., 2022; Schweder, 2019; Scott et al., 2018; Toh & Kirschner, 2020; Truchly et al., 2019; Uus et al., 2021)	21
Social constructivism	(Abdullah et al., 2019; Alotaibi & Alanazi, 2021; Alwadaeen & Piller, 2022; An et al., 2022; Bishara, 2021; Blaschke, 2021; Chen et al., 2021; Erlina et al., 2022; Geng et al., 2019; Gerard et al., 2022; Jordaan & Havenga, 2020; Labonte & Smith, 2022; Lin et al., 2019; Mentz & Van Zyl, 2018; Newman & Farren, 2018; Sukardjo & Salam, 2020; Sumuer, 2018; Uus et al., 2022)	18
Engagement	(Abdullah et al., 2019; An et al., 2022; Blaschke, 2021; Campbell et al., 2020; Chatwattana, 2021; Gerard et al., 2022; Gozzard & Zadnik, 2021;	15

	Kırıkkaya & Yıldırım, 2021; H. L. Liu et al., 2022; Palaniappan & Noor, 2022; Prasetio et al., 2019; Rini et al., 2022; Scott et al., 2018; Toh & Kirschner, 2020; Truchly et al., 2019)	
Constructivism	(Al Mamun et al., 2020; Alotaibi & Alanazi, 2021; Bishara, 2021; Erlina et al., 2022; Geng et al., 2019; Labonte & Smith, 2022; Lim et al., 2018; Marra et al., 2022; Onah et al., 2021; Threekunprapa & Yasri, 2020; Zhu & Kadirova, 2022; Zulu et al., 2018)	12
Self-theory	(Blaschke, 2021; Jin et al., 2022; Lim et al., 2018; Lin et al., 2019; Newman & Farren, 2018; Power & Goodnough, 2019; Schweder, 2019; Toh & Kirschner, 2020; Zhu & Bonk, 2019)	9
Malone and Lepper's taxonomy of motivation	(Alotaibi & Alanazi, 2021; Alwadaeen & Piller, 2022; Bishara, 2021; Campbell et al., 2020; Schweder, 2019)	5
Cognitive stage	(Budiastra et al., 2020; Prasetio et al., 2019; Sukardjo & Salam, 2020; Uus et al., 2021)	4
Zone of proximal development (ZPD)	(Brennan, 2021; Scott et al., 2018; Zulu et al., 2018)	3
Online collaborative learning	(Chatwattana, 2021; Kırıkkaya & Yıldırım, 2021)	2
Meaningful learning	(Al Mamun et al., 2022; Brennan, 2021)	2
Control-value	(An et al., 2022)	1

Overall, the studies we analysed sought to accomplish effective SDL and were based on learning principles and methodologies appropriate for their study goals. The following are the key findings from the papers we examined: 1. Prior knowledge of a learner can either aid or hinder learning; 2. encouragement determines, directs, and sustains what students do to learn; 3. the arrangement of students' knowledge impacts how they learn and use what they know; 4. to build mastery, students must absorb ability components, practise integrating them, and understand when to apply what they have learned. Goal-directed exercises paired with tailored feedback promote student learning; 6. interactions between students and their social, emotional, and intellectual environments are intended to affect their autonomous learning; and 7. to become independent learners, students must learn to monitor and adapt their learning process.

Table 4. The Strategies Used in Combining SDL in STEM-TL

Strategies	**References**	**Frequencies**
Self-directed learning strategy	(Alwadaeen & Piller, 2022; Balakrishnan, 2018; Bishara, 2021; Campbell et al., 2020; Chatwattana, 2021; Gozzard & Zadnik, 2021; Jin et al., 2022; Jordaan & Havenga, 2020; Labonte & Smith, 2022; Li et al., 2021; Lim et al., 2018; Lin et al., 2019; Power & Goodnough, 2019; Scott et al., 2018; Sumuer, 2018; Zhu & Bonk, 2019; Zulu et al., 2018)	17
Online-Based Learning	(Al Mamun et al., 2020, 2022; Blaschke, 2021; Jin et al., 2022; Kırıkkaya & Yıldırım, 2021; Prasetio et al., 2019; Rini et al., 2022; Zhu & Kadirova, 2022; Zhu & Bonk, 2019)	9
Problem-based learning	(Abdullah et al., 2019; Mann & Willans, 2020; Marra et al., 2022; Schweder, 2019; Threekunprapa & Yasri, 2020)	5
Game-based learning	(H. L. Liu et al., 2022; Palaniappan & Noor, 2022; Toh & Kirschner, 2020; Truchly et al., 2019)	4
Blended learning	(Adinda & Mohib, 2020; Erlina et al., 2022; Geng et al., 2019; Onah et al., 2021)	4
Inquiry-based learning	(Al Mamun et al., 2020, 2022; Gerard et al., 2022)	3
Design-based learning	(Uus et al., 2022; Uus et al., 2021)	2
Project-based learning	(Blaschke, 2021; Sukardjo & Salam, 2020)	2
Collaborative learning	(Labonte & Smith, 2022; Lin et al., 2019)	2
Research-based learning	(Newman & Farren, 2018)	1
Cooperative learning	(Mentz & Van Zyl, 2018)	1

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

All the research we analysed agreed that technology is critical in developing students' SDL skills. The use of information and communication technology for learning activities that allow students to organize, implement, and analyse their learning is referred to as SDL technology. For example, Toh and Kirschner (2020) presented research that indicated the potential of video games in SDL. Video games are entertaining and have characteristics that aid students' abilities to study independently, such as the presence of a safe space and an authentic learning environment. Digital environments, such as video games, can be utilised to develop students' capacity for independent learning. To make a coding system for player self-learning methods, participant play recordings were evaluated using user experience methods like interviews and "think-aloud" procedures.

This study uncovered a series of criteria that encourage players to learn independently in video games based on their experience as players in three aspects, namely: 1. the meta-behavior aspect, where students will do trial and error, observation and modelling, and reinforcement learning; 2. the meta-cognition aspect, where students will do connected learning, reflect and improve, logical and analytic reasoning, inquiry-based learning, and synthesis; and 3. the meta-emotional aspect, where students will practise dissatisfaction, anger, curiosity, and satisfaction as meta-emotional aspects. Using this paradigm, game designers and educators can evaluate the educational potential of games to enhance students' independent learning activities. By employing the proposed self-learning strategy framework as a coding scheme in a user experience study, teachers and researchers can get an empirical basis for understanding which games can be used in formal or informal situations to practise specific self-learning techniques. Also, teachers and researchers can use coding schemes to study how low-level self-learning strategies can help people learn throughout their lives.

Table 5. Technology Platforms in SDL Research in STEM-TL

Technology		**References**	**Frequencies**
Platforms	**Types**		
Computer-supported	Web-based	(Al Mamun et al., 2020, 2022; Alwadaeen & Piller, 2022; Avsec & Ferk Savec, 2022; Balakrishnan, 2018; Blaschke, 2021; Erlina et al., 2022; Gerard et al., 2022; Jin et al., 2022; Kırıkkaya & Yıldırım, 2021; Labonte & Smith, 2022; Lim et al., 2018; Sumuer, 2018)	13
	Learning management	(Adinda & Mohib, 2020; Erlina et al., 2022; Geng et al., 2019; Labonte & Smith,	7

	system	2022; Li et al., 2021; H. L. Liu et al., 2022; Rini et al., 2022)	
	MOOCs	(Blaschke, 2021; Chatwattana, 2021; Chen et al., 2021; Onah et al., 2021; Zhu & Kadirova, 2022; Zhu & Bonk, 2019)	6
	Youtube™	(Blaschke, 2021; Lim et al., 2018; Scott et al., 2018; Zhu & Kadirova, 2022)	4
	Computer applications	(An et al., 2022; Brennan, 2021; Mentz & Van Zyl, 2018; Threekunprapa & Yasri, 2020)	4
	Microsoft excel™	(Campbell et al., 2020)	1
	Video game	(Toh & Kirschner, 2020)	1
	Virtual laboratory	(Truchly et al., 2019)	1
Mobile Based	Mobile gaming	(Palaniappan & Noor, 2022)	1
	Virtual reality	(Abdullah et al., 2019)	1
	Mobile application	(Prasetio et al., 2019)	1
	Mobile-assisted seamless science learning	(Lin et al., 2019)	1

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

Without learning outcomes, teaching and learning are often incomplete. Learning outcomes instruct teachers on the meaning of learning from the student's perspective and how it should be handled, as well as those who want to learn about how learning may be applied in real life. To identify learning outcomes, we must look at them through the eyes of the learner. Learning outcomes are statements that employ illustrative phrases to show what students should have learned, understood, or been able to achieve after a specific time period (Birtwistle et al., 2016). As a result, learning outcomes will explain what students will know, how they will think, and what they will be able to do after engaging in learning or completing tasks.

Table 6. The Impact of the Relationship between SDL and STEM-TL on Learning Outcomes

Learning Outcomes	References	Frequencies
Self-Directed Learning Skills	(Adinda & Mohib, 2020; Al Mamun et al., 2020, 2022; Blaschke, 2021; Erlina et al., 2022; Geng et al., 2019; Jin et al., 2022; Jordaan & Havenga, 2020; Marra et al., 2022; Mentz & Van Zyl, 2018; Newman & Farren, 2018; Onah et al., 2021; Prasetio et al., 2019; Truchly et al., 2019; Zhu & Bonk, 2019)	15
Achievement in knowledge	(Al Mamun et al., 2020, 2022; Alotaibi & Alanazi, 2021; Bishara, 2021; Erlina et al., 2022; Geng et al., 2019; Gozzard & Zadnik, 2021; Jin et al., 2022; Kırıkkaya & Yıldırım, 2021; Palaniappan & Noor, 2022; Scott et al., 2018; Sukardjo & Salam, 2020; Truchly et al., 2019; Uus et al., 2022)	14
Motivation	(Balakrishnan, 2018; Geng et al., 2019; Lim et al., 2018; Onah et al., 2021; Palaniappan & Noor, 2022; Power & Goodnough, 2019; Schweder, 2019)	7
Attitude	(Bishara, 2021; Gozzard & Zadnik, 2021; Kayacan & Ektem, 2019; H. L. Liu et al., 2022; Mann & Willans, 2020; Uus et al., 2021)	6
Self-directed Learning Readiness	(Alwadaeen & Piller, 2022; Chen et al., 2021; Kayacan & Ektem, 2019; Sumuer, 2018)	4
Digital Literacy Skills	(Chatwattana, 2021; Lim et al., 2018; Rini et al., 2022; Sumuer, 2018)	4
Students' perception	(Labonte & Smith, 2022; Li et al., 2021; Zhu & Kadirova, 2022)	3
Problem-solving skills	(Campbell et al., 2020; Lim et al., 2018)	2
Self-efficacy	(Lin et al., 2019; Sumuer, 2018)	2
Creativity	(Jin et al., 2022)	1
Critical thinking	(Jin et al., 2022)	1

Curiosity	(Al Mamun et al., 2022)	1
Group work skill	(Abdullah et al., 2019)	1
Science process skills	(Kayacan & Ektem, 2019)	1
Design Thinking Ability	(Avsec & Ferk Savec, 2022)	1
Awareness	(Avsec & Ferk Savec, 2022)	1
Interpersonal Skills	(Avsec & Ferk Savec, 2022)	1
Metacognition	(Marra et al., 2022)	1
Computational thinking	(Threekunprapa & Yasri, 2020)	1
Cognitive loading	(Zulu et al., 2018)	1

In general, the empirical papers we analysed focused on the impact of SDL in STEM-TL, specifically on learning outcomes. Table 6 displays the impact categories derived from the fifty publications examined. We have classified the impacts into three learning outcomes: 1. intellectual skills, namely problem-solving skills, self-directed learning skills, cognitive loading, digital literacy skills, group work skills, critical thinking, computational thinking, creativity, and knowledge achievement; 2. cognitive strategies, namely science process skills, interpersonal skills, metacognition, design thinking ability, and awareness; and 3. motivation, attitude, self-directed learning readiness, self-efficacy, curiosity, and students' perceptions.

Intellectual skills are the capacity to comprehend how to perform something (Donald, 1985; Rancourt, 2012). The term essentially refers to knowledge. Jin et al. (2022) found that the online self-directed learning environment (OSDLE) that was used considerably improved students' creative performance. Students who use OSDLE are not passive absorbers of knowledge. Instead, they hunt for the best learning resources for their specific needs. This strategy allows students to understand more about things, which can lead to innovative results. Students who have utilised OSDLE can also assess their learning limitations and actively reflect on problem-solving to encourage creativity. OSDLE incorporates input from teachers and peers; feedback from teachers and peers is critical to promoting student creativity. Students have access to teacher comments as well as peer work samples. Students can also critique their OSDLE abilities and knowledge to make room for new ideas and possibilities, which is an essential skill for fostering creativity. Students can choose whether or not to share their reflection journals. The reflection module encourages critical thinking, active debate, and reflective practice. Students use online reflective diaries to think about what they've learned and come up with new ideas based on what they've already done.

Cognitive strategies and intellectual skills are distinct concepts that are frequently confused. According to Dinsmore and Fryer (2019), cognitive strategies include ways of thinking and attitudes about work that are unique to specific professions. It is the ability to combine new and previously acquired knowledge. Kayacan and Ektem (2019) discovered that a biology practicum supplemented with independent learning methodologies substantially impacted students' preparation for independent learning and their attitudes toward science projects. The laboratory encourages students to take ownership of their learning and organise their knowledge. In this way, using self-directed learning techniques in the biology lab will help create an environment where students have more to do and are responsible for their own learning.

The outcome of attitude measures the student's internal condition, which represents the impact of new knowledge, abilities, and experiences on the student's personality (Albarracin & Johnson, 2019). We have studied research that uses attitude as the dependent variable, such as those conducted by Gozzard and Zadnik (2021). This study discovered that most students had positive experiences when undertaking independent learning in astronomy lectures using daily observation books. The impact of this activity on astronomy learning and students' attitudes toward astronomy and science was assessed using an astronomy concept diagnostic test and an attitude survey administered at the start and end of the semester. The results were compared to similar introductory astronomy courses that did not use daily observation books. Daily observation books provide a very positive experience for students who dislike traditional study assessment systems and tests. Furthermore, the book revealed deficiencies in students who were more familiar with traditional procedures, which can be viewed as a positive given the better growth in students' grasp of essential astronomical topics than without the daily observation books.

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

SDL is not a novel educational technique. However, the difficulties associated with adopting it in STEM TL have not been generally acknowledged or reported. These difficulties are revealed explicitly or implicitly in the fifty publications we analysed. Table 7 contains examples of these types of issues.

According to this systematic literature, the most challenging problem in applying SDL in STEM TL is providing a proper educational environment at all levels of education. In SDL, the educational environment represents the operational description of the curriculum notion, which covers everything around the learner (Bahrami et al., 2022). The learning environment and student behaviour are interrelated. These two things are also determining factors for learning motivation within the scope of SDL, so it can be ascertained that the educational environment in SDL will affect student achievement (Kim et al., 2014).

Another significant problem in implementing SDL in STEM TL is technological distraction. The use of technology improves SDL implementation significantly (see Table 5). PCs and smartphones are crucial tools in SDL, but they can divert learners' attention away from their goals while studying alone. As a result, students must maintain awareness, either through increased self-awareness or with the assistance of others, such as parents, friends, and teachers. Cheong et al. (2016) provide an idea about managing student distraction in a learning environment with technology through their research, namely that teachers should build their dominance with various forms of communication, such as codified rules, intentional transference, discursive punishment, and deflection.

Learning autonomy, at the heart of SDL in the STEM-TL field, also presents a barrier for students learning complicated concepts, such as mathematics. According to Alotaibi and Alanazi (2021), students' ability to absorb mathematical concepts in an independent learning environment significantly impacts learning results in mathematics. Students must adopt a learning method when studying complex mathematical concepts within the context of SDL. As a theoretical framework, Dolmans et al. (2015) developed a student learning strategy. This framework was created using a deep learning method. Deep and superficial learning methods combine student intent (motives) and supporting learning activities. The surface approach to learning is typically defined as the desire to duplicate material through a memorization-based learning process. Deep learning is a student's goal of grasping the content, connecting and organising concepts, seeking underlying principles, weighing relevant evidence, and critically evaluating knowledge.

The abundance of learning resources available on the internet creates a typical difficulty, namely communication. Several studies have connected SDL to STEM-TL in countries whose education is not particularly advanced and who tend to seek learning resources other than their country's language. Thus, students must take several steps to understand the language. For example, a study by Kırıkkaya and Yıldırım (2021) from Turkey complained about Web 2.0 learning tools that did not support their country's language. Similarly, Erlina et al. (2022) created training materials for Indonesian students studying atomic physics to strengthen SDL skills in distance learning.

Another problem that becomes a challenge is time. Research that we studied shows that the time in SDL feels quite long, which might lead to students becoming complacent and delaying their goals. Furthermore, some studies revealed obstacles in the form of a lack of group-work abilities, so Abdullah et al. (2019) undertook research to address this by creating a virtual reality environment that can increase students' ability to work in groups. The third difficulty we discovered was information overload. Therefore, students must have digital literacy skills to assist them in choosing the best learning resources to meet their learning objectives. Mentoring was highlighted as the final challenge. Schools and tertiary institutions are supposed to support students and teachers through guidance and monitoring in the SDL environment rather than simply letting them go.

Table 7. The Challenges in Implementing SDL in the STEM-TL Domain

Challenges	**References**	**Frequencies**
Educational environment	(Adinda & Mohib, 2020; Al Mamun et al., 2022; Alwadaeen & Piller, 2022; Avsec & Ferk Savec, 2022; Balakrishnan, 2018; Blaschke, 2021; Chatwattana, 2021; Chen et al., 2021; Erlina et al., 2022; Gozzard & Zadnik, 2021; Jin et al., 2022; Jordaan & Havenga, 2020; Kayacan & Ektem, 2019; Kırıkkaya & Yıldırım, 2021; Labonte & Smith, 2022; H. L. Liu et al., 2022; Mentz & Van Zyl, 2018; Newman & Farren, 2018; Onah et al., 2021; Palaniappan & Noor, 2022; Schweder, 2019; Scott et al., 2018; Sumuer, 2018; Toh & Kirschner, 2020; Truchly et al., 2019; Uus et al., 2022; Uus et al., 2021; Zhu & Bonk, 2019)	28
Distraction due to technology	(Abdullah et al., 2019; Al Mamun et al., 2020; Alwadaeen & Piller, 2022; An et al., 2022; Balakrishnan, 2018; Chatwattana, 2021; Geng et al., 2019; Kırıkkaya & Yıldırım, 2021; Labonte & Smith, 2022; Lim et al., 2018; Lin et al., 2019; Mentz & Van Zyl, 2018; Onah et al., 2021; Palaniappan & Noor, 2022; Prasetio et al., 2019; Rini et al., 2022; Sumuer, 2018; Threekunprapa & Yasri, 2020; Toh & Kirschner, 2020; Truchly et al., 2019; Zhu & Kadirova, 2022; Zhu & Bonk, 2019)	22
Difficulty in learning complex Concepts	(Alotaibi & Alanazi, 2021; Alwadaeen & Piller, 2022; Bishara, 2021; Campbell et al., 2020; Erlina et al., 2022; Gozzard & Zadnik, 2021; Jordaan & Havenga, 2020; Mann & Willans, 2020; Scott et al., 2018; Sukardjo & Salam, 2020; Threekunprapa & Yasri, 2020; Uus et al., 2021; Zhu & Kadirova, 2022; Zulu et al., 2018)	14
Communication barriers	(Al Mamun et al., 2022; Erlina et al., 2022; Kırıkkaya & Yıldırım, 2021; Labonte & Smith, 2022; Lin et al., 2019; Marra et al., 2022; Rini et al., 2022; Sumuer, 2018; Zhu & Kadirova, 2022)	9

Time constraints	(Alotaibi & Alanazi, 2021; Brennan, 2021; Lim et al., 2018; Marra et al., 2022; Power & Goodnough, 2019)	5
Lack of organizational skills	(Abdullah et al., 2019; Brennan, 2021; Gozzard & Zadnik, 2021; Li et al., 2021; Lim et al., 2018)	5
Information overload	(Al Mamun et al., 2020; Alwadaeen & Piller, 2022; An et al., 2022; Li et al., 2021; Rini et al., 2022)	5
Faculty guidance	(Gerard et al., 2022)	1

Research Question 7: What are the future opportunities for SDL research in the context of STEM teaching and learning?

All the examined research recognises that what they investigate is far from perfect, so they propose several things for future researchers to investigate further about the application of SDL in the context of STEM-TL. Table 8 lists the proposals they make as research options.

Some of the topics discussed in this part, such as the use of multiple or more sophisticated research method techniques in studying SDL in the STEM-TL sector, are research directions that demonstrate that no research method approach can explain all situations in general. Using various study method approaches will finally offer a more straightforward pattern for the application of SDL in STEM-TL. This technique can take the form of recommendations for researching multiple subjects, conducting mixed-method research, or conducting longitudinal studies. The goal is to revisit and expand on theories, frameworks, or models discussed in prior studies. The debate over using SDL in STEM-TL by experimenting with other or more complicated research method approaches appears to be an exciting future research direction.

A more thorough and critical examination of other aspects can potentially influence SDL in STEM-TL. Based on the variables analysed, several studies we reviewed believe that their reasons for solving research questions were not carried out critically and thoroughly. Furthermore, they advise that a more comprehensive evaluation includes assessing the findings in new circumstances, such as analysing external events that may arise and how other variables can change SDL subjects in STEM-TL.

Several studies we analysed also suggested that future studies should consider students' initial conditions. For example, in the STEM sector, initial learning motivation, initial grasp of scientific concepts, and initial understanding of the technology used in SDL. This is related to students' self-concept in responding to a new culture (in this case, SDL) that is indirectly imposed on them. As a result, future studies can foresee problems resulting from students' beginning circumstances.

Finally, the limited use of SDL in STEM TL technology in several of the studies we analysed suggests that more complicated technological integration is needed. This suggestion is expected to expose the flaws in prior technology, resulting in an independent learning environment with better-suited technology.

Table 8. SDL Research Opportunities in the STEM Domain

Research Opportunities	**References**	**Frequencies**
Application of different or more complex research methods	(Al Mamun et al., 2020; Alotaibi & Alanazi, 2021; An et al., 2022; Avsec & Ferk Savec, 2022; Bishara, 2021; Brennan, 2021; Chen et al., 2021; Erlina et al., 2022; Gerard et al., 2022; Jin et al., 2022; Kırıkkaya & Yıldırım, 2021; Labonte & Smith, 2022; Lim et al., 2018; Marra et al., 2022; Mentz & Van Zyl, 2018; Onah et al., 2021; Palaniappan & Noor, 2022; Power & Goodnough, 2019; Schweder, 2019; Sumuer, 2018; Threekunprapa & Yasri, 2020; Toh & Kirschner, 2020; Zhu & Kadirova, 2022; Zhu & Bonk, 2019; Zulu et al., 2018)	25
More comprehensive investigation	(Adinda & Mohib, 2020; Al Mamun et al., 2020, 2022; Alotaibi & Alanazi, 2021; Avsec & Ferk Savec, 2022; Chen et al., 2021; Geng et al., 2019; Gozzard & Zadnik, 2021; Kayacan & Ektem, 2019; Labonte & Smith, 2022; Li et al., 2021; Lin et al., 2019; Threekunprapa & Yasri, 2020; Toh & Kirschner, 2020; Uus et al., 2022; Uus et al., 2021; Zhu & Kadirova, 2022; Zulu et al., 2018)	18
Different initial conditioning	(Bishara, 2021; Li et al., 2021; Marra et al., 2022; Onah et al., 2021; Power & Goodnough, 2019; Schweder, 2019; Sukardjo & Salam, 2020; Toh & Kirschner, 2020; Zhu & Bonk, 2019)	9
More complex technology integration	(Abdullah et al., 2019; Balakrishnan, 2018; Budiastra et al., 2020; Gerard et al., 2022; Jordaan & Havenga, 2020; Li et al., 2021)	6

CONCLUSION

This systematic review was conducted to analyse empirical evidence regarding the application of self-directed learning in the STEM field from 50 articles published between 2018 and 2022, specifically by knowing the data characteristics in the form of the country of research, research objectives, and level of education. Other purposes are to learn about research techniques, theories, and approaches; the technology employed; the beneficial impact of the interaction between SDL and STEM-TL; problems in adopting SDL in STEM-TL; and ultimately, the SDL research potential in STEM.

The findings reveal that the application of SDL in STEM-TL has been accepted by many nations worldwide, with American and European dominance, and that most research methodologies are used to explore the relationship between SDL and the use of technology at various levels of education. The researchers also discovered that the implementation of SDL in the STEM field is done mainly at the higher education level, with few students being prepared to learn independently from an early age. Since SDL is an important skill for students to have in the 21st century, this evidence can be used by future researchers who want to learn more about SDL in the STEM field at the secondary education level.

The analysed literature frequently employs theories, learning process types, and technological platforms. However, learning theories, strategies, and technology are favourable to researchers without specifically reviewing what students already have, in this case, self-concept, learning style, initial motivation, technology mastery, and their initial conception of a specific learning topic. This information can help researchers in the future predict a number of problems that could affect how SDL is used in the STEM-TL field.

Another conclusion was that most of the literature studied looked into the effect of applying SDL in STEM-TL on learning outcomes. However, most focus on the cognitive part, with a few exceptions on the attitude aspect, considering the psychomotor aspect. Since learning outcomes are made up of three parts (cognitive, affective, and psychomotor), these results can be used as a basis for future research on how SDL affects attitude and psychomotor domains in STEM-TL.

Finally, all the articles discussed the obstacles and opportunities of applying SDL in STEM-TL, either directly or indirectly. So, the problems seen may be of interest to teachers, schools, and policymakers when they set up a curriculum for self-directed learning. They may also be of interest to future researchers when they face problems and opportunities when studying SDL in the STEM-TL sector.

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