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A meta-analysis of interdisciplinary teaching abilities among elementary and secondary school STEM teachers

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Abstract

Background In the context of global educational reform, science, technology, engineering, and math (STEM) education, as an interdisciplinary educational model, has become increasingly central to foundational pedagogical reforms. However, research on the impact and development of STEM teachers' interdisciplinary teaching abilities is relatively limited. This meta-analysis explored STEM education's impact on elementary and secondary school teachers' interdisciplinary teaching abilities. The review encompassed 21 empirical studies published between 2010 and 2023 and aimed to quantify the effect size of STEM interventions on teachers' interdisciplinary abilities.

Results A moderately positive correlation (r = 0.452) was found between STEM education and teachers' interdisciplinary teaching abilities. The role of potential moderating variables, including demographic traits, gender, academic qualifications, subject specialization, pedagogical tenure, and prior exposure to interdisciplinary learning, was scrutinized. The findings highlighted a substantial improvement in teachers' interdisciplinary teaching abilities through STEM education, emphasizing the critical role of knowledge integration. STEM programs significantly aided educators in bridging and amalgamating diverse disciplinary insights. Variations in the efficacy of STEM education across different educational tiers, subject domains, levels of teaching seniority, and interdisciplinary familiarity were identified, indicating that the benefits of STEM training were contingent upon individual teacher profiles. Notably, gender disparities in the enhancement of interdisciplinary teaching abilities through STEM education were not observed. Despite the methodological diversity of the included studies, which encompassed various research paradigms, sampling strategies, and evaluation instruments, the integration of findings across these diverse methodologies added intricacy to the interpretation of the meta-analytic results. The study's potential limitations, such as the risk of sample selection bias and the use of potentially imprecise assessment tools, were acknowledged as possibly having influenced the meta-analytic outcomes.

Conclusions The findings had two implications. First, they provided a roadmap for the strategic design and execution of STEM initiatives aimed at fostering excellence in interdisciplinary teaching. Second, they highlighted the imperative for tailored approaches to the development of STEM teachers, which recognize the heterogeneous needs and potential based on their unique professional and experiential backgrounds.

Keywords STEM education, Teachers, Interdisciplinary teaching abilities, Meta-analysis

Introduction

Given the rapid development of technology and the transformation of the global economy, the United Nations Educational, Scientific and Cultural Organization's (UNESCO) Education 2030 agenda underscores the pivotal role of interdisciplinary teaching abilities

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in educational reform, deeming them crucial for cultivating students' comprehensive abilities and preparing them to meet future challenges (Marope, 2016). In this context, science, technology, engineering, and math (STEM) education, as an interdisciplinary educational model, has emerged as a critical focus of foundational pedagogical reforms in many countries. STEM education requires that instructors integrate knowledge and skills from these disciplines to foster students' innovative thinking, problem-solving ability, and sense of teamwork. This approach aims to better equip students to adapt to the future demands and challenges of society (Lin et al., 2023). Within the framework of traditional education, which encompasses specialized disciplines, teacher training in interdisciplinary instruction is often constrained. This limitation arises from the traditional practice of compartmentalizing subjects, where educators are primarily trained within their specific fields of expertise, with less emphasis on integrating knowledge across different disciplines. As a result, teachers may lack the comprehensive strategies and interdisciplinary teaching methods necessary to effectively incorporate STEM principles into their curriculum and foster students' innovative thinking, problem-solving abilities, and collaborative skills. However, the rise of STEM education has created new teaching opportunities for elementary and secondary school teachers. STEM education positively affects their teaching abilities, providing them with a broader range of pedagogical strategies and methods with which to promote students' holistic growth (Brown et al., 2019; Thibaut et al., 2018a). Nevertheless, a research gap remains concerning the influence of STEM education on teachers' interdisciplinary teaching abilities. Researchers have found a certain heterogeneity in the impact of STEM education on teachers' instructional abilities, with the influencing factors not yet comprehensively identified (Zhou et al., 2021). Additionally, the research scope has predominantly been limited to math and science, with less attention paid to other subjects at different education levels (Hubber et al., 2022; Martins, 2012). Hence, we examined the impact of STEM education on elementary and secondary school teachers' interdisciplinary teaching abilities to address the professional development issues experienced by STEM educators. Through a comprehensive analysis of extant research, we sought to gain a deeper understanding of whether STEM education significantly impacts elementary and secondary school teachers' interdisciplinary teaching abilities. Accordingly, we pursued answers to the following questions: What influence does STEM education have on teachers' interdisciplinary teaching abilities (value recognition, knowledge integration, practical applications, cooperation and communication, development awareness)? What are its specific effects? Do moderating variables (e.g., gender, education level, teaching experience, and interdisciplinary experience) differ in their impact on teachers' interdisciplinary teaching abilities? By addressing these questions, we aimed to provide valuable insights into teachers' pedagogical practices and policy formulation, thereby advancing the in-depth development of STEM education. The study's critical value lies in our thorough analysis of how STEM education shapes elementary and secondary school teachers' interdisciplinary teaching abilities, thus providing a solid empirical foundation for the progress of educational reform. By fostering professional growth, optimizing teaching practices, and propelling the education system in a more integrated and innovative direction, this study directly contributes to enhancing students' learning outcomes and holistic growth.

Literature review

Interdisciplinary teaching abilities are critical for teachers to synthesize knowledge from different fields, design interdisciplinary curricula, and enhance students' interdisciplinary thinking ability. We examined the impact of STEM education on elementary and secondary school teachers' interdisciplinary teaching abilities. Specifically, we constructed a conceptual framework by reviewing and analyzing relevant research on the factors influencing teachers' interdisciplinary teaching abilities. This framework divided the influencing factors into two parts: The first focused on the impact of STEM education on teachers' professional development, including its influence on teachers' cognitive literacy, teaching methods, and interdisciplinary integration abilities; the second part examined the factors potentially affecting teachers' interdisciplinary teaching abilities, such as gender, education level, subject, teaching experience, and interdisciplinary experience. Through this conceptual framework, we interpreted existing research findings to reveal STEM teachers' key interdisciplinary teaching abilities and the impact of these abilities on students' learning outcomes. We aimed to gain a deeper understanding of the formation and development of STEM teachers' interdisciplinary teaching abilities and these abilities' influencing factors, thus providing valuable guidance and recommendations for pedagogical practices and teachers' professional development.

STEM education on teachers' professional development

With the proliferation of STEM education, teachers' professional development has garnered considerable attention. We conducted a literature review of the impact of STEM education on teachers' professional development, focusing on three main aspects. First, we explored how

STEM education influences teachers' cognitive literacy; this refers to teachers' ability to understand and apply knowledge and information, which is crucial for them to comprehend and impart STEM knowledge. Second, we investigated how STEM education transforms teachers' pedagogical methods. STEM education encourages practical, inquiry-based teaching approaches and places new demands on teachers' instructional strategies. Finally, we explored how STEM education enhances teachers' interdisciplinary integration abilities. Interdisciplinary integration is a vital teaching strategy in STEM education that requires teachers to organically combine knowledge and skills from different fields to address complex real-world problems. By focusing on these three aspects, we aimed to better understand the impact of STEM education on teachers' professional development and provide valuable suggestions for promoting it.

Teachers' cognitive literacy

STEM education plays a significant role in enhancing teachers' cognitive literacy. Acquiring knowledge related to STEM fields is crucial for teachers to improve their interdisciplinary cognitive literacy (Kurup et al., 2019; Slavit et al., 2016). Kurup et al. (2019) argued that interdisciplinary cognition encompasses teachers' understanding of the value of interdisciplinary education, educational contexts, and pedagogical approaches, which form a knowledge base for integrating interdisciplinary elements into the design and teaching of STEM curricula. In the process of implementing STEM curricula, teachers must design, conduct, and research STEM teaching flexibly and effectively based on their interdisciplinary cognition (Slavit et al., 2016). Akerson et al. (2018) further revealed how engineering design can be successfully incorporated into science teaching to significantly enhance students' scientific and engineering abilities. Conversely, teachers participating in STEM projects learn how to apply STEM knowledge to solve real-world problems, thereby enhancing their innovative thinking, problem-solving ability, and critical thinking skills, which are essential for making effective decisions in the teaching process (English & King, 2015). These studies have underscored the importance of STEM-related disciplinary knowledge in boosting teachers' interdisciplinary cognitive literacy and highlighted teachers' pivotal role in designing and implementing STEM curricula. However, despite the support for STEM education's positive impact on teachers' interdisciplinary cognitive literacy, some studies have suggested that these effects are not always significant (Liu et al., 2018). This discrepancy may be influenced by various external factors, including teachers' gender, the education level at which they teach, the subject in which they specialize, their teaching experience, and whether they have interdisciplinary teaching experience. These factors may play a moderating role in the impact of STEM education on the enhancement of teachers' cognitive literacy, thus affecting their absorption and application of STEM education. For instance, teachers' gender and teaching experience may influence their acceptance and implementation of STEM education, which, in turn, affect their interdisciplinary cognitive literacy (Tytler et al., 2019). Additionally, the subjects they teach and the educational level at which they do so may influence their understanding and implementation of STEM education. For example, middle and high school teachers may be more likely than elementary school teachers to understand and master the concepts and methods of STEM education; thus, their interdisciplinary cognitive literacy may be more greatly improved (Akiri et al., 2021). Furthermore, whether teachers have interdisciplinary experience may also affect their interdisciplinary cognitive literacy, with those who possess interdisciplinary experience potentially understanding and accepting STEM education more easily and thus reaping more effective enhancement of their interdisciplinary cognitive literacy (Zhou et al., 2023). Future research should consider these factors in greater detail to deepen the understanding of STEM education's impact on teachers' cognitive literacy.

Teachers' pedagogical methods

Amidst the global educational reforms of the twenty-first century, STEM education has emerged as a significant focal point. Numerous studies have revealed the profound impact of STEM education on teachers' pedagogical methods and educational reforms (Akerson et al., 2018; Roehrig et al., 2021; Wang et al., 2011). First, STEM education emphasizes instructional methods such as practice, inquiry, and project-based learning. This approach not only helps students comprehensively understand and master STEM knowledge but also enhances their innovative thinking and problem-solving ability (Roehrig et al., 2021). Akerson et al. (2018) found that teaching STEM through engineering design effectively promoted students' creativity, problem-solving ability, and teamwork skills and increased their interest and engagement in science and math, even sparking career interest in STEM fields. Second, STEM education has profoundly impacted educational reform (Cabello et al., 2019). Many schools and academic institutions have begun reforming their curricula and teaching methods to meet the demands of STEM education. For example, some schools have reformed their curricula to

place greater emphasis on practice and project-based learning to cultivate students' STEM skills (Murray et al., 2020). Additionally, some schools have reformed their instructional methods to encourage teachers to adopt more inquiry-based and student-centered approaches rather than traditional lectures (Wu et al., 2019). STEM education assessment practices are crucial to this process. According to Falloon et al. (2020), teachers should reflect on and improve their pedagogical methods through assessment practices to achieve professional development. Assessment practices not only focus on students' learning outcomes but also include teachers' instructional practices and strategies to ensure teaching effectiveness. Such assessments enable teachers to effectively adjust and improve their teaching methods to meet students' learning needs. Furthermore, assessment practices promote teachers' adoption of inquiry-based and student-centered pedagogical methods. By reforming assessment practices, teachers can better understand and apply pedagogical methods, thereby improving their teaching quality and achieving professional development (Skowronek et al., 2022). Hence, assessment practices play a critical role in STEM educational reform. However, certain challenges may be encountered in the process of implementing STEM education to drive innovation and improve teaching methods. These challenges stem primarily from teachers' personal characteristics and experiences, which may influence their receptiveness to new instructional methods (Al Salami et al., 2017; Lin et al., 2022; Papagiannopoulou et al., 2023). For instance, male teachers may be more inclined to adopt STEM pedagogical methods, whereas female teachers may be more inclined to adhere to traditional instructional approaches (Hernández-Serrano & Muñoz-Rodríguez, 2020). This could be due to the influence of gender on teachers' beliefs and attitudes about teaching, or it may be related to sociocultural factors. Additionally, the subject teachers teach may affect their receptiveness to new instructional techniques. For example, science and engineering teachers may find it easier to understand and accept the concepts and methods of STEM education, whereas humanities teachers may perceive them as unfamiliar or confusing (Smith et al., 2015). Some related studies have found that STEM education may not significantly impact the innovation and improvement of teachers' pedagogical methods. For instance, despite teachers' receipt of STEM education training, no significant changes or improvements were observed in their subsequent teaching practices (Brown et al., 2019). These results suggest that, in the process of implementing STEM education to drive innovation and improve instructional approaches, we must fully consider these factors and seek appropriate strategies to overcome the corresponding challenges.

Teachers' interdisciplinary integration abilities

STEM education is considered an effective approach to cultivate teachers' interdisciplinary integration abilities owing to its unique characteristics of interdisciplinary integration (English, 2016; Wu, 2023). English (2016) corroborated this view, having found that STEM education can help students understand the interconnections between disciplines by incorporating knowledge and skills in science, technology, engineering, and math, thereby promoting interdisciplinary learning and thinking. This integration model not only benefits students but also presents a challenge and opportunity for teachers, who must be able to combine knowledge and skills from different fields to provide students with meaningful and challenging learning experiences (Skowronek et al., 2022). Through the integration of scientific knowledge, STEM education can help students understand scientific phenomena and enhance their literacy. Teachers must also be able to merge scientific knowledge with expertise from other disciplines to design challenging scientific learning tasks. Technology provides teachers with effective tools and offers students a rich learning experience. For example, teachers can use various educational technological tools such as virtual laboratories, programming software, and three-dimensional (3D) printing to design and implement a diverse range of STEM teaching activities; these can help students gain a deeper understanding of STEM and enhance their innovative thinking and problem-solving ability (Kurup et al., 2019; Liu et al., 2018). Additionally, teachers must know how to incorporate engineering knowledge with knowledge from other areas and design challenging engineering tasks to boost engineering literacy (Skowronek et al., 2022). Teachers' interdisciplinary integration abilities are particularly important in this process. Lin et al. (2021) further revealed this by exploring teachers' thought processes and proposing a series of strategies and methods for cultivating their interdisciplinary integration abilities. For instance, teachers can participate in interdisciplinary team collaborations and attend professional development activities and trainings, which can help them acquire the latest teaching concepts and methods as well as enhance their teaching skills and professional qualities (Falloon et al., 2020). These studies suggest that STEM education effectively enhances teachers' interdisciplinary integration abilities. However, the impact of STEM education on these abilities may be influenced by various external factors, and the outcomes may vary depending

on factors such as the teacher's gender, teaching experience, and interdisciplinary background (Lin et al., 2022; Takeuchi et al., 2020). For instance, female teachers have been found to be more willing to engage in interdisciplinary integration (Smith et al., 2015). This could be because female teachers tend to emphasize students' holistic growth, and interdisciplinary integration is an effective means to achieve this goal. Moreover, experienced teachers may find it easier to embrace the concepts and methods of interdisciplinary integration, thereby effectively enhancing their interdisciplinary integration abilities (Smith et al., 2015). Additionally, teachers with interdisciplinary experience may find it easier to accept the concepts and methods of interdisciplinary integration, thereby boosting their interdisciplinary integration abilities (Margot & Kettler, 2019). Accordingly, our research questions (RQs) addressed how to consider and adjust these external factors to implement STEM education more effectively and boost teachers' interdisciplinary integration abilities.

In sum, we found that teachers' cognitive literacy, pedagogical methods, and interdisciplinary integration abilities are key factors in their interdisciplinary teaching abilities. Most studies support this result. However, some studies have implied that the influence of these factors on teachers' interdisciplinary teaching abilities is not always significant. This may be due to the moderating effects of external factors such as the teacher's gender, education, subject, teaching experience, and whether they have interdisciplinary experience. This suggests that we cannot directly equate teachers' cognitive literacy, pedagogical methods, and interdisciplinary integration abilities with their interdisciplinary teaching abilities; instead, we need to more comprehensively consider the influence of other factors. Hence, we focused on the impact of STEM education on various aspects of teachers' interdisciplinary teaching abilities (e.g., value recognition, knowledge integration, practical application, cooperation and communication, development awareness) while also establishing the extent to which factors such as teachers' gender, education level, subject, and teaching experience affect their interdisciplinary teaching abilities. Simultaneously, this paper discusses potential bias or other latent research biases in existing studies that may have influenced the results; it is only in this way that teachers' professional development can be effectively promoted.

Moderating variables

In education, interdisciplinary teaching is widely recognized as an effective instructional strategy that aids students in establishing connections between different disciplines when addressing complex problems, thereby enhancing their overall abilities. However, teachers' success in implementing interdisciplinary teaching is not solely dependent on their pedagogical beliefs and methods; it is also influenced by various external factors. The extent and direction of these influences are not always consistent and may sometimes yield contradictory outcomes. Therefore, we reviewed the relevant research on the impact of teachers' gender, the education level at which they teach, the subject they teach, their teaching experience, and their interdisciplinary experience on their interdisciplinary teaching abilities to provide a more comprehensive perspective for understanding and enhancing teachers' interdisciplinary teaching abilities.

Gender

The current research landscape encompasses a diverse range of perspectives on how various factors influence educational practices. Some studies have suggested that gender may influence teachers' understanding and application of connections between different fields (Ho et al., 2020; Sansone, 2019). UNESCO data indicate that only 28% of global researchers are women and that female underrepresentation in STEM fields significantly hinders sustainable global development (United Nations Children's Fund, 2020). Johnson and Wang (2019) found that female teachers may help dispel stereotypes regarding gender differences in mathematical and scientific abilities. They reported that in classes led by female teachers, students are less likely to believe that boys are inherently better at math and science, a belief that can adversely affect girls' performance in high school math and science courses (Johnson & Wang, 2019). Male teachers tend to favor interdisciplinary teaching methods in classroom practice, particularly regarding integrating knowledge from different disciplines and designing comprehensive curricula (Camacho-Javier & Castillo, 2022), whereas female teachers focus more on emotional education and attention to individual differences and tend to reap advantages in classroom management and interpersonal relationship building (Beilock et al., 2010). These studies imply that there may be differences between male and female teachers in certain aspects of interdisciplinary teaching abilities. By contrast, some studies have found that gender does not significantly impact teachers' interdisciplinary teaching abilities (Al Salami et al., 2017). Smith and Jones (2018) found no significant differences in the interdisciplinary teaching abilities of male and female teachers in terms of professional development and teaching practice. This finding denotes that gender is not a key determinant of teachers' interdisciplinary teaching abilities; other factors such as teaching resources, school policies, and cultural environment also influence teachers' interdisciplinary teaching abilities (Chiu et al., 2021; Margot & Kettler, 2019; Thibaut et al., 2018a, 2018b; Yang

et al., 2020). Therefore, the impact of gender on interdisciplinary teaching abilities remains worthy of further investigation. Future research should explore how and to what extent gender affects teachers' interdisciplinary teaching abilities by considering a broader range of potential influencing factors.

Education level

Teachers teaching at different education levels exhibit distinct characteristics in their interdisciplinary teaching abilities. First, teachers' interdisciplinary teaching abilities vary at different educational levels. Dong et al. (2020) found that STEM education at the elementary school level focuses more on cultivating children's scientific thinking abilities of observation, inquiry, and practice by creating scenarios similar to their real-life experiences, whereas STEM education at the secondary school level stresses guiding students to synthesize knowledge from various fields for problem-solving and technological innovation. Elementary school teachers excel at integrating knowledge from different areas and designing comprehensive curricula, whereas secondary school teachers are adept at imparting in-depth disciplinary knowledge (Galanti & Holincheck, 2022; Lie et al., 2019). This indicates that elementary and secondary school teachers have different emphases when integrating knowledge from different fields and designing comprehensive curricula. Second, teachers at different education levels face distinct challenges in interdisciplinary teaching. Elementary school teachers must pay more attention to cultivating students' basic knowledge and skills, whereas secondary school teachers must focus more on developing students' higher-order thinking and analytical abilities (Al Salami et al., 2017). These findings suggest that different stages have unique requirements for teaching abilities: Elementary school teachers need a broader range of instructional knowledge and skills, whereas secondary school teachers must have more in-depth disciplinary expertise (Krajcik & Czerniak, 2018). However, some studies have argued that the education level at which teachers teach does not significantly impact their interdisciplinary teaching abilities. For example, Lie et al. (2019) surveyed and observed elementary and secondary school teachers and found no significant differences in their interdisciplinary teaching abilities. This may be because teachers have opportunities for professional development and training through which they receive support and resources for interdisciplinary teaching. Additionally, teachers' interdisciplinary experiences and personal interests play important roles in the development of their interdisciplinary teaching abilities (Kodkanon et al., 2018; Lindvig & Ulriksen, 2019; Van den Beemt et al., 2020). Teachers who are more interested in and enthusiastic about interdisciplinary teaching are often better able to develop and apply interdisciplinary teaching strategies (Frommelt et al., 2021). These results suggest that education level is not the only factor that determines teachers' interdisciplinary teaching abilities; teachers' individual professional qualities, interdisciplinary experience, personal interests, and professional development also significantly impact their interdisciplinary teaching abilities.

Subject and teaching experience

Teachers' subject and teaching experience are two significant factors influencing interdisciplinary teaching abilities. Regarding subject, a positive correlation has been noted between teachers' educational background and their interdisciplinary teaching abilities. Subject is known to be crucial for integrating interdisciplinary knowledge and designing comprehensive curricula (Brown & Smith, 2017). Despite this, existing research has primarily focused on teaching and learning processes in science and math education. By contrast, research on technology and engineering education is somewhat scarce (Asunda & Mativo, 2015). The literature explicitly points out this research gap, but it has not yet received sufficient attention. Hence, future research should delve into the fields of technology and engineering education, particularly to investigate how teachers use their subject to conduct effective interdisciplinary teaching in these areas. Additionally, the subject not only affects pedagogical methods but also how teachers integrate and apply interdisciplinary knowledge. For example, teachers with STEM backgrounds may have an advantage in designing and implementing interdisciplinary projects related to science and technology, whereas teachers with arts backgrounds may be more adept at integrating interdisciplinary teaching into the arts and humanities (Liu et al., 2023; Marcone, 2022). However, the subject is not the only factor that affects interdisciplinary teaching abilities. Experienced teachers may be better able to design curricula, select teaching strategies, and identify students' needs (Ryu et al., 2019). Teachers with over 10 years of teaching experience have been noted as possessing outstanding interdisciplinary teaching abilities (Johnson & Lee, 2018). They tend to exhibit strong interdisciplinary teaching abilities across different education levels and have been observed as showing greater familiarity with the challenges that may arise while teaching, enabling them to flexibly apply different pedagogical approaches to overcome these challenges (Roehrig et al., 2021). Furthermore, teachers' teaching experience can help them better understand students' learning needs and backgrounds, allowing for the more targeted

design and implementation of interdisciplinary teaching. Experienced teachers are often better able to adjust their teaching content and techniques to meet students' diverse learning needs (Neil-Burke, 2016). However, in an iSTEM (an interdisciplinary teaching method integrating science, technology, engineering, and math) teaching study, the subject influenced teachers' attitudes toward iSTEM teaching, whereas teaching experience and seniority were negatively correlated with the consistency of teachers' attitudes toward iSTEM teaching principles. Teachers' pedagogical philosophies and methods may be further influenced by their personal qualities and professional development paths (Thibaut et al., 2019). This may imply that, as teaching experience accumulates, teachers become more entrenched in traditional teaching approaches and hold more conservative attitudes toward the principles of iSTEM teaching. This finding suggests that when promoting and supporting STEM teaching, we must consider teachers' backgrounds and experiences to foster positive attitudes and practices toward STEM teaching.

Interdisciplinary experience

Interdisciplinary experience is critical for enhancing teachers' interdisciplinary teaching abilities by helping them transcend disciplinary boundaries, integrate knowledge and concepts from different fields, and design more innovative and comprehensive teaching activities (Kjellberg et al., 2023). After participating in interdisciplinary projects and activities, teachers often adopt more diverse and innovative teaching methods such as problem-solving, cooperative learning, and project-driven learning, which can effectively promote students' interdisciplinary thinking and learning abilities (Yang et al., 2018). Teachers who have been involved in interdisciplinary projects have subsequently demonstrated greater creativity and extensive abilities in curriculum and project design (Slavit et al., 2016). When collaborating with teachers from other areas, they can more effectively integrate knowledge and skills from different fields to provide students with a more holistic, diverse learning experience (Struyf et al., 2019; Zhou et al., 2021). Such collaborations also contribute to teachers' professional development, thereby enhancing their interdisciplinary teaching abilities (Chaovanapricha & Chaturongakul, 2020; Wang et al., 2020). Moreover, different types of collaboration opportunities have varying effects on teachers' interdisciplinary teaching abilities. For example, working with teachers from other disciplines to design interdisciplinary curricula and co-teaching promote the development of teachers' interdisciplinary teaching abilities. However, the effectiveness of collaboration opportunities may be influenced by time and resource constraints, which could affect the full realization of teachers' interdisciplinary teaching abilities (Tinnell et al., 2019). Interdisciplinary experiences are not the sole determinants of teachers' interdisciplinary teaching abilities. Teachers' performance in interdisciplinary teaching is influenced by multiple factors, including educational background, teaching experience, and personal attitudes (Margot & Kettler, 2019; Ryu et al., 2019). Therefore, to maximize the enhancement of teachers' interdisciplinary teaching abilities, interdisciplinary experience must interact with and support these other factors.

Integrating the aforementioned research revealed that STEM education positively affects teachers' interdisciplinary teaching abilities. However, some studies have not found any significant effects of STEM education on teachers' cognitive literacy or innovative pedagogical methods. This suggests that, although STEM education can enhance teachers' interdisciplinary teaching abilities to some extent, its effectiveness may be influenced by various external factors. Thus, further exploration of how these factors affect teachers' interdisciplinary teaching abilities is necessary to successfully promote the implementation of STEM education and the enhancement of these abilities. However, the overall effect of STEM education on elementary and secondary school teachers' interdisciplinary teaching abilities remains unclear. Does it have a significant positive effect? What factors most significantly affect teachers' interdisciplinary teaching abilities? Do teachers' characteristics, such as teaching experience, gender, and education level, moderate the impact of STEM education on their interdisciplinary teaching abilities? These unanswered questions necessitated a systematic meta-analysis to synthesize and integrate the existing research findings to gain a more comprehensive understanding of STEM education's impact on elementary and secondary school teachers' interdisciplinary teaching abilities. We analyzed a large amount of data and identified patterns, trends, and effect sizes, which yielded useful information to guide future research and educational practices, draw more accurate and reliable conclusions, further validate or modify existing theoretical viewpoints, and provide new directions and methods for future research and scholars. Hence, this study is of great significance for promoting teachers' professional development and optimizing the implementation of STEM education.

The present study

We employed a meta-analytical approach to integrate and statistically analyze the results of multiple independent studies and reveal the overall impact of STEM education on elementary and secondary school teachers'

interdisciplinary teaching abilities. We systematically analyzed the collected data, evaluated their quality for inclusion, quantified the overall effect, explored sources of heterogeneity, evaluated publication bias, and derived meaningful insights into the research issues under investigation. Our RQs were as follows:

RQ1: Is there any publication or other potential research bias that may have affected the findings?
RQ2: Does STEM education affect elementary and secondary school teachers' interdisciplinary teaching abilities? Which factors significantly influence elementary and secondary school teachers' interdisciplinary teaching abilities?
RQ3: Do different individual factors, such as gender, education level, subject, teaching experience, and interdisciplinary experience, moderate the impact of STEM education on elementary and secondary school teachers' interdisciplinary teaching abilities?

Methods

We employed a meta-analysis to comprehensively explore the impact of STEM education on elementary and secondary school teachers' interdisciplinary teaching abilities. We gathered data from various studies using measures such as Pearson's correlation coefficient r as the effect size, sample sizes, and p values to determine the impact of STEM education on interdisciplinary teaching abilities. We adhered to a rigorous research process to collect, analyze, and summarize empirical evidence pertinent to the RQs. The analysis conformed to the meta-analysis criteria proposed by Shelby and Vaske (2008) to ensure the reliability and accuracy of our results.

Literature search

We searched extensive Chinese- and English-language databases to find relevant literature. The main Chinese-language databases were the Chinese National Knowledge Infrastructure, the Chinese Scientific Journal, and Wanfang. We primarily searched for English-language literature using Web of Science, Science Direct, SpringerLink, Wiley, and the ProQuest full-text database of master's and doctoral theses. *STEM education*, *STEM teaching*, *STEM integration*, *STEM concept*, *STEM curriculum*, *interdisciplinary teaching abilities*, *literacy*, *teaching practices*, *awareness*, and *integration* were the relevant keywords for our search. We restricted the literature search to articles published between January 2010 and December 2023. We summarized the results and removed duplicate entries, after which we obtained 4,817 English- and Chinese-language articles.

Inclusion and exclusion criteria

We adhered to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses criteria to determine which articles to include in our meta-analysis based on our research requirements. First, a given article had to have been published between 2010 and 2023 in Chinese or English. Second, the study population could only include research from general elementary and secondary schools, both in China and internationally, excluding preschools, vocational schools, and higher education institutions. Third, a given article had to focus on STEM education's impact on elementary and secondary school teachers' interdisciplinary teaching abilities. Fourth, the research method was limited to empirical research, and the study had to present clear, explicit, and complete statistical data (e.g., the mean, standard deviation, sample size, t-value, and F-value) to ensure that the effect size could be calculated. Figure 1 outlines the screening process. In addition to the electronic database search, we also conducted a manual search; we reviewed relevant journals, books, and conference proceedings. Additionally, we utilized reference chaining to identify further relevant studies by examining the included papers' reference lists. Ultimately, we identified 21 studies that met the criteria for meta-analysis. Among these, 11 were publicly available English-language sources, and 10 were Chinese-language sources (see Additional File). Some studies involved multiple experiments with multiple effect sizes, resulting in a total of 62 independent effect sizes (Fig. 1).

Coding framework

We included three types of variables: independent, dependent, and moderating. We coded these separately (Table 1). STEM education was the independent variable. The dependent variable was interdisciplinary teaching abilities, which included five aspects: (1) recognizing the value of interdisciplinary teaching, (2) integrating knowledge of interdisciplinary teaching, (3) applying the practices of interdisciplinary teaching, (4) cooperation and communication as they relate to interdisciplinary teaching, and (5) development awareness in relation to interdisciplinary teaching. The moderating variables were gender, education level, subject, teaching experience, and interdisciplinary experience. The included articles were screened twice to ensure coding validity. First, the articles were independently coded for evaluation according to the coding scheme. Second, a postgraduate student studying research methodology reviewed them. Finally, inconsistent coding instances were jointly reviewed in the original study. We resolved disagreements through discussion, and methodology experts solved any remaining problems through meta-analysis (Brown et al., 2003). The results

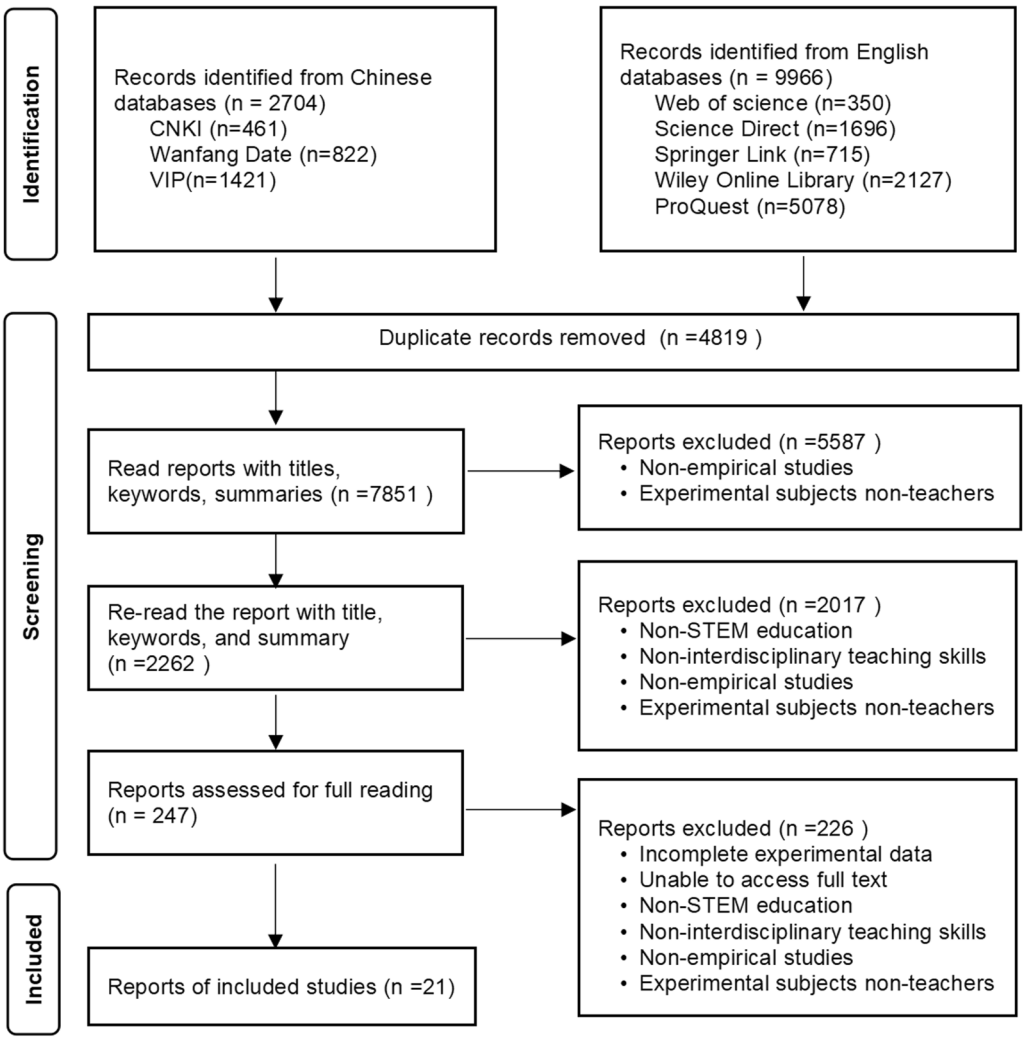

Fig. 1 Literature screening flow chart

showed 97% coding agreement and confirmed the validity of the screening criteria.

Data analysis

We employed a meta-analysis using Comprehensive Meta-Analysis (CMA) V3 software and selected Pearson's correlation coefficient r to measure the effect size. Using the following methods, we addressed the three key RQs. First, to ensure the reliability and accuracy of our results, we thoroughly assessed the overall effectiveness, which entailed testing for publication bias and heterogeneity. The publication bias test involved building a funnel plot and applying Egger's test, and we assessed heterogeneity by calculating the Q and I^2 statistics to evaluate variability between the studies. This helped us identify any potential publication or research bias that could have affected the research results. Second, we performed a main effect test to assess the impact of STEM education on elementary and secondary school teachers' interdisciplinary teaching abilities and identified specific factors within STEM education that significantly influence interdisciplinary teaching abilities. Finally, through the moderator effect test, we examined whether different individual factors (e.g., gender, education level, subject, teaching experience, and interdisciplinary experience) moderate the impact of STEM education on teachers' interdisciplinary teaching abilities.

Results

We structured our research outcomes to address three pivotal RQs, each of which evoked an answer that contributes to a comprehensive understanding of the impact of STEM education on teachers' interdisciplinary teaching abilities. The results are delineated into three main segments. The first segment focuses on overall

Table 1 Codes

Variable	Coded field	Coding
Independent variable	STEM education	STEM education, integrating STEM, STEM concepts
Dependent variable	Interdisciplinary teaching abilities (ITA)	Value recognition (CI): recognizing the value of interdisciplinary teaching; understanding the core value of literacy; endogenous motivation to practice interdisciplinary teaching
		Knowledge integration (IN): conceptual knowledge of interdisciplinary teaching; understanding the characteristics of interdisciplinary teaching; knowledge of interdisciplinary pedagogy
		Practical application (PA): the ability to organize interdisciplinary classroom activities; the ability to guide interdisciplinary learning processes; the ability to apply interdisciplinary teaching strategies
		Cooperation and communication (CO): organization and communication as they relate to interdisciplinary teaching; awareness of interdisciplinary cooperation; the ability to work in a team for interdisciplinary teaching
		Development awareness (AE): independent professional development; interdisciplinary teaching innovation; the ability to reflect on interdisciplinary teaching
Moderating variable	Gender (B)	Male (M), Female (W)
	Education level (L)	Elementary school (P), Middle school (J), High school (H)
	Subject (S)	Math (Ma), Science (Sc), Language (La), Physics (Ph), Biology (Bi)
	Teaching experience (P)	Less than 3 months (X), 3 months to 1 year (D), More than 1 year (A)
	Interdisciplinary experience (I)	With interdisciplinary experience (Y), Without interdisciplinary experience (N)

effectiveness, considering the tests for publication bias and heterogeneity. The second segment delves into the main effect test. The final segment centers on the moderator effect test, considering gender, education level, subject, teaching experience, and interdisciplinary experience. These moderating variables are essential factors in empirical research as they influence the effectiveness of STEM education's impact on elementary and secondary school teachers' interdisciplinary teaching abilities.

Overall effectiveness

Publication bias test

Publication bias refers to biased results obtained because the published literature did not fully represent the overall situation of the actual study (Dickersin & Min, 1993). Before the meta-analysis, we performed a test to avoid deviation of the results due to publication bias to help to ensure the outcomes' reliability and validity. Commonly used methods include funnel plots and Egger's test (Sutton, 2009). We employed both methods to assess publication bias in the study sample, and we generated a funnel plot for the study sample using CMA V3. The funnel plot indicated that the data for each sample were predominantly clustered at the top and evenly distributed on both sides of the median axis of the mean effect value, suggesting a symmetrical trend. This observation suggests a low likelihood of publication bias. We used Egger's test for additional analysis to further validate the above findings. Egger's test assesses publication bias by examining the significance of statistical values (Song & Gilbody, 1998). Egger's test results showed that the t-value was 1.070, and the p-value was 0.289, which exceeded 0.05, suggesting that it did not reach the level of significance. The results denote a low probability that the meta-analytic findings were influenced by publication bias (Fig. 2).

Heterogeneity test

When conducting a meta-analysis, the heterogeneity test is used to assess whether there is significant variation (i.e., whether the differences between studies are beyond the range of random errors) in the results of the included studies. Heterogeneity is primarily assessed using the Q-value and I^2 (Higgins et al., 2003). The Q-value indicates the degree of heterogeneity. A significant Q-value and a small p-value of the Q statistic (usually < 0.05) indicate heterogeneity among the studies. I^2 represents the proportion of the heterogeneous component in the total variance of the effect size. No heterogeneity is observed when $I^2 = 0$. A range of 0–40% suggests mild heterogeneity, 40–60% denotes moderate heterogeneity, 50–90% indicates high heterogeneity, and 75–100% implies very high heterogeneity (Higgins et al., 2003). The heterogeneity test results revealed a Q-value of 582.589 ($p < 0.05$) and an I^2 value of 89.53%, which exceeded the critical value of 75%. This denotes significant heterogeneity among the variables, with the effect sizes showing greater variability than expected based on random error. When a study's heterogeneity is significant, it is analyzed using a

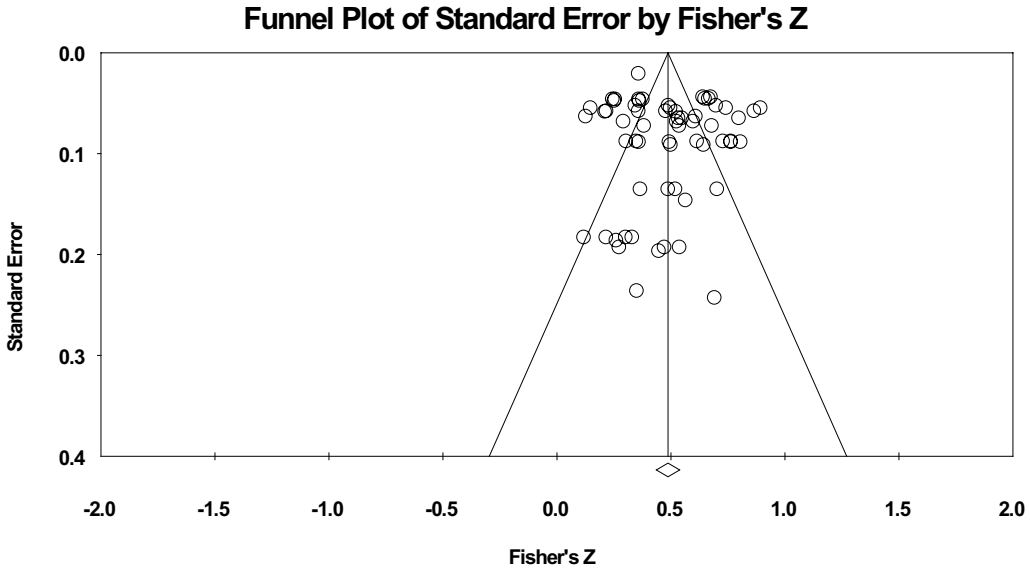

Fig. 2 Funnel plot to assess publication bias

random-effects model. Conversely, when the study's heterogeneity is minimal, it is analyzed using a fixed-effects model (Borenstein et al., 2021). Hence, in this study, we employed a random-effects model to calculate the combined effect values, and we analyzed the moderating variables to elucidate the sources of heterogeneity.

Main effect test

We selected the correlation coefficient as the effect size. According to Cohen's effect size statistical theory, an effect size of approximately 0.2 indicates a small effect, 0.5 suggests a moderate effect, 0.8 denotes a significant effect, and 1 denotes a high effect (Cohen, 2013). As shown in Table 2, the number of effect sizes representing the impact of STEM education on teachers' interdisciplinary teaching abilities was 62, and the combined effect value was 0.452, implying that STEM education moderately positively impacted teachers' interdisciplinary teaching abilities. The upper and lower values of the 95% confidence interval exceeded 0, and the two-tailed test reached a statistically significant level, denoting that the overall effect was not due to chance.

To further analyze the impact of STEM education on teachers' interdisciplinary teaching abilities in various dimensions, we examined teachers' recognition of the value of interdisciplinary teaching, their integration of knowledge of interdisciplinary teaching, their application of the practice of interdisciplinary teaching, cooperation and communication as they relate to interdisciplinary teaching, and teachers' development awareness of interdisciplinary teaching. Table 3 presents results showing that STEM education significantly impacted teachers' interdisciplinary teaching abilities, with effects ranging from moderate to substantial. We observed the impact of STEM education on the following interdisciplinary teaching abilities in descending order: knowledge integration ($r=0.517$), development awareness ($r=0.468$), practical application ($r=0.430$), value recognition ($r=0.420$), and cooperation and communication ($r=0.409$). Among these, we found that STEM education significantly impacted the integration of interdisciplinary knowledge and the awareness of interdisciplinary development. The strongest effect was seen on the ability to integrate interdisciplinary

Table 2 Heterogeneity test and random-effects model analysis results

Model	Number of effect sizes	Point estimate (*r*)	Effect size and 95% interval		Test of null (2-tail)		Heterogeneity			
			Lower limit	Upper limit	*z*-value	*P*-value	*Q*-value	*df* (*Q*)	*p*-value	I^2
Fixed	62	0.437***	0.425	0.450	59.276	0.000	582.589	61	0.000	89.530
Random	62	0.452***	0.410	0.492	18.558	0.000				

*$p<0.05$, **$p<0.01$, ***$p<0.001$

Table 3 Effectiveness analysis of the impact of STEM education on teachers' interdisciplinary teaching abilities

Groups	Number of effect sizes	Point estimate (r)	Tau-squared		Effect size and 95% confidence interval		Heterogeneity (Q-value)
			Variance	Standard error	z-value	p-value	
Value recognition	9	0.420***	0.000	0.015	0.325	0.508	41.740***
Knowledge integration	12	0.517***	0.000	0.020	0.424	0.599	98.115***
Practical application	18	0.430***	0.000	0.019	0.350	0.504	163.113***
Cooperation and communication	9	0.409***	0.000	0.020	0.299	0.508	63.577***
Development awareness	14	0.468***	0.001	0.027	0.360	0.563	171.960***
Total between-group effect	$Q_{Between} = 3.437, p > 0.05$						

*$p < 0.05$, **$p < 0.01$, ***$p < 0.001$

teaching knowledge, followed by a moderate effect on using interdisciplinary teaching practices and identifying interdisciplinary teaching values. Cooperation and communication in relation to interdisciplinary teaching showed moderate facilitating effects on teachers. We performed a between-group heterogeneity test to determine whether the variances in the numerous dimensions of teachers' interdisciplinary teaching abilities were statistically significant. The results of the between-group effect test indicated that $Q_{Between} = 3.437$, $p > 0.05$, suggesting no statistically significant difference in the impact of STEM education on the diverse dimensions of interdisciplinary teaching abilities among elementary and secondary school teachers.

Moderating effect tests

Gender

Teachers of different genders face unique challenges and opportunities in interdisciplinary teaching. Hence, we assessed the effect of STEM education on the interdisciplinary teaching abilities of teachers of different genders. Table 4 presents the results. According to the statistical analysis, the effect size for male teachers ($r = 0.488$, $p < 0.001$) was higher than that for female teachers ($r = 0.456$, $p < 0.001$), suggesting that STEM education had a slightly greater impact on the interdisciplinary teaching abilities of male versus female teachers. The results of the between-group effect test showed that $Q_{Between} = 0.038$, $p > 0.05$, indicating no statistically significant difference in the impact of

Table 4 Differences in the effects of regulated variables on teachers' interdisciplinary teaching abilities

Moderating variable	Manifestation	Number of effect sizes	Point estimate (*r*)	τ^2		Effect size and 95% confidence interval		Heterogeneity (*Q*-value)
				Variance	Standard error	*z*-value	*p*-value	
Gender	Male	32	0.488***	0.000	0.012	0.392	0.500	0.038
	Female	30	0.456***	0.000	0.014	0.390	0.519	
Education level	Elementary school	20	0.262***	0.000	0.002	0.224	0.299	127.039***
	Middle school	25	0.581***	0.000	0.006	0.542	0.618	
	High school	17	0.431***	0.000	0.006	0.382	0.477	
Subject	Science	17	0.569***	0.000	0.009	0.518	0.617	36.150***
	Math	14	0.412***	0.000	0.009	0.349	0.472	
	Language	7	0.482***	0.000	0.011	0.398	0.559	
	Physics	13	0.310***	0.000	0.009	0.233	0.382	
	Biology	11	0.449***	0.000	0.020	0.346	0.541	
Teaching experience	Less than 3 months	16	0.260***	0.000	0.003	0.215	0.305	185.811***
	3 months to 1 year	25	0.420***	0.000	0.003	0.388	0.451	
	More than 1 year	21	0.607***	0.000	0.003	0.580	0.633	
Interdisciplinary experience	Yes	35	0.543***	0.000	0.005	0.509	0.576	57.741***
	No	27	0.312***	0.000	0.007	0.260	0.362	

*$p < 0.05$, **$p < 0.01$, ***$p < 0.00$

STEM education on the interdisciplinary teaching abilities of teachers of different genders. This suggests a significant influence of STEM education on male and female teachers' interdisciplinary teaching abilities, but no disparity was found between them. Furthermore, no significant impact of STEM education on teachers' interdisciplinary teaching abilities was found for both high and low interdisciplinary teaching abilities.

Education level

Teachers who teach at different levels of education are at different stages of teaching according to the education level, and the degree to which STEM influences their work differs. We investigated the impact of STEM education on teachers' interdisciplinary teaching abilities at different education levels. Table 4 presents the results. Statistical analysis revealed that STEM education had a significant positive effect on the interdisciplinary teaching abilities of elementary ($r=0.262$, $p<0.001$), middle ($r=0.581$, $p<0.001$), and high school teachers ($r=0.431$, $p<0.001$). STEM education had the greatest impact on teachers' interdisciplinary teaching abilities at the middle school level and a moderate impact on high school teachers. Notably, STEM education had the weakest impact on elementary school teachers. This may be related to the insufficient application of the interdisciplinary curriculum at the elementary school level and the fact that the relevant level and influence of teachers' interdisciplinary teaching abilities have not been fully reflected. The results of the between-group effect test showed that $Q_{Between}=127.039$, $p<0.001$, which indicates a statistically significant difference in the effects of STEM education on teachers' interdisciplinary teaching abilities at different school levels.

Subject

The characteristics of the discipline in which teachers teach influence teachers' interdisciplinary teaching performance. Existing research has primarily focused on teaching and learning processes in science and math education; there is no research related to teaching the subjects of technology and engineering. In addition to the various STEM disciplines, the field of language is also important in STEM education, mostly in terms of understanding, expressing, and communicating scientific and mathematical concepts. Additionally, language skills impact students' STEM career development. Therefore, we further investigated the influence of STEM education on the interdisciplinary teaching abilities of teachers of diverse subjects. Table 4 presents the findings. According to the statistical outcomes, the effect sizes for all subjects were approximately 0.5, and all reached statistical significance ($p<0.001$). This suggests that the interdisciplinary teaching abilities of teachers in all subjects moderately or significantly improved under STEM education. The strengths of the interdisciplinary effects, in descending order, were as follows: science ($r=0.569$, $p<0.001$) > language ($r=0.482$, $p<0.001$) > biology ($r=0.449$, $p<0.001$) > math ($r=0.412$, $p<0.001$) > physics ($r=0.310$, $p<0.001$). The impact of science subjects was greater than 0.5, indicating that STEM education significantly improved science teachers' interdisciplinary teaching abilities. The results of the between-group effect test revealed that $Q_{Between}=36.150$, $p<0.001$, which indicates a statistically significant difference in the effects of STEM education on teachers' interdisciplinary teaching abilities across diverse subjects.

Teaching experience

Teachers with different levels of teaching experience demonstrate varying abilities to teach interdisciplinary subjects. Hence, we investigated the effects of STEM education on the interdisciplinary teaching abilities of teachers with diverse durations of teaching experience. Table 4 presents the findings. According to the statistical results, the impact values for teachers with less than 3 months, 3 months to 1 year, and over 1 year of teaching experience were all positive ($p<0.001$). This suggests that STEM education significantly affected the interdisciplinary teaching abilities of teachers with different levels of teaching experience. In particular, STEM education had the greatest impact on teachers with more than 1 year of teaching experience ($r=0.607$, $p<0.001$), and a moderate impact on teachers with 3 months to 1 year ($r=0.420$, $p<0.001$) and less than 3 months ($r=0.26$, $p<0.001$) of teaching experience. We also noted a significant positive correlation between the impact of STEM education and teachers' teaching experience. The effect value demonstrated a gradually increasing trend, suggesting that the impact of STEM education on elementary and secondary school teachers' ability to teach interdisciplinary subjects became more pronounced as their teaching experience deepened. This may be attributed to teachers' interdisciplinary teaching abilities improving with the accumulation of teaching experience. The results of the between-group effect test showed that $Q_{Between}=185.811$, $p<0.001$, denoting a statistically significant effect. This implies a significant difference in the effects of STEM education on teachers' interdisciplinary teaching abilities, which vary according to their teaching experience.

Interdisciplinary experience

Whether a teacher has changed majors, pursued a double major, completed an inter-professional graduate degree, or participated in inter-professional collaborative research during their college years can affect perceptions

of developing interdisciplinary teaching abilities. Thus, we also examined the effect of STEM education on the interdisciplinary teaching abilities of teachers both with and without interdisciplinary experience. Table 4 outlines the results. Statistical analysis indicated that teachers' interdisciplinary experience ($r=0.543$, $p<0.001$) moderately positively impacted their interdisciplinary teaching abilities and that the impact was statistically significant. By contrast, teachers' lack of interdisciplinary experience ($r=0.312$, $p<0.001$) had a smaller positive influence on interdisciplinary teaching abilities. The results of the between-group effect test revealed that $Q_{Between}=57.741$, $p<0.001$, which indicates a statistically significant difference in the effect of STEM education on the interdisciplinary teaching abilities of teachers with and without interdisciplinary experience.

Discussion

STEM education positively impacts teachers' interdisciplinary teaching abilities

The meta-analysis results for the main effect test indicated that the combined effect sizes of STEM education on the different dimensions of teachers' interdisciplinary teaching abilities reached a moderately high level ($r=0.452$, $p<0.001$). This suggests that STEM education positively impacts teachers' interdisciplinary teaching abilities, including value recognition, knowledge integration, practical application, cooperation and communication, and development awareness. There are several reasons for this observation. First, interdisciplinary teaching is a core feature of STEM education, which requires teachers to have interdisciplinary knowledge and the ability to effectively integrate content for different subjects (Dierking & Falk, 2016). Second, STEM education emphasizes practicality and innovation and cultivates students' innovation and problem-solving ability through hands-on activities (Morrison, 2006). This approach requires teachers to have rich practical experience and innovative abilities. STEM education involves multiple stakeholders such as students, teachers, parents, and the community. This teaching approach requires collaborative communication skills that enhance teachers' interdisciplinary teaching abilities (Lin et al., 2022).

STEM education has different effects on teachers' interdisciplinary teaching abilities under different moderating variables

The results of the meta-analysis of the moderating effect test indicated that gender, education level, subject, teaching experience, and interdisciplinary experience had significant positive moderating effects on teachers' interdisciplinary teaching abilities. However, the impact of gender on teachers' interdisciplinary teaching abilities was not significant.

Gender

No significant difference was noted in the impact of STEM education on the interdisciplinary teaching abilities of teachers of different genders; however, the degree of impact varied such that male teachers demonstrated stronger interdisciplinary teaching abilities in STEM education; the effect values of male and female teachers were $r=0.488$, $p<0.001$ and $r=0.456$, $p<0.001$, respectively. This variance may be attributed to social roles, gender cognition, education level, expertise, teaching resources, and opportunities. First, regarding social roles and gender cognition, STEM fields are generally perceived as male-dominated. This may stimulate male teachers to be more interested in STEM education and exhibit greater confidence and enthusiasm in this area (United Nations Children's Fund, 2020). Second, regarding education level and expertise, male teachers may have chosen STEM-related majors during their university studies and thus possess deeper professional knowledge of STEM education (Thibaut Knipprath et al., 2018a, 2018b). This makes it easier for students to understand and apply STEM principles and methods. Finally, regarding teaching resources and opportunities, male teachers may have easier access to STEM education-related training and resources, enabling them to better apply these resources in teaching practice. Further, they may have more opportunities to participate in STEM projects and practical activities, which would enhance their interdisciplinary teaching abilities (Shernoff et al., 2017). It is important to stress that although the effect size for male teachers was higher than that for female teachers, the difference was not significant ($Q_{Between}=0.038$, $p>0.05$). This finding implies that the impact of STEM education on the development of interdisciplinary teaching abilities is not strongly related to gender.

Education level

In terms of different education levels, STEM education had a greater impact on the interdisciplinary teaching abilities of middle school teachers ($r=0.581$, $p<0.001$) and high school teachers ($r=0.431$, $p<0.001$) than on those of elementary school teachers ($r=0.262$, $p<0.001$). This may be due to differences in teaching content, teachers' professional backgrounds, teaching resources, and the environment. First, regarding teaching content, STEM education emphasizes the integrated application of science, technology, engineering, and math, and involves complex theoretical and practical knowledge (Sanders, 2008). The subject content at the middle and high school levels is more specialized and in-depth,

requiring teachers to possess more subject knowledge and skills. In contrast, science, math, and technology teaching at the elementary school level is simpler, focusing on the mastery of basic knowledge and piquing students' interest. Second, regarding teachers' professional backgrounds, middle and high school teachers typically have more specialized subject backgrounds and educational experiences, enabling them to demonstrate a deeper understanding and application of the principles and methods of STEM education (Roehrig et al., 2021; Skowronek et al., 2022; Yang et al., 2020). However, elementary school teachers tend to have little professional background and educational experience, a trend that limits their understanding and application of STEM education. Finally, regarding teaching resources and the environment, middle and high schools often have richer teaching resources and laboratory equipment, which can better support the implementation of STEM education (Stains et al., 2018). By contrast, elementary schools may have limited teaching resources and laboratory equipment, restricting the practical application of STEM education among elementary school teachers.

Subject

STEM education significantly enhanced the interdisciplinary teaching abilities of teachers who teach specific subjects, with a particularly significant impact on science teachers ($r = 0.569$, $p < 0.001$). This may be due to differences in subject characteristics, teaching content, and teaching practices. First, regarding subject characteristics, STEM education encourages the integration of disciplines, helping teachers venture into different subject areas. Through STEM projects, teachers learn how to organically combine concepts from science, technology, engineering, and math, thereby promoting the integrated application of knowledge of a given subject (Vasquez et al., 2013). However, researchers have primarily focused on the teaching and learning processes of science and math education (Hubber et al., 2022; Martins, 2012); relatively little research has been conducted on technology and engineering education (Asunda & Mativo, 2015). The literature explicitly identifies this research gap, but it has not yet received sufficient attention. This gap has significant implications for future research. Owing to the lack of research on technology and engineering education, we might not fully understand the areas encompassed by STEM education. This could affect our understanding of the integrity and diversity of STEM education, thereby impacting its quality and effectiveness (Frady et al., 2023). However, this could also influence teachers' interdisciplinary teaching abilities, which are crucial in STEM education (Akgunduz & Mesutoglu, 2021). To address this research gap, future studies should pay greater attention to technology and engineering education to enhance the quality and effectiveness of STEM education. Second, teaching content differs by subject. The design of STEM education blurs the boundaries between subjects, strengthens the integration of different teaching content for various subjects, and enables teachers to be more flexible and experienced in interdisciplinary integration, which positions them to guide students to apply knowledge from multiple subjects (Morrison, 2006). For example, science teachers can enhance their interdisciplinary teaching abilities by providing comprehensive teaching content that addresses real-world problems. Finally, regarding teaching practices, STEM education emphasizes practicality and focuses on problem-solving and project-based learning (Stohlmann et al., 2012). Teachers who teach specific subjects help students apply their theoretical knowledge to solve real-world problems through project-based teaching. Science teachers are familiar with scientific experimental design and the application of scientific methods, which are crucial for practical learning in STEM projects. They can effectively guide students to use scientific methods and experimental designs to solve interdisciplinary problems.

Teaching experience

The impact of STEM education on teachers with different levels of teaching experience also varied, with teachers with more than 1 year of teaching experience ($r = 0.607$, $p < 0.001$) demonstrating higher interdisciplinary teaching abilities. This may be due to differences in teachers' teaching experience, interdisciplinary teaching strategies, subject knowledge, and professional background. First, regarding teaching experience, experienced teachers have accumulated rich experiences and knowledge in teaching practice. They are more familiar with students' learning needs and teaching methods, enabling them to better integrate STEM education with other subjects and create more interdisciplinary teaching opportunities (Aslam et al., 2023). Second, experienced teachers usually have a broader repertoire of interdisciplinary pedagogical strategies, which they can flexibly apply to integrate STEM education with other subjects, thereby providing a more comprehensive and enriched learning experience (Sellami et al., 2022). Finally, experienced teachers often have a deeper knowledge of one or more subjects, which enables them to better understand and apply the concepts and principles of STEM education and integrate them organically with other subjects. With cumulative teaching experience, the impact of STEM education on elementary and secondary school teachers' interdisciplinary teaching abilities becomes more significant. Teachers with less teaching experience may still be adapting to teaching and accumulating

experience, and their interdisciplinary teaching abilities may require more time to cultivate (Estonanto, 2017).

Interdisciplinary experience

Teachers with interdisciplinary experience ($r=0.543$, $p<0.001$) demonstrated superior interdisciplinary teaching abilities in STEM education, whereas teachers without it ($r=0.312$, $p<0.001$) showed a lower effectiveness in their interdisciplinary teaching. This may be due to structural differences in interdisciplinary thinking and knowledge, comprehensive abilities, problem-solving ability, and interdisciplinary cooperation and communication. First, regarding the structures of interdisciplinary thinking and knowledge, teachers' rich interdisciplinary experiences can positively develop their interdisciplinary teaching abilities. Teachers with interdisciplinary experience are exposed to ways of thinking from different fields during their learning process, allowing them to cultivate structures for interdisciplinary thinking and knowledge. They can better understand the connections and interactions between disciplines, thereby integrating STEM education with other subjects (Tan & Leong, 2014). Second, teachers with interdisciplinary experience have developed comprehensive skills and problem-solving abilities through their learning process. They can better cope with complex problems and challenges and possess stronger analytical and judgment abilities, which are crucial in STEM education. Finally, teachers with interdisciplinary experience have acquired interdisciplinary cooperation and communication abilities through their learning process. They are adept at working with colleagues from different fields and facilitating effective interdisciplinary collaboration in STEM education (Chai et al., 2020).

Conclusion

Key findings

We explored the impact of STEM education on elementary and secondary school teachers' interdisciplinary teaching abilities and derived three key findings. First, STEM education had a moderately positive impact ($r=0.452$) on the interdisciplinary teaching abilities of elementary and secondary school teachers. This means that STEM education not only enhances students' skills in science, technology, engineering, and math, but also effectively improves teachers' interdisciplinary teaching abilities. Second, STEM education significantly enhanced teachers' recognition of the value of interdisciplinary teaching ($r=0.420$), integration of knowledge of interdisciplinary teaching ($r=0.517$), application of the practice of interdisciplinary teaching ($r=0.430$), cooperation and communication ($r=0.409$), and development awareness ($r=0.468$). Finally, the impact of STEM education on teachers' interdisciplinary teaching abilities differed significantly based on teachers' education level ($Q_{Between}=127.039$, $p<0.001$), subject ($Q_{Between}=36.150$, $p<0.001$), teaching experience ($Q_{Between}=185.811$, $p<0.001$), and interdisciplinary experience ($Q_{Between}=57.741$, $p<0.001$). However, gender did not significantly affect STEM education's impact on teachers' interdisciplinary teaching abilities ($Q_{Between}=0.038$, $p>0.05$). In sum, STEM education is an effective tool for enhancing elementary and secondary school teachers' interdisciplinary teaching abilities, but its effect is influenced by factors such as education level, subject, teaching experience, and interdisciplinary experience. When implementing STEM education, these factors should be considered to enhance teachers' interdisciplinary teaching abilities. Additionally, although gender is an important aspect of individual differences across teachers, in this study, it did not significantly promote the impact of STEM education on teachers' interdisciplinary teaching abilities, indicating that STEM education's enhancing effect is not limited by gender. Furthermore, we observed several key gains in interdisciplinary teaching abilities via STEM education.

Based on the above findings, this study also explored the advantages of STEM education for enhancing interdisciplinary teaching abilities. First, implementing STEM education is key to enhancing teachers' interdisciplinary teaching abilities. STEM education, as a teaching model that integrates science, technology, engineering, and math, has been shown to significantly improve teachers' interdisciplinary teaching abilities. This teaching model encourages teachers to thoroughly analyze instructional content from multiple perspectives and design a series of innovative teaching activities, such as experimental exploration and project-based learning. These activities not only stimulate students' interest in learning and boost their enthusiasm for it, but also help them understand and master interdisciplinary knowledge in practical operations, thereby improving learning effectiveness. Second, project-based learning is an effective tool for enhancing teachers' interdisciplinary teaching abilities. It requires teachers to design comprehensive projects that cover knowledge and skills from multiple fields, which can effectively enhance their design and collaborative abilities. Cooperation among teachers while executing such a project is particularly important. Interdisciplinary cooperation can help teachers learn from each other, promote communication and collaborative abilities, and provide students with rich 3D learning experiences. Simultaneously, project-based learning encourages teachers to reflect on and adjust their teaching strategies and explore more flexible, innovative teaching methods during the teaching process. Finally, we found that teacher training is key to enhancing teachers' interdisciplinary teaching

abilities. Through training, teachers can understand and master the concepts, methods, and skills of interdisciplinary teaching to effectively implement STEM education.

Limitations

This study had several limitations. The first concerns differences in research design. The studies considered in this meta-analysis used different research designs, sample selection methods, and assessment tools, and these differences may have impacted the findings. Some studies may have had methodological limitations, such as sample bias and inaccurate measurement tools, which may have affected the meta-analytic results. Second, the present study had heterogeneity issues. Teachers' interdisciplinary teaching abilities are affected by many factors, including personal experience, education level, and professional knowledge. The variability of different subjects may have led to greater heterogeneity of the outcomes, complicating the interpretation of the meta-analysis results. A third limitation concerns cultural differences. Education systems, cultural backgrounds, and teaching philosophies differ across countries, which may have led to differences in the evaluation criteria used and the focus on STEM teachers' interdisciplinary teaching abilities. The outcomes of the meta-analysis may have been affected by cultural factors; hence, caution is required when making cross-cultural comparisons. Finally, our analysis indicated that the existing research primarily focused on teaching and learning processes in science and math education, whereas relatively less attention has been paid to technology and engineering education. Our study ignored this dimension, which may have influenced our understanding of the comprehensiveness and diversity of STEM education. Future research should focus on the impact of technology and engineering education.

Future research directions

Based on these limitations, we suggest that future research consider the following aspects. First, to examine the influencing factors more deeply, future research should explore how STEM education factors impact teachers' interdisciplinary teaching abilities. These include education level, professional development, training, and the teaching environment. Identifying these factors can lead to a better understanding of the performance of teachers from different backgrounds in STEM education, thereby providing a basis for the targeted development of teachers' interdisciplinary teaching abilities. Second, considering the global spread of STEM education, future studies should compare teachers' performance in different countries and regions regarding their interdisciplinary teaching abilities. This will help in understanding the impacts of culture, the education system, and other factors on teacher training and will provide a reference for international cooperation and the exchange of experiences. Third, research should be conducted on the long-term effects of STEM on teachers' interdisciplinary teaching abilities. Long-term tracking studies can help us understand the ongoing impact of STEM education on teachers' careers and identify the optimal timing and strategies for educational interventions. Building on this foundation, greater attention should be paid to enhancing pedagogical abilities in fields such as technology and engineering. This approach is crucial for bridging existing research gaps and fostering the evolution of a more holistic paradigm for STEM education. Finally, among the 21 articles included in our study, we noted significant differences in the nature of the independent variable in terms of duration, location, participation, and pedagogy. This may be due to different research backgrounds, purposes, and objects. Such differences may have affected the results. Future research should further explore the effects of these differences in independent variables on the outcomes and seek more effective ways to control or adjust these variables to enhance the reliability and validity of the research.

Abbreviations

3D	Three-dimensional
CMA	Comprehensive meta-analysis
RQ	Research question
STEM	Science, technology, engineering, and mathematics
UNESCO	United Nations Educational, Scientific and Cultural Organization

Supplementary Information

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Supplementary Material 1.

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Author contributions

Conceptualization, X.W, methodology, Y.Y., software, H.L., validation, H.L., data curation, Y.Y., writing—original draft preparation, X.W. and Y.Y., writing—review and editing, X.W. and X.Z., visualization, Y.X., supervision, X.Z. and Y.X.. All authors have read and agreed to the published version of the manuscript.

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Data availability

The data are available upon request from the corresponding author.

Declarations

Competing interests

The authors declare that they have no competing interests.

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