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Research Trends and Issues of Engineering Design Process for STEM Education in K-12: A Bibliometric Analysis

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Abstract

The study performed a bibliometric analysis on research literature related to ‘engineering design process’ (EDP) that has emerged as a popular approach for STEM education in K-12. The literature comprised 142 journal articles published from 2011 to 2021. There are three objectives of the study. Firstly, to identify the leading research trends of EDP for STEM education that have developed since the release of *A Framework for K-12 Science Education* in 2011. This framework is pivotal as it paved the way for the establishment of the *Next Generation Science Standards* in the United States. Secondly, to discern possible research issues on the aforesaid topic by analyzing the research trends. Lastly, to identify publications and authors that have generated prominent citation impact. Since EDP is an emergent approach for STEM education, fulfilling these three objectives can be conducive in facilitating future researchers to build upon the past foundation of research. In this study, the bibliometric data was identified and exported from *Web of Science Core Collection*: a database with rich scientific literature. The results identified major research trends and issues on EDP pertaining to professional development, design thinking and computational thinking, STEM competencies, scientific inquiry, and gender gaps in STEM education.

Introduction

There is a growing emphasis on implementation of ‘engineering design process’ (EDP) for STEM education in K-12 (Bybee, 2011; Honey, Pearson, & Schweingruber, 2014; Kelley & Knowles, 2016). The rationale behind this implementation has three major objectives. Firstly, to enrich K-12 science and mathematics curricula (Bybee, 2011; Kelley & Knowles, 2016). Secondly, to develop students' 21st century competencies (Chiu et al., 2013; Hu, Yeh, & Chen, 2020). Lastly, to blossom students' interest and learning motivation towards STEM disciplines by making learning connected, relevant, and meaningful (Cheng et al., 2020; Dasgupta, Magana, & Vieira, 2019).

The above rationale is first ‘officially’ proffered in *A Framework for K-12 Science Education* by the National Research Council (NRC, 2011) of the National Academy of Sciences in the United States. It proposes three key dimensions for STEM education, namely *Science and Engineering Practices*, *Crosscutting Concepts*, and

Disciplinary Core Ideas. The science and engineering practices are defined as the fundamental practices in scientific inquiry and EDP (Bybee, 2011; Kelley & Knowles, 2016); the crosscutting concepts are the cross-disciplinary commonalities that exist among different STEM disciplines (Bybee, 2011; Kelley & Knowles, 2016); while the disciplinary core ideas are the knowledge elements essential to a STEM discipline (Bybee, 2011). In summary, these three dimensions largely provide the policy directives for STEM education in the United States: they have laid the groundwork for the *Next Generation Science Standards* (NGSS) (NRC, 2013) that aims to provide educators with intelligible aims and objectives (Moore, Tank, Glancy, & Kersten, 2015) for STEM education.

Since 2011, EDP has emerged as a prominent approach for 'effective' STEM education (Cunningham et al., 2020; English & King, 2015; Shahali, Halim, Rasul, Osman, & Zulkifeli, 2017) because it acts "as an anchor" (Dasgupta et al., 2019, p. 124) that connects the crosscutting concepts in science and mathematics through an authentic learning context (Honey et al., 2014; Roehrig, Dare, Whalen, & Wieselmann, 2021). In this study, *effective STEM education* is defined as an endeavor to integrate two or more STEM disciplines (Sanders, 2009) within a unit, class, or lesson based on the cross-disciplinary connections (Bybee, 2011; NRC, 2011) between the disciplines and an authentic learning context (Kelley & Knowles, 2016), such as a real-world (inspired) problem that is ill-structured and lacks a predetermined solution path (S. Li, Chen, Xing, Zheng, & Xie, 2020; Moore et al., 2014; Roehrig et al., 2021).

Research Background

In different K-12 STEM education contexts, the interpretation and rigor of EDP varies due to two reasons. Firstly, because EDP is a multi-level construct (Atman et al., 2007; Dym, Agogino, Eris, Frey, & Leifer, 2005; Purzer, Strobel, & Cardella, 2014) that variegates a plethora of models with similar nomenclature (in literature), such as *engineering design process* (Hu et al., 2020; C. Kim et al., 2015; Zheng et al., 2020), *engineering design cycle* (Chiu et al., 2013; Zheng et al., 2020), and *engineering design thinking* (Chiu et al., 2013; Kuen-Yi, Ying-Tien, Yi-Ting, & John, 2021). Secondly, the rigor of an EDP is encompassed by the complexity of its STEM integration (i.e., the cross-disciplinarity of STEM education) that can be of three kinds, namely multidisciplinary, interdisciplinary, and transdisciplinary (English, 2016; Roehrig et al., 2021; Vasquez, 2013). In general, transdisciplinary STEM education is more meticulous, because it addresses 'complex' real-world problems, as compared to multidisciplinary STEM education that involves 'inspired' or 'simplified' real-world problems (Roehrig et al., 2021; Takeuchi, Sengupta, Shanahan, Adams, & Hachem, 2020; Vasquez, 2013). To put it succinctly, the interpretation and rigor of EDP is dependent on the nature of problems under consideration, which in turn is stipulated by the complexity of STEM education.

The complexity of STEM education has a major consequence on the research on EDP: it has led educationists to devise different models of EDP for primary STEM education (e.g., Capobianco, Yu, & French, 2015; C. Kim et al., 2015; Marulcu & Barnett, 2013) and secondary STEM education (e.g., Lie, Aranda, Guzey, & Moore, 2019; Zheng et al., 2020; Zhou et al., 2019) that may share *a priori* similarities. However, it is uncertain how the research on the development and application of such models has interacted and progressed thus far, especially in terms of its research trends and issues for implementation of STEM education in different K-12 contexts. Answering this question can be efficacious to future researchers who intend to systematically understand and build upon the past foundation of research on EDP. Arık and Topçu (2020) have asserted that a comprehensive literature review is necessary for this purpose. They have tried to address this gap by conducting a literature review based on the descriptive analysis approach. Their study albeit merely analyzed 46 research articles that may be insufficient to develop a comprehensive understanding of the subject matter.

The present study addressed the research gap in the following ways. Firstly, it employed a bibliometric approach (Hallinger & Kovačević, 2019; Martinez, Al-Hussein, & Ahmad, 2019) that analyzed 142 relevant journal articles in order to identify and visualize leading research trends and possible research issues of EDP in a comprehensive manner. Secondly, the study primarily analyzed the articles from 2011 to 2021, though it did take in consideration other publications from before 2011 that were highly co-cited within the 142 articles. This is important because even though EDP is 'officially' proffered for STEM education in 2011 (Bybee, 2011; NRC, 2011; Cunningham et al., 2020), it has a long and rich history of research development. Lastly, the study identified publications and authors that generated prominent citation impact.

Research Questions

Subsequently, based on the above rationale, the present study addressed the following research questions:

1) What are the leading research trends and possible research issues of engineering design process for STEM education in K-12 from 2011 to 2021?
2) Which publications and authors have generated prominent citation impact in this research?

What is Engineering Design Process?

As the name suggests, engineering design process (EDP) originates from the field of engineering (Dieter & Schmidt, 2009; Pahl, Wallace, & Blessing, 2007), especially during the advancements in *descriptive geometry* in the 16th and 17th centuries (Huda, 2018). The descriptive geometry represents the 'drawing techniques' for drafting a three-dimensional (3D) object onto a two-dimensional (2D) plane (Huda, 2018). And before the advent of computer-aided design (CAD), these techniques were extensively used by engineers to solve design-based problems (Dieter & Schmidt, 2009; Huda, 2018).

Traditionally, this *drafting process* was interpreted as EDP (Pahl et al., 2007). But nowadays, this process has been supplanted by modern technological advancements in the field of engineering, especially CAD – writ large (Dasgupta et al., 2019; Dieter & Schmidt, 2009; Huda, 2018; Pahl et al., 2007). Subsequently, a more contemporary interpretation of EDP is postulated by Dym et al. (2005). They define it as an 'intelligent' and 'systematic' process where engineers devise, design, and evaluate specific solutions to address a practical (design-based) problem on the basis of requirements specified by end-users. During this process, engineers first analyze and decompose the practical problem into multitudinous smaller parts (Chiu et al., 2013; Dasgupta et al., 2019), and then they engage in a series of iterative steps (Shahali et al., 2017) to resolve the smaller parts through an 'intelligent' and 'systematic' modus operandi.

Dym et al. (2005)'s interpretation has been quite well received by educationists in K-12 STEM education (e.g., Arık & Topçu, 2020; Chiu et al., 2013; Kuen-Yi et al., 2021; Ladachart et al., 2021; Purzer et al., 2014). In addition, it has guided the development of pertinent EDP models for different K-12 contexts (e.g., Dasgupta et al., 2019; English & King, 2015; Moore et al., 2014). For instance, English and King (2015)'s model is for primary STEM education and comprises five key stages, namely (1) *Problem Scoping*, (2) *Idea Generation*, (3) *Design & Construct*, (4) *Design Evaluation*, (5) *Redesign* (p. 4).

Their STEM-based project underscored 'hands-on' designing activities, such as drawing, sketching and origami, suitable for primary students. In contrast, Moore et al. (2014)'s model is applicable to both primary and secondary STEM education. It also consists of five key stages, namely (1) *Ask*, (2) *Imagine*, (3) *Plan*, (4) *Create*, and (5) Test & *Improve* (p. 40), that are delineated as an iterative design cycle. Shahali et al. (2017) successfully implemented this model for a STEM-based project on designing solar cars in a secondary school context. Their project, though, heavily emphasized on the STEM integration aspect.

By analyzing the two afore-discussed EDP models, one may observe *a priori* similarities among their design stages. Dasgupta et al. (2019) have drawn a similar conclusion: they have asserted that design stages of most EDPs, whether simple or complex, are classifiable into three 'iterative phases', namely (1) *Analysis phase*, (2) *Synthesis phase*, and (3) *Evaluation phase* (see Figure 1).

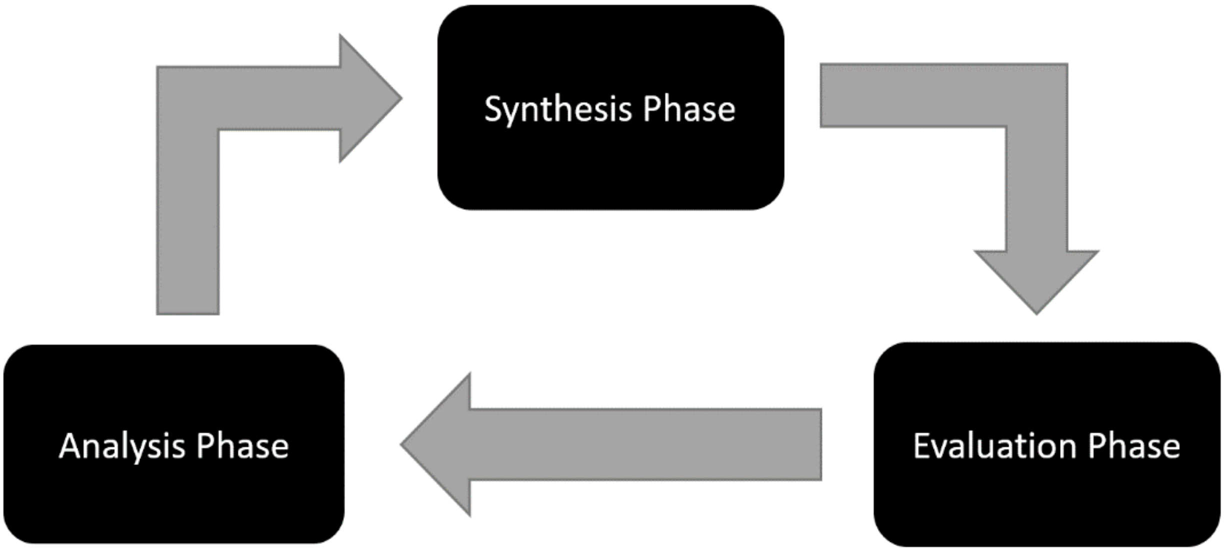

Figure 1. The EDP Model by Dasgupta et al. (2019, pp. 124-125)

These phases, however, entail several ill-structured processes that can be cognitive or metacognitive in nature (S. Li, G. Chen, et al., 2020; S. Li, H. Du, et al., 2020; Zheng et al., 2020). The details of these phases, especially how they may encompass the design stages of other models, are described in Table 1.

Table 1. The Details of the EDP Models

The EDP Models			
Dasgupta et al. (2019)	**English and King (2015)**	**Moore et al. (2014)**	**Descriptions**
Analysis Phase	Problem Scoping	Ask	▪ Identify and understand the function and constraints of the design problem. ▪ Decompose the larger design problem into smaller low-order problems.
	Idea Generation	Imagine	▪ Focus on *idea fluency* by negotiating the design constraints and generating multiple ideas based on an initial idea: *primary generator*. ▪ Avoid getting fixated on any single idea by using counter examples.
Synthesis Phase	Design & Construct	Plan	▪ Consolidate the ideas based on the design constraints to generate a solution path. ▪ The solution path should address each low-order problem by taking in consideration their complexity and feasibility.
		Create	▪ Complete a working prototype using the solution path, otherwise redo the *analysis phase*.
Evaluation Phase	Design Evaluation	Test & Improve	▪ Test the prototype on the basis of the design constraints. ▪ Identify the limitations of the current solution path. ▪ Adjust the solution path and complete the next prototype. ▪ Repeat the *evaluation phase* until all the design constraints are appropriately addressed.
	Redesign		

What is Bibliometric Analysis?

The bibliometric analysis (a.k.a. bibliometrics) involves 'techniques' for quantitatively analyzing scientific literature (Hallinger & Kovačević, 2019; Khalil & Gotway Crawford, 2015; Liao et al., 2018). Though these techniques date back to the development of *statistical bibliography* in the early 20th century, they were not considered as a distinct discipline back then (Liao et al., 2018; Pritchard, 1969). In 1969, Allan Pritchard categorized these techniques into a distinct discipline: *bibliometrics* (Khalil & Gotway Crawford, 2015; Pritchard, 1969; Thompson & Walker, 2015). Pritchard (1969) defines bibliometrics as "the application of mathematics and statistical methods that sheds light on the processes of written communication" (p. 348), such as articles, journals, and books. His definition has stood the test of time and is still quite relevant to contemporary bibliometric studies (e.g., Khalil & Gotway Crawford, 2015; X. Li, Pak, & Bi, 2020; Liao et al., 2018; Thompson & Walker, 2015). In general, bibliometrics are utilized to statistically analyze 'information patterns' within and across scientific literature in order to identify and visualize the development of research trends and issues of a particular research field (Ellegaard & Wallin, 2015; Liao et al., 2018; Martinez et al., 2019). The information patterns can include citation, authorship, co-citation, co-authorship, co-occurrence, and bibliographic coupling related patterns (e.g., Bhatt, Ghuman, & Dhir, 2020; Hallinger & Kovačević, 2019; Liao et al., 2018; Martinez et al., 2019). These patterns have extensive applications in information and data management (Corrall, Kennan, & Afzal, 2013) because they enable organization of scientific literature in terms of its publication locations, publication sources, publication years, authors, and citation numbers (e.g., Bhatt et al., 2020; Hallinger & Kovačević, 2019; Liao et al., 2018; Martinez et al., 2019).

The bibliometrics in the present study utilized two techniques, namely keyword co-occurrence and co-citation analyses. The *keyword co-occurrence analysis* searches for keywords which co-occur frequently (Hallinger & Kovačević, 2019; Martinez et al., 2019) in order to highlight ‘common concepts’ within given literature (Hallinger & Kovačević, 2019; Zupic & Čater, 2015). Subsequently, this technique is suitable for identifying major ‘research hotspots’ (i.e., research trends and issues) within a research field (Liao et al., 2018). In the case of *co-citation analysis*, it computes the frequency of two publications being cited together in given literature (Hallinger & Kovačević, 2019; Liao et al., 2018; Martinez et al., 2019). Zupic and Čater (2015) have ascertained that a high co-citation frequency of a publication indicates its broad significance. This is also evidenced by the popularity of this approach for identifying articles, authors, and sources with prominent citation impact within a research field (e.g., Hallinger & Kovačević, 2019; Liao et al., 2018; Martinez et al., 2019).

VOSviewer (https://www.vosviewer.com/) was the software program employed in the present study (see Figure 2). It is an optimized software developed by Van Eck and Waltman (2010). It has been extensively used by researchers in numerous bibliometric studies (e.g., Bhatt et al., 2020; Hallinger & Kovačević, 2019; Khalil & Gotway Crawford, 2015; Liao et al., 2018; Martinez et al., 2019). It can create network maps of keyword co-occurrence and co-citation related information patterns within given literature (Van Eck & Waltman, 2010, 2018). Additionally, it is highly compatible with *Web of Science Core Collection* database (Van Eck & Waltman, 2018) that was used in the study.

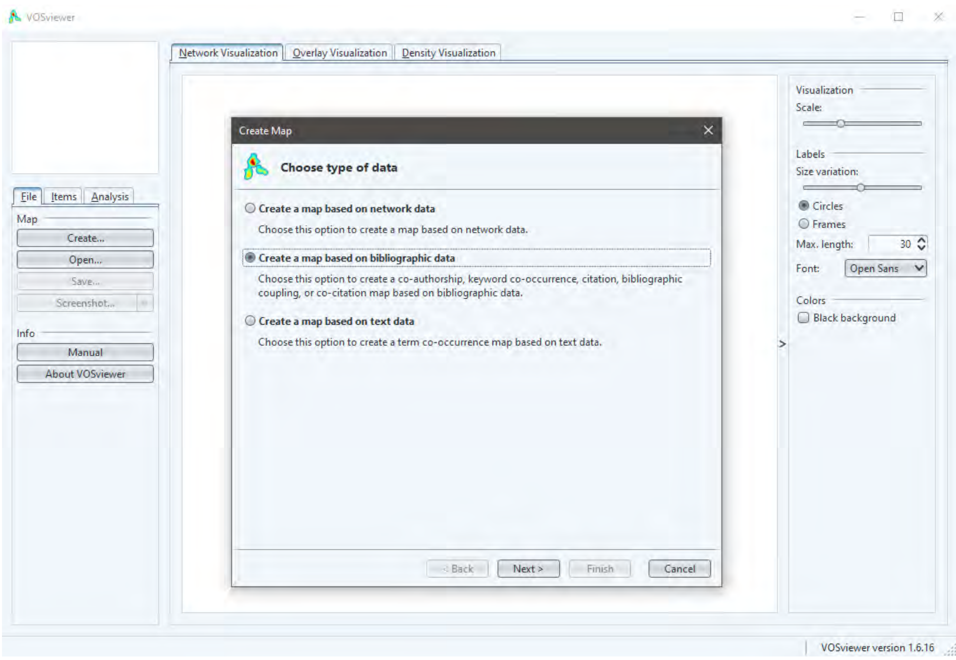

Figure 2. The User Interface (UI) of VOSviewer Software Program

Method

Data Collection

The bibliometric data was collected from *Web of Science Core Collection* (https://www.webofscience.com/wos/woscc/advanced-search) database based on the 'inclusion criteria' described in Table 2.

Table 2. The Inclusion Criteria for Data Collection

No.	Items	Descriptions
1	**Database:** Web of Science Core Collection (WOSCC)	▪ WOSCC is an online database that provides comprehensive coverage to more than 21,000 peer-reviewed scholarly journals from across the globe. These journals encompass various research fields from the social sciences, physical sciences, and life sciences, as well as arts and humanities-related disciplines. Additionally, the database provides detailed catalogs of its literature (e.g., titles, authors, abstracts, keywords, and bibliographies) that can be readily exported for bibliometric analysis.
2	**Terms:** engineering design process, engineering design, design process, engineering design thinking, design thinking, design cycle, STEM education, K-12 education	▪ The present study searched for research literature on EDP for STEM education in K-12. For this purpose, the advanced search feature of the database was utilized. The syntax placed relevant 'terms' within quotation marks ("") and separated them with 'AND/OR' operators for specificity. For a publication to be considered, the relevant terms should appear at least within its title, abstract or keywords.
3	**Publication Period:** 01/01/2011 – 31/12/2021	▪ The study selected literature that was published from 1st January 2011 to 31st December 2021.
4	**Literature Type:** Journal Articles	▪ Only journal articles were considered: all other types of literature (e.g., proceedings papers, book chapters, books, etc.) were excluded from the bibliometric data.
5	**Language:** English	▪ The selected literature should only be written in the English language.
6	**Accessibility:** Full-text Available	▪ The literature should have full-text availability to ensure that the researchers could access them for review.

A total of 142 journal articles from the database satisfied the inclusion criteria. The distributions of these articles with respect to their 'publication years' and 'yearly citations' are shown in Figure 3. These distributions, especially the publication years, corroborated the assertion that the trajectory of the research on EDP for STEM education (in K-12) accelerated after 2011 – the year when *A Framework for K-12 Science Education* (NRC, 2011) was first published that 'officially' proffered the importance of EDP in STEM education and laid the groundwork for the NGSS. Moreover, 68 out of the 142 articles (about 48% of the total) were published in the United States, indicating its dominance in the research throughput. Türkiye came 2nd while China (PRC) took the 6th position with 21 and 6 articles, respectively. The 10 regions/countries with the most articles are shown in Figure 4.

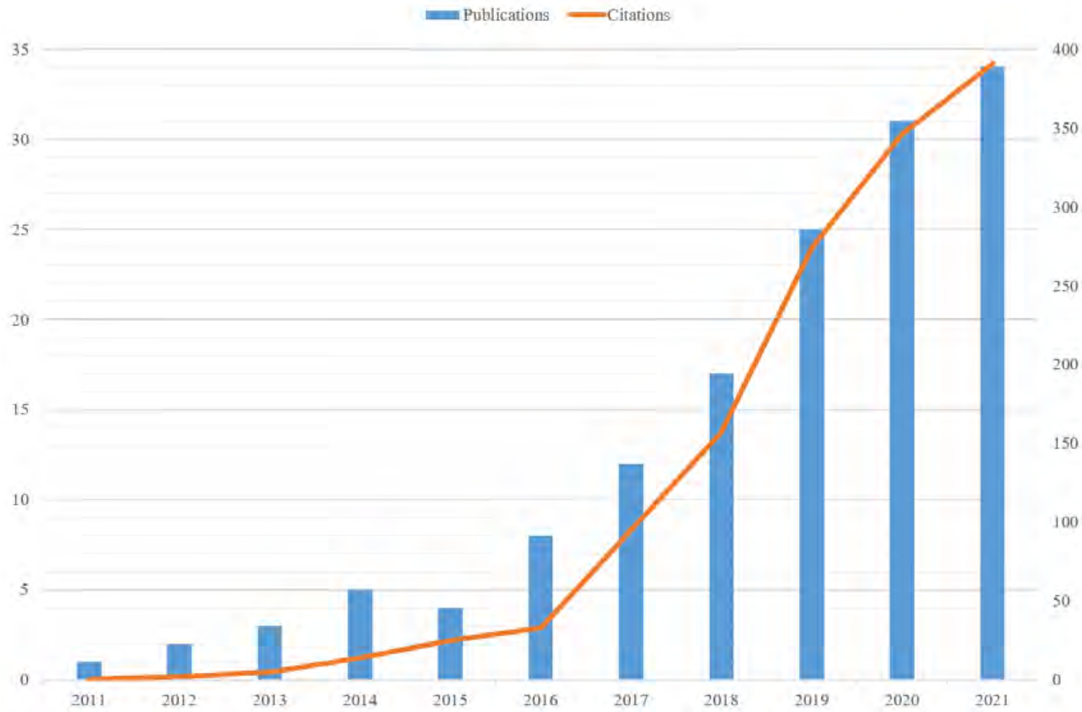

Figure 3. The Distributions of Articles as Per Their Publication Years and Yearly Citations

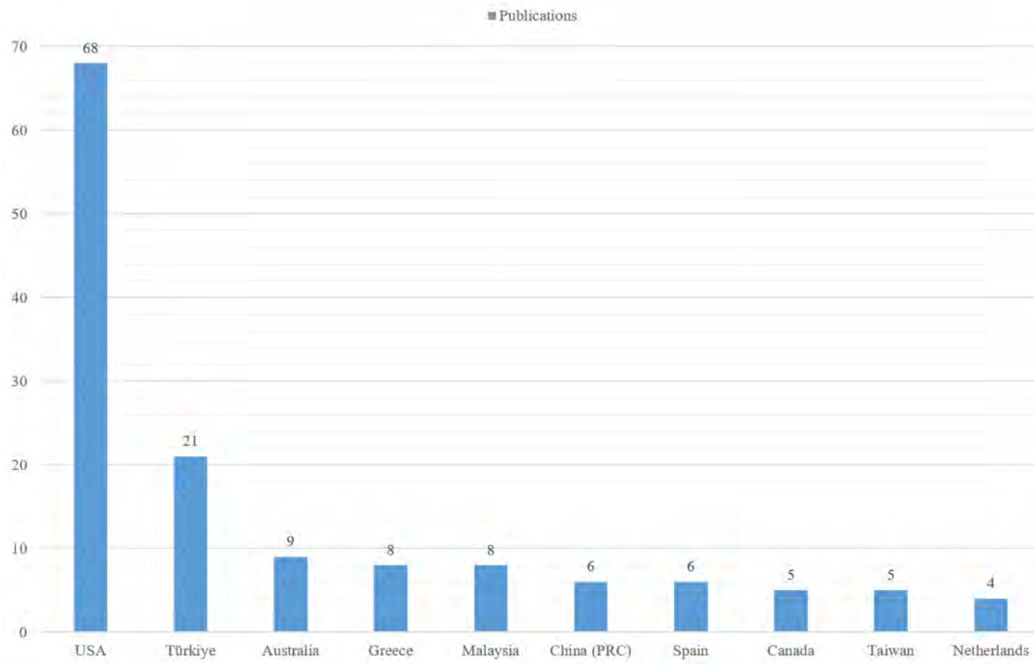

Figure 4. The 10 Regions/countries with the Most Articles

Data Analysis

The data analysis (see Figure 5) consisted of two bibliometric techniques, namely keyword co-occurrence and co-citation analyses, and was conducted through *VOSviewer* software. The rationale behind these techniques, especially their suitability, has already been discussed in the section titled: *What is bibliometric analysis?* In summary, *keyword co-occurrence analysis* was used to identify the leading research trends and issues, whereas *co-citation analysis* highlighted the publications and authors with prominent citation impact.

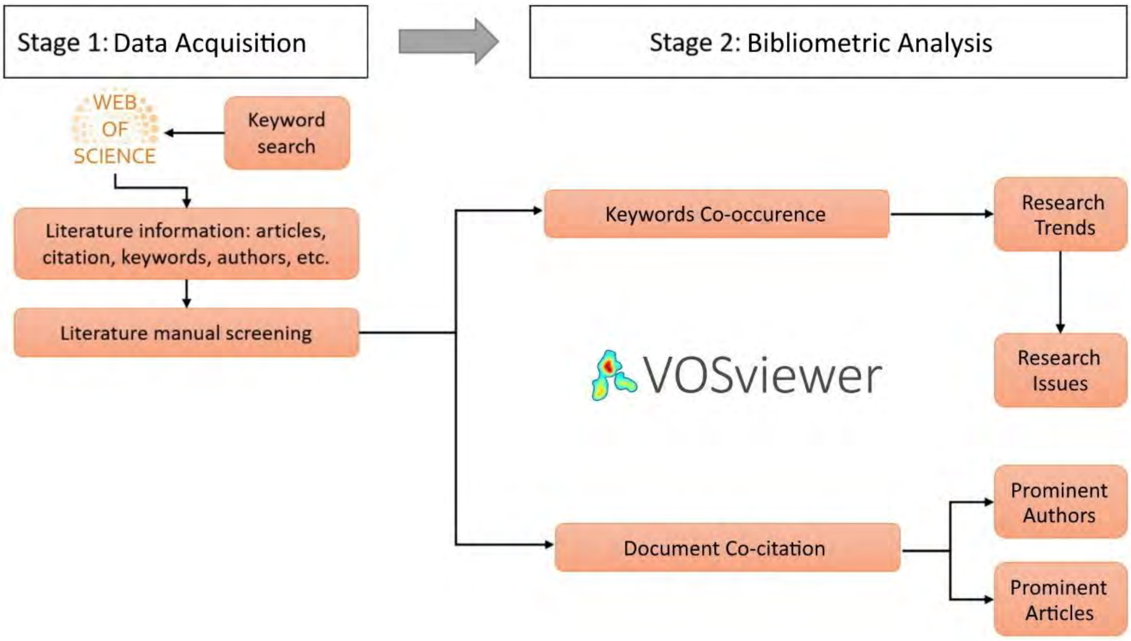

Figure 5. The Schematics of Data Analysis Adapted from Martinez et al. (2019, p. 2)

Results

Keyword Co-occurrence Analysis

In the present study, a total of 66 co-occurring keywords were identified with a *minimum co-occurrence* of 3: each keyword co-occurred in three or more articles (Van Eck & Waltman, 2010). This was within the optimal data range (e.g., 40-120 keywords) of comparable studies (e.g., Hallinger & Kovačević, 2019; Liao et al., 2018; Martinez et al., 2019). Based on this data, *VOSviewer* created a network visualization map (see Figure 6) that depicted the keywords as circles whose sizes represented their co-occurrence weights (Van Eck & Waltman, 2010). These circles were clumped in different clusters on the basis of their common co-occurrence (Van Eck & Waltman, 2010) – the keywords that 'co-occur regularly together' were placed in the same clusters.

To facilitate the analysis of each cluster, the articles containing the co-occurring keywords of that cluster were cataloged. Afterwards, these articles were carefully reviewed in order to identify and understand the leading research trends emerging within that cluster, as accomplished by comparable studies (e.g., Hallinger & Kovačević, 2019; Liao et al., 2018). In this manner, a total of 7 clusters were discovered and subsequently analyzed in the study (see Table 3).

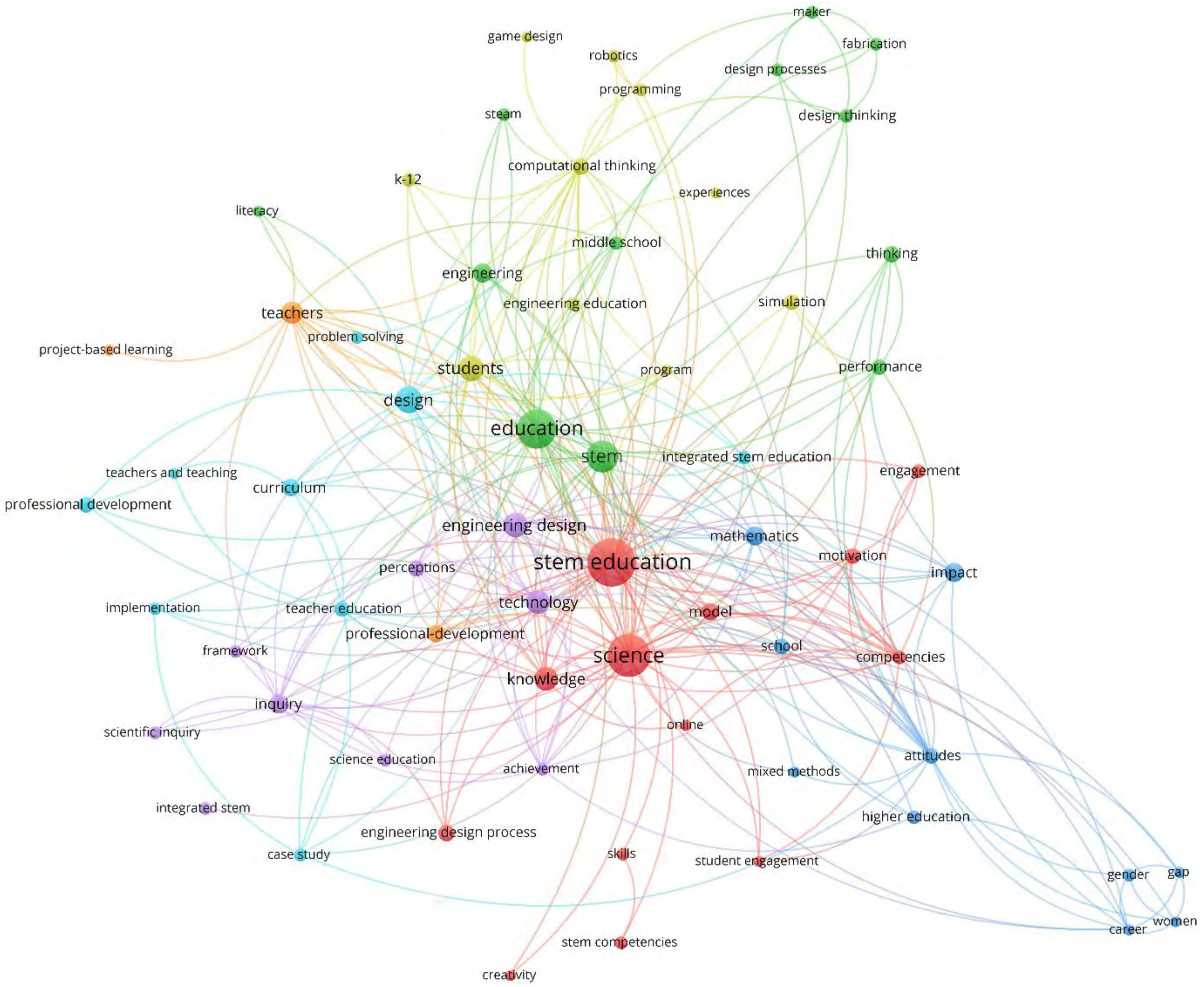

Figure 6. The Network Visualization Map of the *Keyword Co-occurrence Analysis*

Table 3. The 7 Clusters (from Figure 6) Consist of 66 Co-occurring Keywords

No.	Keywords
Cluster 1	▪ professional development, teacher education, teachers and teaching, curriculum, design, implementation, problem solving, integrated STEM education, case study
Cluster 2	▪ professional-development, teachers, project-based learning
Cluster 3	▪ design thinking, thinking, design processes, engineering, fabrication, maker, performance, literacy, middle school, STEAM, STEM, education
Cluster 4	▪ computational thinking, robotics, programming, program, game design, simulation, experiences, students, K-12, engineering education
Cluster 5	▪ STEM competencies, competencies, skills, knowledge, creativity, student engagement, engagement, motivation, online, model, engineering design process, science, STEM education
Cluster 6	▪ scientific inquiry, inquiry, science education, framework, integrated STEM, perceptions, achievement, engineering design, technology
Cluster 7	▪ women, gender, gap, career, attitudes, impact, school, higher education, mathematics, mixed methods

Leading Research Trends of Engineering Design Process in STEM Education

The literature reviews of the articles, corresponding to each cluster (see Table 3), spotlighted the following leading research trends: First (1), the keywords in clusters 1 and 2 (e.g., professional development, teacher education, teachers and teaching, curriculum, design, implementation, etc.) highlighted the research trends related to the professional development (PD) of K-12 teachers on EDP for STEM education. For instance, educationists have underscored the exigency of PD to improve K-12 teachers' readiness for EDP (e.g., Chiu et al., 2013; Moore et al., 2015; Ryu, Mentzer, & Knobloch, 2018).

To address such concerns, certain PD programs have provided 'in-service' teachers with collaborative learning opportunities, including professional workshops and joint trainings on EDP and STEM education, with other 'in-service' teachers, engineering graduates, and STEM professionals (e.g., Brand, 2020; Pleasants, Olson, & De La Cruz, 2020; Radloff & Capobianco, 2019). These programs have reported improvements in the readiness of their teacher trainees but have provided limited evidence of their trainees successfully implementing EDP in their STEM classrooms. Conversely, certain PD programs have focused on equipping 'pre-service' teachers with *technical engineering skills* on educational robotics, software programming, and electronics (e.g., Hu et al., 2020; C. Kim et al., 2015; Kuen-Yi et al., 2021). Regardless, apart from Kuen-Yi et al. (2021), most of these programs lacked any control groups that may affect the validity of their findings.

Second (2), the keywords in clusters 3 and 4 (e.g., design thinking, design processes, fabrication, maker, engineering, computational thinking, robotics, programming, program, game design, etc.) accentuated the research trends on promoting design thinking and computational thinking through EDP in STEM education. For example, researchers assert that *design thinking* represents the different cognitive and metacognitive processes (see Figure 7) engaged by engineers during a design process (e.g., Chiu et al., 2013; Gordon, Rohrbeck, & Schwarz, 2019; Kuen-Yi et al., 2021; Y. Li et al., 2019). It has been observed that STEM-based activities embracing 'hands-on learning' experiences can promote these processes in K-12 students (Cheng et al., 2020; Chiu et al., 2013; Ladachart et al., 2021). These activities can involve virtual laboratories (Potkonjak et al., 2016), makerspaces (Kapon, Schvartzer, & Peer, 2021; Lin, Chang, & Li, 2020) and digital fabrication techniques (Chiu et al., 2013) – such as CAD (Dasgupta et al., 2019; C. Xie, Schimpf, Chao, Nourian, & Massicotte, 2018) and 3D printing (Cheng et al., 2020; Şen, Ay, & Kiray, 2020).

Likewise, *computational thinking* is another problem-solving approach in STEM education that incorporates 'hands-on learning' experiences based on educational robotics (Bers, Flannery, Kazakoff, & Sullivan, 2014; Pérez & López, 2019), block-based programming (Fidai, Capraro, & Capraro, 2020; Waite, Curzon, Marsh, & Sentance, 2020), game designing (Ishak, Din, & Hasran, 2021), as well as unplugged teaching-learning activities (Ung, Labadin, & Mohamad, 2022). According to Wing (2006), computational thinking is an approach for "solving problems, designing systems, and understanding human behavior, by drawing on the concepts fundamental to computer science" (p. 33). Albeit, due to the similarities between design thinking and computational thinking processes, it may be challenging to distinguish them during an EDP (Kelly & Gero, 2021). Thus, further research is suggested to explore their interrelationship.

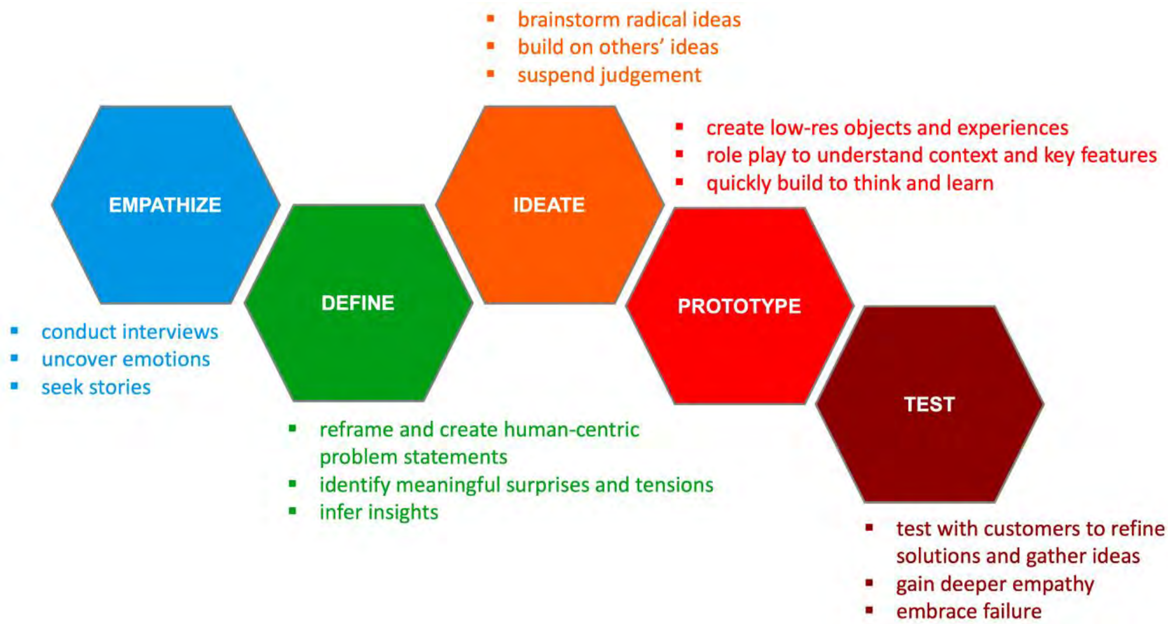

Figure 7. The Different Processes involved in Design Thinking (Gordon et al., 2019, p. 32)

Third (3), the keywords in cluster 5 (e.g., STEM competencies, competencies, skills, knowledge, creativity, student engagement, motivation, etc.) spotlighted the research trends on enhancing K-12 students' STEM competencies through EDP in STEM education. Hu et al. (2020) define STEM competencies as a multifaceted construct that can be divided into three broad categories, namely STEM attitudes, STEM skills, and STEM knowledge. In the case of STEM attitudes, they encompass students' learning motivation and engagement towards STEM disciplines (Cheng et al., 2020; Dasgupta et al., 2019; Hu et al., 2020). For STEM skills, they include students' metacognitive skills, such as critical thinking and creativity; and non-cognitive (soft) skills, such as collaboration and communication (Hu et al., 2020; Y. Xie, Fang, & Shauman, 2015). While STEM knowledge entails the disciplinary core ideas of each STEM discipline (Bybee, 2011; NRC, 2011), and the crosscutting concepts among STEM disciplines (Kelley & Knowles, 2016; NRC, 2011). It has been argued that STEM-based activities involving EDP can enhance K-12 students' STEM competencies (Bybee, 2011; Kelley & Knowles, 2016; Roehrig et al., 2021) as demonstrated by several research studies (e.g., Baran, Canbazoglu, Mesutoglu, & Ocak, 2019; Cunningham et al., 2020; Dasgupta et al., 2019; Shahali et al., 2017). However, the findings of these studies are potentially non-generalizable due to small sample sizes.

Fourth (4), the keywords in cluster 6 (e.g., scientific inquiry, inquiry, science education, framework, integrated STEM, etc.) highlighted the research trends involving scientific inquiry and EDP in STEM education. In general, *scientific inquiry* is a 'process of inquiry' based on the scientific method to investigate and understand a natural phenomenon (NRC, 2011; Purzer, Goldstein, Adams, Xie, & Nourian, 2015). But in the context of EDP for STEM education, it is commonly rationalized as a scaffolding process (Chiu et al., 2013; Merritt, Chiu, Burton, & Bell, 2018) for assisting students in decomposing, understanding, and analyzing design-based problems (Yu, Wu, & Fan, 2020). For instance, educationists have devised *conceptual frameworks* of STEM education (see Figure 8) where scientific inquiry is depicted as the scaffolding process (e.g., Kelley & Knowles, 2016; Yata, Ohtani, & Isobe, 2020). However, scientific inquiry alone may be insufficient to scaffold a complex 'real-world' design-based problem (Chao et al., 2017) that also draws insights from disciplines other than science. In such cases, interdisciplinary or transdisciplinary STEM integration can be deployed in tandem.

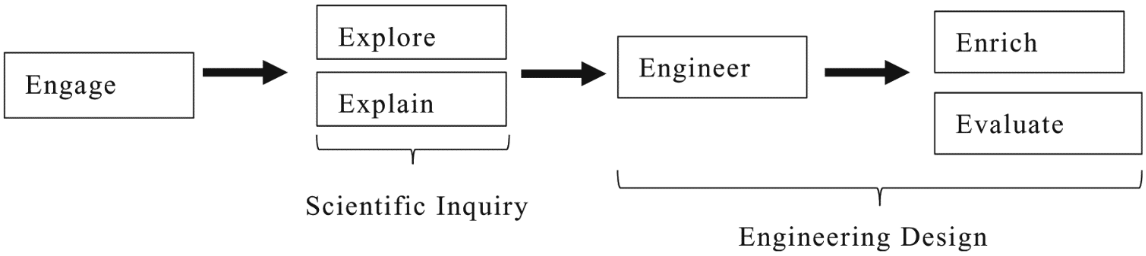

Figure 8. Scientific Inquiry as the Scaffolding Process for EDP (Yata et al., 2020, p. 3)

Fifth (5), the keywords in cluster 7 (e.g., women, gender, gap, career, impact, school, higher education, etc.) accentuated the research trends on EDP for narrowing gender gaps in STEM education. In various STEM fields of science, engineering and mathematics females are usually underrepresented compared to their male counterparts resulting in gender gaps (Pleasants & Olson, 2019; Yıldırım, Öcal, & Topalcengiz, 2021) possibly caused by various 'social determinants' in education, see Table 4 (Takeuchi et al., 2020; Y. Xie et al., 2015). Y. Xie et al. (2015) assert that STEM education can narrow these gaps by addressing some of the underlying social determinants, especially the *school characteristics* and *individual-level factors*, that strongly influence the participation of female students in the STEM fields. Their assertion has been supported by some research studies that evidence that STEM-based activities involving EDP can improve STEM learning, motivation, and interest of female students more than their male counterparts (e.g., Cheng et al., 2020; Waite et al., 2020). In contrast, other studies have reported no such differences in learning behaviors between the two genders (e.g., Chao et al., 2017; Zheng et al., 2020). Subsequently, more comprehensive research may be required to elucidate the matter.

Table 4. The Social Determinants Causing the Gender Gaps in STEM Fields (Y. Xie et al., 2015, pp. 334-339)

Social Determinants in STEM Education				
Contextual Factors		**Family-level Factors**	**Individual-level Factors**	
Neighborhood Disadvantages		*Family Structure*	*Metacognitive Skills*	Critical Thinking
School Characteristics	Teacher Quality	*Socio-economic Status*		Creativity
	Class Size	*Parenting Styles*	*Non-cognitive Skills*	Collaboration
	Infrastructure			Communication
				Motivation
				Confidence

Co-citation Analysis

In the present study, 36 out of 6808 cited references were identified with a *minimum number of citations* of 6: each reference was uniquely cited six or more times (Van Eck & Waltman, 2010) across the 142 articles. The network visualization map of these references is shown in Figure 9, whereas Table 5 displays the '10 most cited publications and authors' (see Appendix I for the full list). Furthermore, 30 out of 3731 publication sources were recognized with a *minimum number of references* of 24: each source had twenty-four or more uniquely cited references (Van Eck & Waltman, 2010) across the 142 articles. The network visualization map of these sources is shown in Figure 10, whereas Table 6 displays the ‘10 most cited sources’ (see Appendix II for the full list).

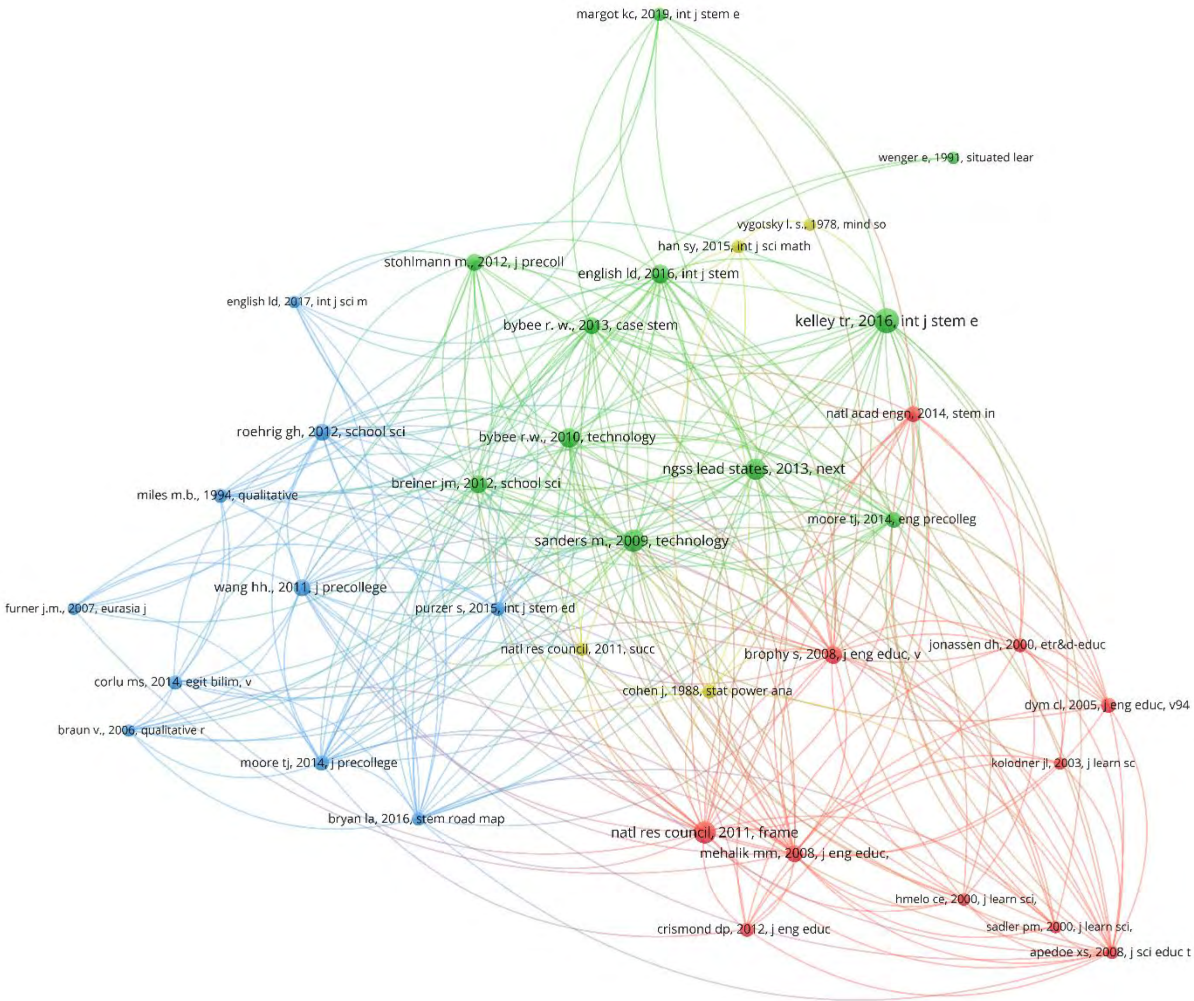

Figure 9. The Network Visualization Map of the ‘Document’ Co-citation Analysis

Table 5. The 10 Most Cited Publications and Authors (see Appendix I for the full list)

No.	Author(s)	Year	Title	Citations	Link Strength
1	Todd R. Kelley, J. Geoff Knowles	2016	A Conceptual Framework for Integrated STEM Education	25	117
2	Mark Sanders	2009	STEM, STEM Education, STEMmania	20	141
3	National Research Council	2011	A Framework for K-12 Science Education: Practices, Crosscutting Concepts, and Core Ideas	20	88
4	National Research Council	2013	Next Generation Science Standards: For States, By States	18	88

No.	Author(s)	Year	Title	Citations	Link Strength
5	Rodger W. Bybee	2010	Advancing STEM Education: A 2020 Vision	15	86
6	Lyn D. English	2016	STEM Education K-12: Perspectives on Integration	14	94
7	Jonathan M. Breiner, Shelly Sheats Harkness, Carla C. Johnson, Catherine M. Koehler	2012	What Is STEM? A Discussion About Conceptions of STEM in Education and Partnerships	13	97
8	Sean Brophy, Stacy Klein, Merredith Portsmore, Chris Rogers	2008	Advancing Engineering Education in P-12 Classrooms	13	86
9	Rodger W. Bybee	2013	The Case for STEM Education: Challenges and Opportunities	12	93
10	Matthew M. Mehalik, Yaron Doppelt, Christian D. Schunn	2013	Middle-School Science Through Design-Based Learning versus Scripted Inquiry: Better Overall Science Concept Learning and Equity Gap Reduction	12	90

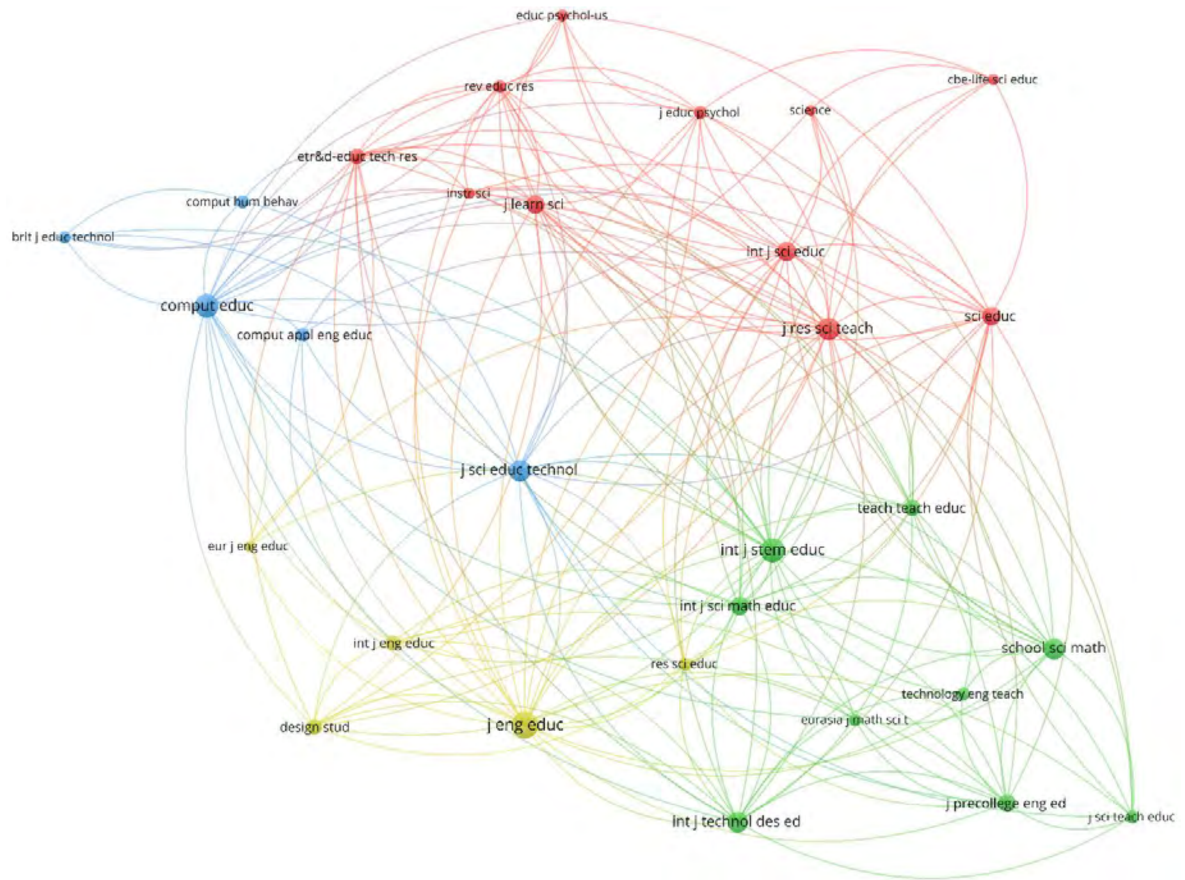

Figure 10. The Network Visualization Map of the 'Sources' Co-citation Analysis

Table 6. The 10 Most Cited Sources (see Appendix II for the full list)

No.	Type	Title	Citations	Link Strength
1	Journal	Journal of Engineering Education	139	1963
2	Journal	International Journal of STEM Education	118	1803
3	Journal	Computers & Education	108	1476
4	Journal	Journal of Research in Science Teaching	96	1569
5	Journal	School Science and Mathematics	89	1317
6	Journal	Journal of Science Education and Technology	87	1279
7	Journal	International Journal of Technology and Design Education	81	1336
8	Journal	International Journal of Science Education	70	1091
9	Journal	Science Education	68	963
10	Journal	Journal of the Learning Sciences	66	1104

Discussion

Possible Research Issues within the Clusters of Keyword Co-occurrence Analysis

The articles corresponding to each cluster of *keyword co-occurrence analysis* were carefully re-reviewed, especially their sections pertaining to *discussion*, *limitations*, and *conclusion*, in order to discover common themes alluding to possible research issues, as accomplished by comparable studies (e.g., Liao et al., 2018; Martinez et al., 2019). In this manner, a total of four possible research issues (see table 7) were discovered that are discussed below.

Table 7. Possible Research Issues Within the Clusters of Keyword Co-occurrence Analysis (from Table 3)

Clusters	Research Issues
1, 2, 5, 6	▪ Lack of explicit STEM knowledge integration through EDP
1, 2	▪ Deficiency of comprehensive professional development programs on EDP
3, 4	▪ Challenges in differentiating the roles of computational thinking and design thinking in EDP
5, 7	▪ Issues pertaining to the research on the manifestation of K-12 students' learning behaviors during EDP

First (1), there is a general lack of explicit STEM knowledge integration within STEM-based activities involving EDP, especially in the context of integrating the disciplinary core ideas and crosscutting concepts from different STEM disciplines (Bybee, 2011; Kelley & Knowles, 2016; Roehrig et al., 2021). For instance, research studies that have properly incorporated the knowledge integration aspect within the design of their interventions have reported significant improvements in their students' STEM knowledge (e.g., Bowen, DeLuca, & Franzen, 2016; Chiu et al., 2013) as compared to studies that have predominantly neglected this aspect (e.g., Dasgupta et al., 2019; Zheng et al., 2020). Moreover, some studies, though, have claimed to improve their students' STEM knowledge have lacked any rigorous quantitative evidence to back their pretense (e.g., English & King, 2015; Şen et al., 2020; Shahali et al., 2017). It is, therefore, suggested that future research should investigate how to properly achieve STEM-knowledge integration within the design and implementation of STEM-based activities for different K-12 STEM education contexts.

Second (2), there is a general deficiency of comprehensive professional development (PD) programs on EDP that can simultaneously integrate the conceptual knowledge (CK), technical knowledge (TK), and pedagogical knowledge (PK) of EDP for STEM education. For instance, the present PD programs can, perhaps, be divided into two categories. In the first category, the programs (e.g., Brand, 2020; E. Kim, Oliver, & Kim, 2019; Pleasants et al., 2020; Radloff & Capobianco, 2019) have placed a greater emphasis on the integration of the PK and CK; while in the second category, the programs (e.g., Hu et al., 2020; C. Kim et al., 2015; Kuen-Yi et al., 2021) have focused more on the integration of the TK and CK. Nevertheless, in order to achieve the overall integration of the "Technological, Pedagogical, and Content Knowledge" (TPACK) (Schmidt et al., 2009) of EDP, teacher trainees are potentially required to attend multiple PDs from both the categories. This is not only time-consuming but also resource-intensive for both the trainees and organizers. To address such issues, researchers have proposed alternate PD frameworks based on the TPACK model that can be explored in future research (e.g., Çakıroğlu & Kiliç, 2020; Chai, 2018; Chai, Jong, Yin, Chen, & Zhou, 2019; Ung et al., 2022).

Table 8. The Comparison between the Processes of CT (Anderson, 2016, pp. 228-229) and DT (Gordon et al., 2019, p. 32)

CT Processes	Descriptions	DT Processes	Descriptions
Problem Decomposition	▪ Break a complex problem into multiple smaller parts.	*Empathize*	▪ Identify and analyze the design preferences of the end-users.
Pattern Recognition	▪ Analyze for similar constraints within these parts.	*Define*	▪ Decompose the design problem into its constraints based on the preferences.
Abstraction	▪ Identify the critical parts from the superficial ones.	*Ideate*	▪ Negotiate the constraints to generate multiple solutions paths.
Algorithm Design	▪ Create a step-by-step solution to address each part.	*Prototype*	▪ Create different prototypes based on the solution paths.
Evaluation	▪ Evaluate the solution and optimize it if necessary.	*Test*	▪ Test the prototypes and improve them based on the design preferences.

Third (3), there are challenges in differentiating the roles of computational thinking (CT) and design thinking (DT) in EDP (Kelly & Gero, 2021). Primarily, because of the *a priori* similarities between the two in terms of the problem-solving processes (Kelly & Gero, 2021; Shute, Sun, & Jodi, 2017), see Table 8. One way to compare CT and DT is by identifying the different types of problems they can assiduously address (Shute et al., 2017). For instance, it has been asserted that CT excels in solving computational problems that have theoretical constraints (Bull, Garofalo, & Hguyen, 2020) while DT excels in solving design-based problems that have physical constraints (Y. Li et al., 2019). However, some researchers have duly pointed out that CT has applications beyond computer science (e.g., Anderson, 2016; Shute et al., 2017; Ung et al., 2022) – they have asserted that CT can solve a variety of problems that can also be design-based, open-ended, and non-computational in nature. These contrasting assertions have been carefully reviewed by Kelly and Gero (2021) in their theoretical analysis. And based on their analysis, they have suggested that perhaps CT and DT are "mirror images of each other in relation to the two ontological categories of solutions and framing" (p. 13). Subsequently, there is an emerging research gap to explore and compare the CT and DT processes (see Table 8), especially in terms of their interrelationship within EDP for STEM education.

Fourth (4), there are potential issues pertaining to research on the manifestation of K-12 students' learning behaviors during EDP. The first issue concerns behavior profiling that differs among studies. For example, studies can have three behavior profiles (S. Li, G. Chen, et al., 2020; S. Li, H. Du, et al., 2020), four behavior profiles (Zheng et al., 2020), or sometimes no (comprehensive) behavior profiles at all (Purzer et al., 2015). This issue raises the questions of whether behavior profiling is even necessary; and if it is, which of the profiling methods is more desirable and why? The second issue is regarding the 'stability' of the behavior profiles during EDP. For instance, S. Li, H. Du, et al. (2020) have stated that students' behavior profiles are stable, while S. Li, G. Chen, et al. (2020) and Zheng et al. (2020) have suggested otherwise, that these profiles are dynamic and may change with interventions. Lastly, the third issue pertains to the fact that the aforementioned studies do not strictly take in consideration the 'contextual factors' (e.g., gender, ethnicity, and other social determinants in education, see Table 4) that have known effects on students' learning behaviors (Y. Xie et al., 2015). It is, thus, suggested that future research should investigate these aforesaid issues in a rigorous manner.

Significance and Implications of Highly Co-cited Publications

The results of the *co-citation analysis* highlighted the most frequently cited publications within the bibliographies of the 142 articles. However, it was soon discovered that several of these publications (see Table 5 and Appendix I) were not part of the original 142 articles. This was primarily due to the requirements imposed by the inclusion criteria in Table 2. For example, certain publications were published prior to 2011 (e.g., Brophy, Klein, Portsmore, & Rogers, 2008; Bybee, 2010; Mehalik, Doppelt, & Schuun, 2008; Sanders, 2009), while others had literature types that were not journal articles (e.g., NRC, 2011, 2013). Nevertheless, since these publications generated a high citation impact as evidenced by the *co-citation analysis*, it is imperative to discuss their significance and implications in the research on EDP for STEM education (e.g., Breiner, Harkness, Johnson, & Koehler, 2012; Brophy et al., 2008; Bybee, 2010; English, 2016; Kelley & Knowles, 2016; Mehalik et al., 2008; NRC, 2011; Roehrig, Moore, Wang, & Park, 2012; Sanders, 2009; Wang, Moore, Roehrig, & Park, 2011).

One of the most cited publications was *STEM, STEM Education, STEMmania* by Sanders (2009). He has asserted the importance of defining STEM education from an 'integrative' perspective that promotes knowledge integration of the crosscutting concepts and disciplinary core ideas from science and mathematics. He has underscored the issue of *superficial* STEM education that entails learning of science and mathematics without any explicit integration within STEM-based activities. Likewise, he has criticized the implementation of STEM education as a standalone subject in K-12 because this undermines the cross-disciplinary aspect of STEM education. He has encouraged inclusion of ‘engineering education’ in STEM classrooms to promote applied learning and technological literacy. He did not, though, specify the scope of this engineering education, especially regarding its implementation in different K-12 contexts.

Another most cited publication was *Advancing STEM Education: A 2020 Vision* by Bybee (2010). He has ascertained development of STEM education from a policy point of view. He has concurred with Sanders (2009) on the promotion of an integrative perspective for STEM education in order to develop STEM competencies in K-12 students. He has defined these competencies in terms of three broad abilities. Firstly, the ability to identify and recognize STEM issues that can exist at personal, social, or global scales. Secondly, the ability to explain and resolve the STEM issues through application of cross-disciplinary STEM knowledge. Lastly, the ability to interpret and address socio-economic implications of the STEM issues. In accordance with Sanders (2009) and other educationists (e.g., Brophy et al., 2008; Mehalik et al., 2008), Bybee (2010) asserted for a top-down direction from policymakers to promote ‘integrative or integrated’ STEM education in K-12 through implementation of curriculum reforms and organization of professional development programs on engineering and technology education.

To impart a top-down direction, the NRC (2011) published *A Framework for K-12 Science Education*: the 3rd most cited publication. This framework laid the groundwork for the *Next Generation Science Standards* (NGSS) (NRC, 2013) that largely provided the policy directives for STEM education in the United States. To put it succinctly, the NGSS has stipulated the importance of promoting design thinking and computational thinking in STEM education, which in turn has stimulated the research on EDP for STEM education in K-12, as indicated by the *co-citation analysis* that ranked it as the 4th most cited publication.

The 1st most cited publication: Kelley and Knowles (2016)'s *A Conceptual Framework for Integrated STEM Education* is based on the NGSS. Their framework (see Figure 11) has attempted to elucidate the interrelationship among the four components of ‘situated or effective’ STEM education, namely scientific inquiry, EDP, mathematical thinking, and technological literacy. They have asserted that scientific inquiry should be employed for scaffolding and facilitating EDP for STEM education. Regardless, their framework has a consequential limitation that it assumes a ‘linear relationship’ among the four components (see Figure 11). For instance, in order to achieve technological literacy, the framework gives the impression that scientific inquiry, EDP, and mathematical thinking should be implemented *seriatim*. This impression is misleading because effective STEM education does not always entail integration of all four STEM disciplines but at least two of them (Bybee, 2011; NRC, 2011; Sanders, 2009). Furthermore, the framework does not take in consideration that STEM education can involve non-linear relationships among the four components due the complexity of its integration (i.e., the cross-disciplinarity of STEM education) that can be of three kinds, namely multidisciplinary, interdisciplinary, and transdisciplinary (English, 2016; Roehrig et al., 2021; Vasquez, 2013). For instance, in a transdisciplinary STEM education (Roehrig et al., 2021; Takeuchi et al., 2020), the processes of scientific inquiry, EDP, mathematical thinking, and technological literacy may become increasingly intertwined and hence, may lose their disciplinary distinctiveness.

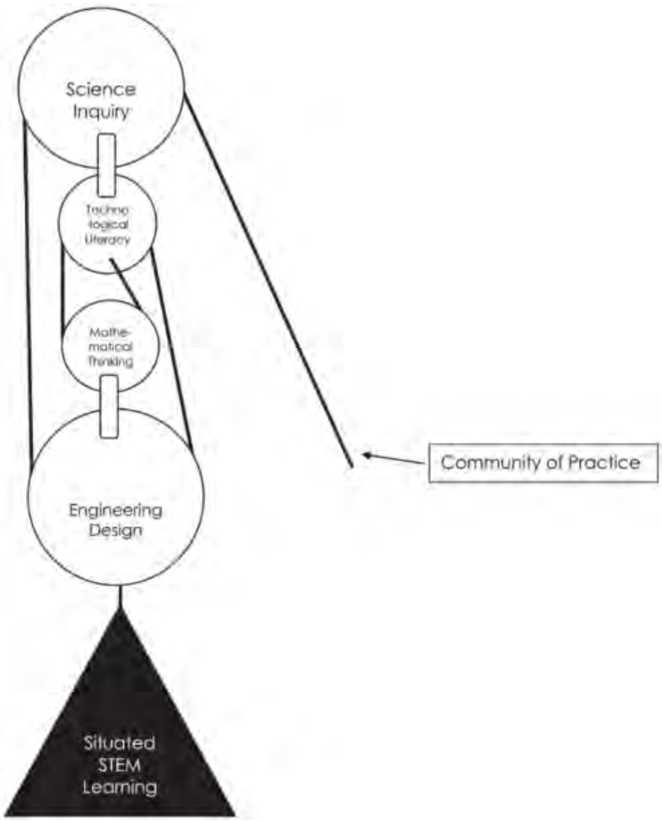

Figure 11. The Conceptual Framework for STEM Education by Kelley and Knowles (2016, p. 4)

Nevertheless, other highly co-cited publications have underscored the importance of providing K-12 teachers with professional development (PD) opportunities to improve their knowledge and readiness for EDP and STEM education (e.g., Breiner et al., 2012; Roehrig et al., 2012; Wang et al., 2011). For instance, Roehrig et al. (2012) have spotlighted the need for improving science and mathematics teachers' content knowledge and pedagogical content knowledge of EDP and STEM education. They have emphasized that PD programs should foster collaborations between science and mathematics teachers for development of theme-based STEM content that incorporates EDP along with scientific inquiry and mathematical thinking. To design such theme-based content, Wang et al. (2011) have asserted that teachers should increase their content knowledge of STEM education, develop their problem-solving skills in EDP, and improve their technological knowledge of engineering, especially regarding “the design, manufacture, operation, and repair of technological artifacts” (The National Academy of Engineering, 2011, as cited in Wang et al., 2011, p. 5). According to the research trends on EDP for STEM education, such artifacts can be based on virtual laboratories (Potkonjak et al., 2016), makerspaces (Kapon et al., 2021; Lin et al., 2020), digital fabrication techniques (Chiu et al., 2013) – such as CAD (Dasgupta et al., 2019; C. Xie et al., 2018) and 3D printing (Cheng et al., 2020; Şen et al., 2020), educational robotics (Bers et al., 2014; Pérez & López, 2019), block-based programming (Fidai et al., 2020; Waite et al., 2020), game designing (Ishak et al., 2021), as well as unplugged teaching-learning activities (Ung et al., 2022).

Conclusion

The study performed a comprehensive bibliometric analysis to identify and analyze the research trends and issues of engineering design process (EDP) for STEM education in K-12 from 2011 to 2021. The results identified five leading research trends: (1) the professional development of K-12 teachers to implement EDP for STEM education; (2) the promotion of design thinking and computational thinking through EDP in STEM education; (3) the importance of EDP in enhancing the STEM competencies of K-12 students; (4) the interplay between scientific inquiry and EDP in STEM education; and (5) the role of EDP in narrowing the gender gaps in STEM education. Moreover, four possible research issues were discovered with respect to the aforementioned trends: (i) the lack of explicit STEM knowledge integration through EDP; (ii) the deficiency of comprehensive professional development programs on EDP; (iii) the challenges in differentiating the roles of computational thinking and design thinking in EDP; and (iv) the issues pertaining to the research on the manifestation of K-12 students' learning behaviors during EDP.

In addition, the study highlighted the publications, authors, and sources that generated prominent citation impact on the research topic (see Appendix I & II). It was discovered that *A Framework for K-12 Science Education* was one of the most cited publications in this research as it laid the groundwork for the *Next Generation Science Standards* (NGSS) that largely provide the policy directives for STEM education in the United States. This was evidenced by the significant increase in the research throughput on EDP for STEM education since the framework's first release in 2011. There are, though, pertinent concerns regarding the implementation of the NGSS, especially at the grassroot level. For instance, educationists and policymakers need to work in conjunction in order to promote effective STEM education (involving EDP) within 'formal' K-12 school-based curricula. Likewise, they need to assiduously collaborate in order to develop 'standardized' evaluation and assessment tools for formative and summative assessments of students' learning performance and outcomes during STEM-based activities.

The study acknowledges the following limitations. Firstly, it analyzed the articles from only a single database. Future studies can include additional databases, such as *Scopus* and *ProQuest*. Secondly, the study utilized only two bibliometric techniques, namely keyword co-occurrence and co-citation analyses. Other techniques, such as bibliographic coupling and co-authorship analyses, can be employed by future studies to augment the analyses. Lastly, the inclusion criteria primarily considered journal articles from 2011 to 2021. This may have led to exclusion of certain research trends that could have developed outside this timeframe. Future studies may identify and analyze these trends by modifying the publication years requirement of the inclusion criteria.

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Appendix I

Most Cited Publications and Authors within the Reviewed Literature

No.	Author(s)	Year	Title	Citations	Link Strength
1	Todd R. Kelley, J. Geoff Knowles	2016	A Conceptual Framework for Integrated STEM Education	25	117
2	Mark Sanders	2009	STEM, STEM Education, STEMmania	20	141
3	National Research Council	2011	A Framework for K-12 Science Education: Practices, Crosscutting Concepts, and Core Ideas	20	20
4	National Research Council	2013	Next Generation Science Standards: For States, By States	18	88
5	Rodger W. Bybee	2010	Advancing STEM Education: A 2020 Vision	15	86
6	Lyn D. English	2016	STEM Education K-12: Perspectives on Integration	14	94
7	Jonathan M. Breiner, Shelly Sheats Harkness, Carla C. Johnson, Catherine M. Koehler	2012	What Is STEM? A Discussion About Conceptions of STEM in Education and Partnerships	13	97
8	Sean Brophy, Stacy Klein, Merredith Portsmore, Chris Rogers	2008	Advancing Engineering Education in P-12 Classrooms	13	86
9	Rodger W. Bybee	2013	The Case for STEM Education: Challenges and Opportunities	12	93
10	Matthew M. Mehalik, Yaron Doppelt, Christian D. Schunn	2013	Middle-School Science Through Design-Based Learning versus Scripted Inquiry: Better Overall Science Concept Learning and Equity Gap Reduction	12	90
11	Gillian H. Roehrig, Tamara J. Moore, Hui-Hui Wang, Mi Sun Park	2012	Is Adding the E Enough? Investigating the Impact of K-12 Engineering Standards on the Implementation of STEM Integration	12	78
12	Hui-Hui Wang, Tamara J. Moore, Gillian H. Roehrig, Mi-Sun Park	2011	STEM Integration: Teacher Perceptions and Practice	11	82

No.	Author(s)	Year	Title	Citations	Link Strength
13	Micah Stohlmann, Tamara J. Moore, Gillian H. Roehrig	2012	Considerations for Teaching Integrated STEM Education	11	73
14	Tamara J. Moore, Micah S. Stohlmann, Hui-Hui Wang, Kristina M. Tank, Aran W. Glancy, Gillian H. Roehrig	2014	Implementation and integration of engineering in K-12 STEM education	10	86
15	Margaret Honey, Greg Pearson, Heidi Schweingruber	2014	STEM Integration in K-12 Education: Status, Prospects, and an Agenda for Research	10	51
16	Tamara J. Moore, Aran W. Glancy, Kristina M. Tank, Jennifer A. Kersten, Karl A. Smith, Micah S. Stohlmann	2014	A Framework for Quality K-12 Engineering Education: Research and Development	9	62
17	Clive L. Dym, Alice M. Agogino, Ozgur Eris, Daniel D. Frey, Larry J. Leifer	2005	Engineering Design Thinking, Teaching, and Learning	9	38
18	Şenay Purzer, Molly Hathaway Goldstein, Robin S. Adams, Charles Xie, Saeid Nourian	2015	An Exploratory Study of Informed Engineering Design Behaviors Associated with Scientific Explanations	8	76
19	Matthew B. Miles, A. Michae Huberman	1994	Qualitative Data Analysis: An Expanded Sourcebook	8	46
20	David P. Crismond, Robin S. Adams	2012	The Informed Design Teaching and Learning Matrix	8	41
21	David H. Jonassen	2000	Toward a Design theory of Problem Solving	8	40
22	Sencer S. Corlu, Robert M. Capraro, Mary Margaret Capraro	2014	Introducing STEM Education: Implications for Educating Our Teachers for the Age of Innovation	8	39
23	Jacob Cohen	1988	Statistical Power Analysis for the Behavioral Sciences	8	36
24	Carla C. Johnson, Erin E. Peters-Burton, Tamara J. Moore	2016	STEM Road Map: A Framework for Integrated STEM Education	7	68

No.	Author(s)	Year	Title	Citations	Link Strength
25	Xornam S. Apedoe, Birdy Reynolds, Michelle R. Ellefson, Christian D. Schunn	2008	Bringing Engineering Design into High School Science Classrooms: The Heating/Cooling Unit	7	46
26	Sunyoung Han, Robert Capraro, Mary M. Capraro	2015	How Science, Technology, Engineering, and Mathematics (STEM) Project-Based Learning (PBL) Affects High, Middle, and Low Achievers Differently: The Impact of Student Factors on Achievement	7	30
27	Kelly C. Margot, Todd Kettler	2019	Teachers' Perception of STEM Integration and Education: A Systematic Literature Review	7	29
28	National Research Council	2011	Successful K-12 STEM Education	7	29
29	Philip M. Sadler, Harold P. Coyle, Marc Schwartz	2000	Engineering Competitions in the Middle School Classroom: Key Elements in Developing Effective Design Challenges	6	49
30	Cindy E. Hmelo, Douglas L. Holton, Janet L. Kolodner	2000	Designing to Learn About Complex Systems	6	44
31	Virginia Braun, Victoria Clarke	2006	Using Thematic Analysis in Psychology	6	36
32	Lyn D. English, Donna King, Joanna Smeed	2017	Advancing Integrated STEM Learning through Engineering Design: Sixth-grade Students' Design and Construction of Earthquake Resistant Buildings	6	35
33	Joseph M. Furner, David D. Kumar	2007	The Mathematics and Science Integration Argument: A Stand for Teacher Education	6	33

No.	Author(s)	Year	Title	Citations	Link Strength
34	Janet L. Kolodner, Paul J. Camp, David Crismond, Barbara Fasse, Jackie Gray, Jennifer Holbrook, Sadhana Puntambekar, Mike Ryan	2003	Problem-Based Learning Meets Case-Based Reasoning in the Middle-School Science Classroom: Putting Learning by Design into Practice	6	33
35	Jean Lave, Etienne Wenger	1991	Situated Learning: Legitimate Peripheral Participation	6	15
36	L. S. Vygotsky	1978	Mind in Society: The Development of Higher Psychological Processes	6	13

Appendix II

Most Cited Sources within the Reviewed Literature

No.	Type	Title	Citations	Link Strength
1	Journal	Journal of Engineering Education	139	1963
2	Journal	International Journal of STEM Education	118	1803
3	Journal	Computers & Education	108	1476
4	Journal	Journal of Research in Science Teaching	96	1569
5	Journal	School Science and Mathematics	89	1317
6	Journal	Journal of Science Education and Technology	87	1279
7	Journal	International Journal of Technology and Design Education	81	1336
8	Journal	International Journal of Science Education	70	1091
9	Journal	Science Education	68	963
10	Journal	Journal of the Learning Sciences	66	1104
11	Journal	International Journal of Science and Mathematics Education	64	992
12	Journal	Journal of Pre-College Engineering Education Research	60	962
13	Journal	Teaching and Teacher Education	53	554
14	Journal	Educational Technology Research and Development	48	1028
15	Journal	Design Studies	47	774
16	Journal	International Journal of Engineering Education	45	712
17	Journal	Computer Applications in Engineering Education	38	448
18	Journal	Journal of Educational Psychology	34	624
19	Journal	Computers in Human Behavior	34	400
20	Journal	Research in Science Education	33	615
21	Journal	Review of Educational Research	32	776
22	Journal	Journal of Science Teacher Education	32	400
23	Journal	Technology and Engineering Teacher	32	380
24	Journal	British Journal of Educational Technology	30	604
25	Journal	Eurasia Journal of Mathematics, Science and Technology Education	30	318
26	Journal	Instructional Science	27	562
27	Journal	CBE – Life Sciences Education	27	307
28	Journal	Educational Psychologist	25	583
29	Journal	European Journal of Engineering Education	24	430
30	Journal	Science	24	376