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Current perspectives on the value, teaching, learning, and assessment of design in STEM education

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Current perspectives on the value, teaching, learning, and assessment of design in STEM education

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Editorial: Current perspectives on the value, teaching, learning, and assessment of design in STEM education

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Editorial on the Research Topic
Current perspectives on the value, teaching, learning, and assessment of design in STEM education

1. Introduction

Despite the value that design methodologies have as a vehicle for learning science, technology, engineering, and mathematics (STEM)-related subject matter, their integration into STEM curricula remains a burgeoning phenomenon. The role of designing and the field's epistemological, ontological, axiological, and methodological foundations are still in the process of being shaped and refined by scholars in STEM-related fields. For instance, the knowledge base of designerly thinking and doing, though growing, is yet to be articulated in terms of "what" constitutes design knowledge, "how" it is constituted, "when" and "how" it is and can be acquired, and "why" it matters (Buckley et al., 2021). Furthermore, methodological frameworks for guiding, measuring, and evaluating designerly thinking, doing, and learning are in their developmental stages, indicating a need for empirical studies (Blom and Bogaers, 2020; Hartell and Buckley, 2021). The ontological perspectives of design—its nature, its purpose, and its role in learning and societal progress—are also subjects of ongoing discourse (Norström and Hallström, 2023). It is these challenges and opportunities that brought us to contribute to the maturation of these foundations, thereby cultivating a more robust understanding of design's role in STEM education.

2. Emergent themes in this Research Topic

Through the establishment of this Research Topic, we aimed to progress the conversation on the role or roles that design has and can have in STEM education. Ultimately, the topic consists of 11 articles which include reviews, original research, and a conceptual analysis. The included articles are diverse in nature, reflecting the myriad of ways in which both design and STEM can be conceived, and serving to advance this conversation while also illustrating its complexities. Several underlying themes permeate the included articles, but two take prominence: how design functions in the establishment of STEM curricula and the purpose of design in terms of the associated outputs. Within these themes, in some cases, solutions or answers are proposed to critical questions. For example, Hallström and Ankiewicz frame design as a critical mechanism for the successful integration of STEM domains. In other cases, design was less prominent in the presented study, but the questions posed remained relevant and thought-provoking. For example, Ghosh et al. present a study on vaccine development knowledge and its association with engagement in formal educational settings. While not explicitly related to design, it is one of the several studies (see, e.g., Behrendt et al.; Sudirman et al.) that stimulate the question of where design-related learning can, does, and should take place, which is related to both central themes. Given the contributions, we see their collective contribution as providing a platform to guide future discourse through their capacity to inform new questions, and as such, present their underlying themes in this way.

2.1. Design and STEM curricula

The first major question raised in considering design and STEM together is what is meant by STEM to begin with. Ilyas et al. discuss the siloed view of STEM, in which each of the four domains is considered separately, the embedded view of STEM, in which one STEM discipline is embedded within another, such as using an engineering design approach to teach a mathematical concept, and the integrated view of STEM, in which teaching and/or learning takes place among or between two or more STEM disciplines. This discourse on the various interpretations of STEM is further developed by Sun et al. by adding the dimension that STEM is often broadened into, among other abbreviated groupings, STEAM. In the silo and embedded views of STEM, design is seen to fit through its positioning within the individual disciplines. Nichols et al. and Oliveira and Bonito provide examples of this by considering how, through the design process, students in science classrooms can develop science and broader STEM competencies. In terms of integrated STEM, as previously noted, Hallström and Ankiewicz highlight the potential of design to act as a means of integration. In contrast, Sun et al., who introduced the idea of STEAM to this Research Topic, questioned how the various STEAM disciplines could be integrated into design education, highlighting a bi-directional relationship between design and STEAM.

2.2. Design outputs in STEM education

A second major theme that emerged is related to the product of the design process within STEM education. It is quite typical to conceive designerly outputs as artifacts, with an associated portfolio describing the design process. In this sense, the artifact is often a physical or virtual artifact, as is the case in the work of Nguyen. Some articles on this topic, however, highlight how this interpretation of an artifact may be too narrow. For example, Saha and Sudirman et al. present empirical studies that capture design through the lens of the teacher, with the output of the design process being a learning activity or experience. In Saha's study, emphasis is given to the teachers' design of a learning activity that mirrors the real-world experience of a transport engineer. Sudirman et al. examine this idea more broadly at a pedagogical framing level and speak to the design of inquiry-based vs. direct-instruction teaching methods. Finally, at the broadest level we see in this topic, Hendriana et al. expand this conversation through a discussion on teachers' capacity to design whole-learning environments within a humanist ethno-metaphorical framework.

3. Conclusion

This Research Topic underscores the dynamic and evolving nature of designerly learning within the context of STEM education and the necessity for these fields to continue to grow. The diversity of perspectives presented highlights the global importance of designerly thinking and doing in STEM education, as well as the shared challenges and triumphs experienced in different educational contexts. The breadth of research that is shared in this Research Topic highlights the urgency for a shift from traditional, siloed approaches toward more integrated, real-world, and student-centered strategies. Furthermore, it foregrounds the critical role that designerly thinking and doing, in combination with STEM education, can provide in addressing broader societal and sustainability issues. We hope this Research Topic will inspire and provoke thought, leading to the advancement of STEM education to meet the needs of learners in a rapidly changing world, and we look forward to continuing this important dialogue and supporting the evolution of STEM education for the betterment of learners and society at large.

Author contributions

All authors listed have made a substantial, direct, and intellectual contribution to the work and approved it for publication.

Conflict of interest

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COVID-19 school closures and chemistry-related competencies: A study of German students transitioning from primary to secondary school

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The COVID-19 pandemic led to temporary closures of schools around the world, resulting in a change from face-to-face teaching to distance teaching, which had been practiced minimally until then. In this study, we investigated the effects of pandemic-related school closures on students' chemistry-related competencies, at the transition from primary to secondary school. We also explored the extent to which at-home or in-school data collection influenced the results. We measured the competencies of 2,262 students from grades 5 to 9 in Germany. Data collection took place before, during, and after the pandemic-related school closures, based on test booklets completed by students. The results showed that the competencies of students in Chemistry, who were taught in school before the closures, were similar to those of students who were taught *via* distance learning. Thus, students' competencies were similar before and after the school closures. The school closures led to differences not only in teaching, but also in the way the data in this study was collected. During school closures, students worked on their test booklets at home, and before and after school closures, the data were collected at school. This also enabled us to examine the effects of the different data collection designs on the test scores. We found differences between the results of the test booklets completed at home, and those completed at school, only for younger students. For students in higher grades, there were no differences.

KEYWORDS

COVID-19, chemistry-related competencies, cumulative learning, transition, primary school, secondary school

Introduction

For successfully learning science, a cumulative learning process is necessary. Cumulative learning refers to integrating new content into the knowledge acquired earlier by students (Lee, 2012). Hence, competencies acquired in primary school should be aligned with the new, more demanding requirements of secondary school (Hempel, 2010). Thus, learning should be cumulative, not only within each type of school, but also across different types of schools. This is especially important since the home and school environment shows a major impact on cumulative learning (Oludare and Alade, 2018). For cumulative learning to succeed at the transition between primary and secondary education, the curricula of various subjects play a crucial role. In these curricula, ideas that build on each other must be clearly defined, so that the development of competencies can be adequately supported over a long period of time (Shin et al., 2017).

The level to which these competencies, expected in different types of schools, are actually aligned, differs between different countries and the science-related subjects taught there. Some countries, such as the United States, teach one integrated subject, science, as shown by the Benchmarks for Science Literacy (American Association for the Advancement of Science, 2001, 2013), and the Next Generation Science Standards (National Research Council, 2013). The competencies formulated in the Benchmarks for Science Literacy span from kindergarten to grade 12, and build on each other (American Association for the Advancement of Science, 2001). Other countries do not provide curricula for one subject for science across all school levels, because science is divided into separate disciplines. In most European countries, for example, a general subject — science, is taught in primary school. This is replaced by the separate subjects of biology, physics, and chemistry in secondary school. Only a few European countries (Italy, Luxembourg, Iceland, Norway, Turkey, and parts of Belgium) teach science throughout lower secondary school as a single subject (Education, Audiovisual and Culture Executive Agency, 2011).

To assess whether scientific competencies can be developed cumulatively at the transition, despite the different subjects taught, the curricula of the various science subjects in the transition period must be compared. In Germany, the expected competencies in chemistry are of special interest for the transition between primary and secondary education. This study focuses on the situation in North Rhine-Westphalia, on behalf of all other German states. In particular, chemistry as an individual subject, only starts in grade 7 or 8 (age: 12/13 years), but is supposed to enhance the existing competencies of students from primary school ending in grade 4 (age: 10 years). The curricula in both primary and secondary school in Germany address competencies in the context of the following content: combustion, states of aggregate, substance properties, solutions, and energy (Ministerium für Schule und Weiterbildung des Landes Nordrhein-Westfalen, 2008, 2013; Ministerium für Schule und Bildung des Landes Nordrhein-Westfalen, 2021). This provides a good foundation for a cumulative learning process, because the competencies in both curricula build on each other. Nevertheless, the transition from primary to secondary school is not always successful. Various international school comparison studies show that there are differences between German students, with regard to their expected and acquired competencies. While 72 % of German 4TH graders achieve an intermediate or high competence level in science, according to the Trends in International Mathematics and Science Study 2019 (Mullis et al., 2020), the Program for International Student Assessment 2018 reveals that only 58 % of German 9TH graders achieve an intermediate or high competence level in science (Organization for Economic Cooperation and Development, 2019). Consequently, the fact that the structure of the competencies of the curricula can enable cumulative learning processes does not mean that this learning process actually occurs. Studies describing the development of science literacy across grades have been undertaken in various countries, such as the United States and the United Kingdom (American Association for the Advancement of Science, 2001; Wiser et al., 2012; Waldo, 2014). For Germany, however, such studies exist only for specific contents, such as magnetism (Möller, 2016), or they refer to specific periods within teaching chemistry, such as the strand maps with learning progressions developed by Celik and Walpuski (2018) for the first years of learning chemistry. Chemistry-related competencies, at the transition between primary and secondary school, still need further study.

During of the COVID-19 pandemic, schools were closed for several weeks, or even months, in many countries around the world, and students had to engage in distance learning. This change in teaching impacted students' learning and performance in different subjects. Hammerstein et al. (2021) summarized the effects of school closures on student achievements, in a review of several independent studies. School closures during the pandemic were found to have a predominantly negative impact on students' achievement. These findings were particularly evident for younger students, and those from families with low socioeconomic status (Hammerstein et al., 2021). For example, Tomasik et al. (2021) investigated students' achievement in mathematics and German, in primary and secondary schools. They found that the learning progress in the period before the school closures in primary school was more than twice of that during the school closures. On the contrary, they could not find this difference at the secondary level (Tomasik et al., 2021).

Most of the studies summarized by Hammerstein et al. (2021) refer to students' achievement in mathematics or different languages, but Maldonado and De Witte (2020) additionally focused on science. Using standardized tests that were administered at the end of primary school in Switzerland, they showed that the test scores decreased significantly from 2019 to 2020 (Maldonado and De Witte, 2020). This result provides preliminary evidence that school closures during the COVID-19 pandemic affected scientific skills at the transition from primary to secondary education negatively; however, chemistry-specific data are missing.

The purpose of the current study was to examine students' chemistry-related competencies, at the transition between primary and secondary education, in general. However, the study was expanded amid the pandemic, to include the influences of COVID-19-related school closures. For this purpose, we collected data before, during, and after the school closures. During school closures, we could not collect the data in a face-to-face teaching environment. Instead, students completed the test booklets at home, for the assessment. The two following research questions were addressed in this study:

1. How do students' chemistry-related competencies differ at the transition between primary and secondary education, before and after COVID-19-related school closures?

2. To what extent does the design of data collection (at home or face-to-face teaching) influence measurement results?

Method

Participants and procedure

To answer the two research questions, we used a sample of 2,262 students from Germany. Parents were informed about the study by a letter to parents, and the respective school principals consented to the data collection. Since the data was collected pseudonymously, no further consent was required. In Germany, one integrated subject comprising all social and natural sciences is taught in primary school (grades 1–4; age: 6–10 years). Chemistry contents are also included in this subject. Subsequently, either biology and physics or one subject including all natural sciences are taught in secondary school from grade 5 onward. As described in the introduction, chemistry as an independent subject starts in grade 7 or 8 (age: 12/13 years). Hence, the transition from primary to secondary education, with respect to the subject of chemistry, covers the period from grades 5–7, or 8. We measured the competencies of students in grades 5–9 to investigate this transition period and their first year in chemistry.

The grade in which chemistry is taught for the first time differs between the participating schools. Therefore, we do not refer to grades, but to the following measurement points within the transition period:

Start of the **t**ransition period (ST).
Middle of the **t**ransition period **1** (MT1).
Middle of the **t**ransition period **2** (MT2).
Start of the first year in **c**hemistry (SC).
End of the first year in **c**hemistry (EC).

The measurement point MT2 exists only in schools that do not teach chemistry in grade 7, and whose transition period, therefore, comprises 3 years. **Figure 1** provides an overview of all assessments and all measurement points of data collection. The first assessment took place before the COVID-19 pandemic, in summer 2019. At that time, we had planned two assessments for each subsample, resulting in a quasi-longitudinal study comprising the beginning of secondary education until the end of the first year of chemistry education. For this reason, the first assessment comprised the measurement points ST, MT2, and SC, while the second assessment covered the measurement points MT1, SC, and EC. In the second assessment, we consulted the same sample as in the first assessment one year later for a longitudinal comparison within the transition period. The second assessment took place during the COVID-19-related school closures, in summer 2020. To obtain an overall larger sample, and more opportunities for comparison, especially regarding the closure effects, we added a third assessment after the school closures in summer 2021. In order to merge the additional data, with the data collected from the first two assessments, it was important to measure the same age groups at the measurement points. The additional, third assessment therefore includes all 5 measurement points of the first two assessments.

We analyzed different subsamples to answer the two research questions. To compare competencies before and after the school closures, we were able to use data from the first and the third assessment. In both cases, data were collected in a face-to-face teaching environment, and therefore, are comparable. Data regarding measurement points ST, MT2, and SC were available for both assessments, so we were able to use the entire sample (990 students) from the first assessment and a subsample (419 students) from the third assessment. To compare the effects of the different assessment situations (school and home), we analyzed data from the second and the third assessment. Both assessments took place after a long period of school closures, and therefore, differed with regard to the assessment situation despite their similarities. For this comparison, data regarding measurement points MT1, SC, and EC were available, so we were able to use the entire sample (496 students) from the second assessment, and a subsample (414 students) from the third assessment.

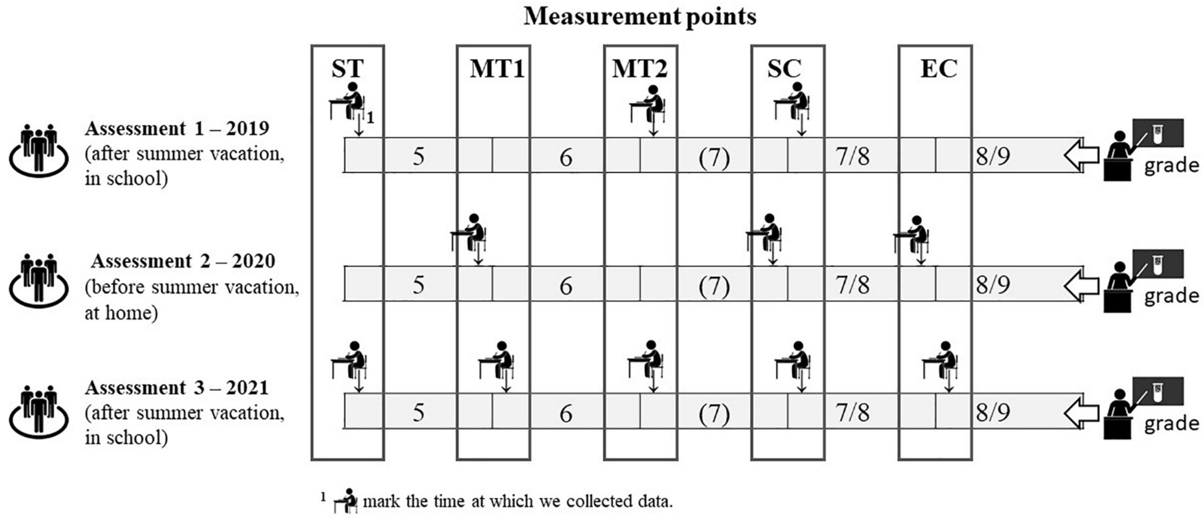

FIGURE 1
Assessments and measurement points.

Instruments

To measure students' chemistry-related competencies, we developed a new test instrument. In the first step, we identified the competencies to be measured, based on the curricula for the subjects containing chemistry-related contents in primary and secondary school. We used these competencies for developing a paper-pencil test with multiple-choice items. Each item contains six answer options. For each option, learners had to decide whether this answer was correct or incorrect, or whether they were unsure about it. Thus, one point could be scored for each answer option, and zero to six points could be scored for each item. Based on the competencies addressed in the chemistry curriculum in Germany, 24 items were developed for content knowledge (CK) with each 8 items each for the key concepts of chemical reactions, structure of matter, and energy, and for procedural knowledge (PK) with the categories of scientific inquiry, communication, and decision-making. To reduce the test time, we created test booklets with either 20 or 32 items, depending on the grade level. All test booklets contained items based on the competencies of the primary school curriculum. In the test booklets for students in the first year of learning chemistry, there were additional items based on the competencies of the chemistry curriculum. The different test booklet versions were linked by a balanced incomplete block design. Each test booklet contained items for two key concepts from the category CK, and for two categories of PK.

To validate the test instrument, we carried out an expert rating in which seven raters were asked to assign the developed items to the categories CK, scientific inquiry, communication, and decision-making. The interrater reliability was $\kappa_{Fleiss} = 0.795$. After a subsequent revision of some items, we administered the test instrument to 760 students (grades 4–8) in a pilot study. To investigate the quality of the test instrument, we conducted separate item response theory (IRT) analyses for CK and PK. Due to the item format, with zero to six achievable points each, we used the rating scale model. We found satisfactory reliabilities (person $reliability_{CK} = 0.75$; item $reliability_{CK} = 0.99$; person $reliability_{PK} = 0.81$; item $reliability_{PK} = 0.99$). For this reason, we only improved the items in which we identified comprehension difficulties during data collection.

In addition to the newly developed test instrument, we used existing test instruments to assess additional skills of the students as control variables. First, we used the Kognitiver Fähigkeitstest (KFT) (Heller and Perleth, 2000) to measure cognitive skills, and second, the Lesegeschwindigkeits- und Verständnistest (LGVT) (Schneider et al., 2017) to measure reading comprehension.

Data processing (main study)

To evaluate the data, we performed separate IRT analyses for CK and PK, using the rating-scale model, as in the pilot study. We used the estimated person parameters, to compare different subsamples. To analyze whether statistically significant differences exist between groups, we performed either a *t*-test for independent samples, or an analysis of covariance (ANCOVA). The ANCOVA allowed us to include the control variables as covariates,

TABLE 1 Reliabilities, infit, and discrimination estimated in the rating scale model.

	Total	MP 1	MP 2	MP 3
Content knowledge				
Person reliability	0.79	0.74	0.86	0.75
Item reliability	1.00	1.00	1.00	0.99
Infit	*M* = 1.08 *SD* = 0.24 *Min*: 0.71 *Max*: 1.55	*M* = 1.07 *SD* = 0.24 *Min*: 0.70 *Max*: 1.52	*M* = 1.08 *SD* = 0.28 *Min*: 0.75 *Max*: 1.73	*M* = 1.10 *SD* = 0.26 *Min*: 0.64 *Max*: 1.58
Discrimination	*Min*: 0.56 *Max*: 1.34	*Min*: 0.67 *Max*: 1.39	*Min*: 0.19 *Max*: 1.35	*Min*: 0.43 *Max*: 1.44
Procedural knowledge				
Person reliability	0.82	0.80	0.89	0.75
Item reliability	1.00	0.99	0.99	0.99
Infit	*M* = 1.03 *SD* = 0.21 *Min*: 0.66 *Max*: 1.54	*M* = 1.02 *SD* = 0.23 *Min*: 0.65 *Max*: 1.62	*M* = 1.04 *SD* = 0.21 *Min*: 0.66 *Max*: 1.58	*M* = 1.04 *SD* = 0.20 *Min*: 0.67 *Max*: 1.41
Discrimination	*Min*: 0.37 *Max*: 1.24	*Min*: 0.28 *Max*: 1.29	*Min*: 0.33 *Max*: 1.32	*Min*: 0.48 *Max*: 1.24

TABLE 2 Comparison of person parameters (measurement points 1 and 3) *t*-test for independent samples.

Group	Sample size	Mean value	Levene-test	*t*-test
Content knowledge				
Total	n_1 = 972 n_3 = 391	M_1 = −0.25 M_3 = −0.19	*p* = 0.543	*t*(1361) = 2.10, *p* = 0.036, *d* = 0.126
ST	n_1 = 458 n_3 = 171	M_1 = −0.30 M_3 = −0.37	*p* = 0.596	*t*(627) = 1.51, *p* = 0.132, *d* = 0.135
MT2	n_1 = 102 n_3 = 142	M_1 = −0.18 M_3 = 0.02	*p* = 0.730	*t*(242) = 3.05, *p* = 0.003, *d* = 0.396
SC	n_1 = 412 n_3 = 78	M_1 = −0.22 M_3 = −0.15	*p* = 0.845	*t*(488) = 0.99, *p* = 0.324, *d* = 0.122
Procedural knowledge				
Total	n_1 = 969 n_3 = 391	M_1 = 0.12 M_3 = 0.16	*p* = 0.318	*t*(1358) = 0.91, *p* = 0.365, *d* = 0.054
ST	n_1 = 457 n_3 = 171	M_1 = 0.04 M_3 = −0.03	*p* = 0.338	*t*(626) = 1.27, *p* = 0.206, *d* = 0.114
MT2	n_1 = 102 n_3 = 142	M_1 = 0.21 M_3 = 0.38	*p* = 0.471	*t*(242) = 2.10, *p* = 0.037, *d* = 0.273
SC	n_1 = 410 n_3 = 78	M_1 = 0.20 M_3 = 0.18	*p* = 0.507	*t*(486) = 0.29, *p* = 0.773, *d* = 0.036

in case the groups differed regarding to those control variables. We used the raw scores of the LGVT, which were identically scaled for all grades, and estimated person parameters for the KFT using IRT analyses, since the items on this test varied across grades, and the raw scores were not comparable.

Results

To check the quality of the test instrument, we first examined the statistical parameters determined in the rating-scale model. Table 1 provides an overview of the statistical parameters. We found good person and item reliabilities for both, CK and PK. In both cases, the person reliability was higher for the second assessment, compared to the first and third assessments. This may indicate that students worked more conscientiously on the test booklets at home, than at school. The infit values and discriminations were almost all satisfactory. Overall, we were able to achieve a good quality of the test instrument. Consequently, we used the person parameters for CK and PK estimated in the rating-scale model across all three assessments, to compare different subsamples in terms of the research questions.

Student performance before and after the school closures

We compared students' competencies before and after the school closures. To do so, we used data from the first and the third assessments. Data from three measurement points (ST, MT2, and SC) were available for the comparison. First, we investigated the comparability of the cohorts from both assessments. We found no significant differences between the two cohorts, in terms of the control variables cognitive skills [$t(1398) = 1.59$, $p = 0.113$, $d = 0.093$] and reading comprehension [$t(1376) = 1.04$, $p = 0.298$, $d = 0.062$]. For this reason, we did not include covariates, but conducted *t*-tests for independent samples when comparing the person parameters for CK and PK.

We compared the person parameters for both assessments, in general as well as for the subsamples at each measurement point. Table 2 provides an overview of the results of all *t*-tests for independent samples. For the total sample, we found a significant difference, with a small effect in CK, with lower person parameters before school closures than after them. By contrast, there was no significant difference in PK. At the measurement point ST, there were no significant differences in CK or in PK. At measurement point MT2, by contrast, we were able to find a highly significant difference with a small effect in CK, and a significant difference with a small effect in PK with lower person parameters before the school closures. At measurement point SC, again, we could not find any significant differences in either CK or PK.

Overall, this finding is contrary to expectations. It is not plausible that the competencies of those who had not previously received any face-to-face science instruction were higher only in the middle of the transition period in grade 7, while no difference could be found either at the beginning or at the end of the transition phase. For this reason, we examined person parameters in more detail, at measurement point MT2. We found an anomaly while comparing the mean person parameters of the classes involved in the data collection. In the third assessment, the three classes that achieved the highest mean person parameters were three classes from the same school. The school could not provide any classes from that grade level for data collection in the first assessment. It is likely that these three classes caused the differences between the two assessments, at measurement point MT2. For this reason, we conducted an additional *t*-test for independent samples for CK and PK, excluding the three classes from the sample. In these *t*-tests, there were no significant differences in either CK [$t(173) = 0.50$, $p = 0.618$, $d = 0.077$] or PK [$t(173) = 0.07$, $p = 0.942$, $d = 0.011$]. Overall, we concluded that chemistry-related competencies did not differ from each other, at any of the three measurement points. Thus, students' competencies were similar before and after the COVID-19-pandemic school closures. We also showed that the difference in competencies, between the beginning and end of the transition period, was similar before and after the school closures. *T*-tests showed that for both the first [CK: $t(868) = 2.25$, $p = 0.025$, $d = 0.153$; PC: $t(835.97) = 3.85$, $p < 0.001$, $d = 0.263$] and the third assessments [CK: $t(247) = 3.13$, $p = 0.002$, $d = 0.428$; PC: $t(247) = 2.85$, $p = 0.005$, $d = 0.390$], person parameters were significantly higher at the end of the transition period, than at the beginning of the transition period. Person parameters differed by approximately 0.1–0.2 logits, in both CK and PK, on both assessments.

A possible explanation for these findings is that the quality of face-to-face and distance teaching was comparable, and that students who engaged in face-to-face learning before the pandemic acquired the same competencies as students engaged in distance learning. However, this explanation would contradict Hammerstein et al.'s (2021) finding, that school closures during the COVID-19-pandemic had a negative impact on school performance, particularly for younger students. Another possible explanation is that the measured chemistry-related competencies were largely not acquired in the classroom. It is possible that these were competencies the students acquired outside the classroom, for instance, in a family context. Kähler et al. (2020) showed that some characteristics of the home environment have influences on the science competencies of kindergarten-aged children in Germany. It would be conceivable that science competencies of young students were influenced not only by school, but also by the family and home environments.

Effects of the different assessment situations

In a further step, we compared the students' person parameters from the second and third assessments, to identify the effects of the different assessment situations. In the second assessment, the students processed their test booklets at home after a long period of school closures. At the third assessment, they completed the test booklets at school, but also after a long period of school closures. We compared both, the total sample from the two assessments, as well as the different measurement points, MT1, SC, and EC, separately. Again, we first examined the extent to which the two cohorts were samples with similar characteristics. We did not consider the control variable reading comprehension, because we could observe from the completely filled in LGVT test booklets that many students had worked on it longer than allowed. As the LGVT is a speed test, we did not compare the LGVT results from either of the assessments. However, we compared the control variable cognitive skills between the assessments. It showed a highly significant difference [$t(784) = 2.87$, $p = 0.004$, $d = 0.205$]. We found this difference for the subsample at measurement point MT2 [$t(261.52) = 2.60$, $p = 0.010$, $d = 0.304$]. For the measurement points SC [$t(143) = 1.52$, $p = 0.131$, $d = 0.271$] and SE [$t(312.59) = 0.20$, $p = 0.841$, $d = 0.022$], we found no significant differences between the two assessments. Consequently, we included the control variable cognitive skills as a covariate, in an ANCOVA for the total sample and for the measurement point MT2 in the comparisons

TABLE 3 Comparison of person parameters (measurement points 2 and 3) *t*-test for independent samples and ANCOVA.

Group	Sample size	Mean value	Levene-test	*t*-test/ANCOVA
Content knowledge				
Total	$n_2 = 495$ $n_3 = 345$	$M_2 = 0.09$ $M_3 = 0.01$	$p = 0.517$	$t(838) = 1.98$, $p = 0.048$, $d = 0.139$
	$n_2 = 381$ $n_3 = 339$	$M_2 = 0.09$ $M_3 = 0.01$	$p = 0.909$	$F(1, 717) = 4.05$, $p = 0.045$, partial $\eta^2 = 0.006$
MT1	$n_2 = 223$ $n_3 = 131$	$M_2 = 0.02$ $M_3 = -0.20$	$p = 0.344$	$t(352) = 3.60$, $p < 0.001$, $d = 0.396$
	$n_2 = 176$ $n_3 = 126$	$M_2 = 0.03$ $M_3 = -0.20$	$p = 0.565$	$F(1, 299) = 12.10$, $p = 0.001$, partial $\eta^2 = 0.039$
SC	$n_2 = 48$ $n_3 = 78$	$M_2 = -0.07$ $M_3 = -0.15$	$p = 0.442$	$t(124) = 0.68$, $p = 0.498$, $d = 0.125$
EC	$n_2 = 224$ $n_3 = 136$	$M_2 = 0.19$ $M_3 = 0.30$	$p = 0.661$	$t(358) = 1.65$, $p = 1.00$, $d = 0.179$
Procedural knowledge				
Total	$n_2 = 490$ $n_3 = 345$	$M_2 = 0.43$ $M_3 = 0.28$	$p = 0.001$	$t(832.999) = 3.55$, $p = 0.001$, $d = 0.235$
	$n_2 = 378$ $n_3 = 339$	$M_2 = 0.48$ $M_3 = 0.28$	$p < 0.001$	$F(1, 714) = 24.46$, $p < 0.001$, partial $\eta^2 = 0.033$
MT1	$n_2 = 222$ $n_3 = 131$	$M_2 = 0.41$ $M_3 = 0.23$	$p = 0.208$	$t(351) = 2.92$, $p = 0.004$, $d = 0.322$
	$n_2 = 176$ $n_3 = 126$	$M_2 = 0.42$ $M_3 = 0.24$	$p = 0.113$	$F(1, 299) = 8.96$, $p = 0.003$, partial $\eta^2 = 0.029$
SC	$n_2 = 47$ $n_3 = 78$	$M_2 = 0.38$ $M_3 = 0.18$	$p = 0.999$	$t(123) = 1.73$, $p = 0.086$, $d = 0.320$
EC	$n_2 = 221$ $n_3 = 136$	$M_2 = 0.46$ $M_3 = 0.38$	$p < 0.001$	$t(348.732) = 1.22$, $p = 0.224$, $d = 0.116$

of the person parameters in CK and PK. Not all students completed the KFT at home, reducing the sample size of the ANCOVA by 120 cases in CK, and by 118 cases in PK. For this reason, we additionally conducted a *t*-test for independent samples.

Table 3 provides an overview of the results. For the total sample, we found differences in both the *t*-test for independent samples, and the ANCOVA in CK and PK. In both cases, the person parameters were higher for the second assessment compared to the third assessment. We also found this difference for the subsample of the measurement point MT2. For the measurement points SC and EC, we did not find a significant difference in the *t*-tests performed, for either CK or PK. In summary, for younger students, we measured higher competencies with the test booklets worked on at home, rather than with the test booklets worked on at school. We did not find these differences for older students, in their first year of learning chemistry.

A possible reason for these findings is that the students might not have adhered to the instructions, during the data collection at home. It is possible that they disregarded the specified time windows, as they did in the LGVT, and also other rules, such as working on the test items without outside help. As a result, they might have had advantages over students whose data were collected through a face-to-face teaching environment. It is also possible that the younger students were supervised more closely by their parents during the tasks at home and therefore, performed better, while the older students mainly worked by themselves. In contrast to these rather negative effects of working on the test booklets at home, we also have to consider that we found higher person reliabilities, in the rating-scale model for the items worked on at home. This suggests that the students worked more conscientiously at home than at school. Therefore, we assumed that the conditions prevalent at home also had a positive effect on the accuracy of the test results. It is possible that the students were less distracted there than in a data collection at school, could concentrate better on the processing of the items, and consequently, achieved better results.

Discussion

Conclusion

First, the results of the study show that chemistry-related competencies of students at the transition, before the COVID-19 pandemic were similar to those after school closures during the pandemic. The research situation is not conclusive in this context. Some studies report disadvantages in learning due to school closures (e.g., Hammerstein et al., 2021), while other studies demonstrate good learning outcomes with digital materials (e.g., Amilyana et al., 2021; Meeter, 2021). Second, the results show that younger students achieved better test scores when they completed the test booklets at home, rather than at school. Evidence from homework-studies suggests desirable effects on completion only for younger students, because they appear to have less developed study and of self-management habits (Patall et al., 2008). This may also apply to testing situations. From these findings, we can draw implications for science education at this transition, and for data collection.

According to the results, it is not relevant for the competencies in the transition phase whether the instruction previously took place in face-to-face or distance learning. On the one hand, it is conceivable that chemistry-related competencies are taught to a lesser extent than, for example, mathematical or linguistic competencies, so that the difference between face-to-face and distance learning is not as significant. On the other hand, before and after the school closures, there was a difference in competencies between the beginning and the end of the transition phase. Consequently, students acquired competencies during that transition phase, regardless of whether they were taught in face-to-face settings. Therefore, it is possible that the students acquired some of the measured competencies outside of the school context. Consequently, we should take care to ensure that students acquire chemistry-related competencies more systematically in school. For that purpose, we should use the curricula of the subjects involved, and ensure an exchange between the teachers of both school types, in order to promote cumulative learning processes.

The results on the different designs of data collection suggest that younger students were less likely to comply with test-taking instructions at home, or that they were better able to concentrate at home. To verify the reasons for the measured differences, we would need to conduct further data collection, and control for conditions at home.

Limitations

This study has the following limitations. First, some of the subsamples are incomplete, or significantly smaller than other subsamples. This is especially true for the second measurement point. Here, only about half of the test booklets distributed to the students were completed and returned. In addition, we cannot substantiate explanatory approaches relating to the conditions of the testing situation at home, based on this data. They are merely assumptions. Finally, we must consider that the sample used is limited to only a few schools in Germany. Therefore, we cannot generalize these results for the whole of Germany, or for other countries.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Ethics statement

Written informed consent was obtained from the individual(s) for the publication of any potentially identifiable images or data included in this article.

Author contributions

All authors listed have made a substantial, direct, and intellectual contribution to the work, and approved it for publication.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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The theoretical framework on humanist ethno-metaphorical mathematics learning model: An impactful insight in learning mathematics

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The educational revolution has posed an immense challenge to the world of education. It demands the development of a generation that can take on the challenges and changes bred by the ever-rapid revolution. It is thus inevitable that education must enable improvements of individual hard skills and soft skills that are required to keep up with such changes, including mathematical hard skills and soft skills. The problem is that not all mathematics learning approaches, particularly in the case of Indonesia, are capable of such improvements and of answering to such demands, challenges, and changes that are posed by the revolution. This research seeks to build a theoretical framework out of a systematic analysis based on various pieces of literature that are relevant and fitting to the theoretical framework under development. In this study, a theoretical framework on humanist ethno-metaphorical mathematics learning is developed as a theoretical foundation. This theory is designed for creating a humanist mathematics learning approach based on ethnomathematics and metaphorical thinking to develop students' mathematical hard skills and soft skills and thus enable them to deal with the current and future problems and changes.

KEYWORDS
humanist ethno-metaphorical mathematics learning, integrative literature review, metaphorical thinking, mathematical soft skills, mathematical hard skills

Introduction

The educational revolution in this era has brought with it various significant challenges and changes to human life (Petrillo et al., 2018). Every single aspect moves rapidly, connections form vastly, and novel innovations emerge. This is especially triggered using Internet of Things (IoT)- and

Artificial Intelligence (AI)-based technology in various human needs and occupational fields (Chou, 2018). Such a condition compels humans to make acceleration and enhance their abilities to take on the challenges and changes posed by this era and to leverage them to bring forth changes that are favorable for the world and human civilization (Teck et al., 2019; Maryanti et al., 2020). It is, thus, important to build humans of innovation and creativity who remain in the realm of humanism and nationalism. One way to arrive at this end is to improve hard skills and soft skills and to instill ethics, culture, character, and nationalism in education or school settings (Hendriana et al., 2017b; Anggadwita et al., 2021), as is summarized in **Figure 1**.

Professional hard skills and soft skills in life and the job world that are technology-based as in today's era are of the utmost importance (Hendriana et al., 2017b; Rohaeti, 2019). In this case, the science of mathematics plays a central role in improving both said hard and soft skills (Hendriana, 2017a). The former include cognitive abilities such as mathematical understanding ability, mathematical reasoning ability, mathematical problem-solving ability, mathematical communication ability, mathematical connection ability, mathematical critical-thinking ability, and mathematical creating thinking ability, to name just a few, while the latter encompasses affective abilities such as mathematical disposition, habits of mind, learning activeness, learning interest, learning motivation, mathematical resilience, self-concept, self-confidence, self-efficacy, self-esteem, and self-regulated learning (Hendriana et al., 2017b). For the innovations that spring out of this era to well-benefit the world, it is of the essence to imprint ethics, culture, character, and nationalism onto every individual (Sasongko, 2019). In the absence of proper imprinting of the aforementioned, it is feared that the power of this era will come to be misused and leave an adverse impact on the world and civilization of mankind (Hendriana, 2017a; Sasongko, 2019). It is, therefore, necessary to make efforts to build hard skills and soft skills and to instill ethics, culture, character, and nationalism hand in hand.

One of the efforts one may make to develop both sets of skills in school instructions is to open up as wide an opportunity as possible for students to express responses, answers, or opinions on mathematical problems they encounter during learning and teaching activities through innovative, creative, humanist, nationalist instructions (Hendriana et al., 2014). Besides, it is recommended to build the habit of free, holistic, comprehensive, innovative, critical, creative, literal thinking ethically to encourage students to build innovativeness, creativity, and criticality in tackling and dealing with the challenges, problems, and changes in life in current era (Liddy, 2012; Hendriana et al., 2017b). This habituation can be commenced in students' environment at school during the learning and teaching process, including in mathematics learning and teaching activities.

In mathematics instructions, it is no easy task to elicit a positive response out of students' thinking process. However, teachers should still facilitate and appreciate students' thoughts as solution alternatives to the problems presented. Not many a student are able to offer arguments, and it is even extremely few to have the courage to argue, so the solutions presented by students are easily and directly understandable to the teacher and/or their peers. Hence, it is needed of the teacher to dig deeper into students' arguments to extract some information. This is because the arguments conveyed by students at times take the form of expressions that explain their true meanings in indirect manners (Hendriana, 2017a; Boldt, 2021). Such expressions are likening or analogous comparations we often refer to as metaphors (Tim Penyusun Kamus Pusat Bahasa Indonesia, 2005).

Metaphors are indirect expressions in the form of analogous comparisons that carry meanings identical to the original meanings (Tim Penyusun Kamus Pusat Bahasa Indonesia, 2005). This is what is frequently encountered in the way in which students answer and make arguments as a step in the process of solving the problems they are presented with. For this reason, teachers hold a key role in giving students an opportunity to put forward some opinions as arguments out of their thinking processes. Teachers are suggested against shutting up the opportunity for students to expand their thinking. All the answers proposed by students that are accompanied with reasons must be appreciated and declared correct on the grounds that a piece of truth can be believed if it is justified with logical arguments (Hahn, 2018; Shabani et al., 2019).

Teachers must also have or exhibit metaphorical thinking. To some, the use of metaphors in interaction or communication with others is nothing but a rhetoric variation. A speaker would use a certain figurative expression when he/she feels that no literal language would be able to render the same effect as, or compare with, figurative language to deliver the meaning he/she intends to deliver and hence derive the response he/she desires (Ricoeur et al., 1977). Therefore, in instructions, especially mathematics ones, giving students an opportunity to think metaphorically in class is of much criticality. Doing so would stimulate a habit in students' thinking process that is free, holistic, comprehensive, innovative, critical, creative, and literal (Lunenburg, 2011).

Outcomes from mathematics instructions that can improve students' mathematical hard skills and soft skills that are necessary in facing the challenges and changes in educational revolution greatly depend on how students understand a problem they are given and how they solve it innovatively. It is as found by Hendriana (2012) that, during the learning and teaching process, students only imitate and take notes of how to solve problems as their teacher did.

If this goes on and on, students will not solve problems as expected. Students' low mathematical understanding may be resulted from a variety of sources, one of which is the fact that they are rarely given the opportunity to think openly and, as a result, ask questions regarding the problems that they are presented with (As'ari et al., 2019). Attracting questions

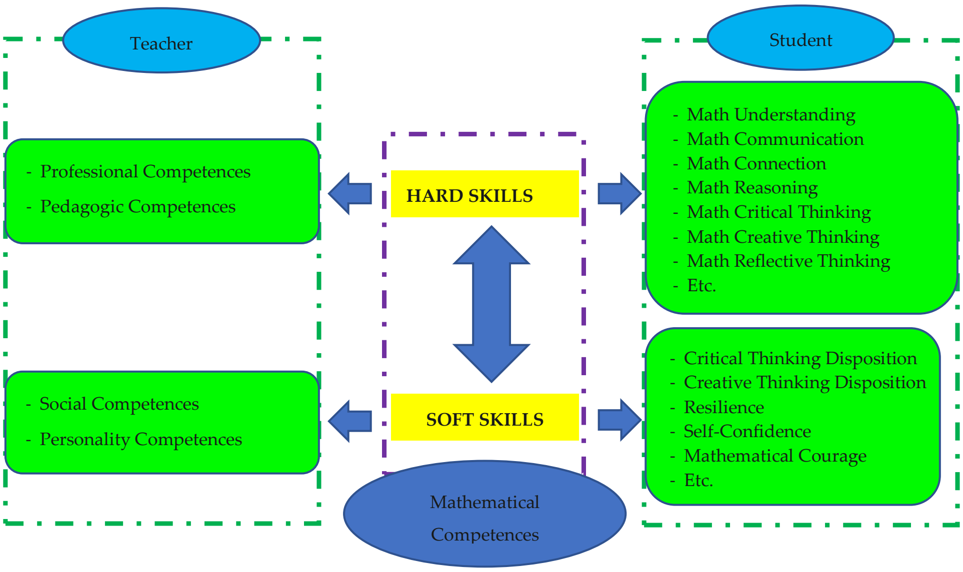

FIGURE 1
Relationship of teacher and student competences.

from student to teacher or from student to student should be accustomed in every instruction in the classroom through stimulating steps that are taken by the teacher, in which case students may respond.

Teacher's role in facilitating student-centered instructions in the classroom is essential (Estes, 2004; Keiler, 2018; Chen and Tsai, 2021). This role must start with teacher's being able to accommodate every student's opinion, developing understanding and appreciation of student-generated mathematical ideas, and assisting students in developing self-confidence, independence, and curiosity. The fact in the field, however, as found by Hendriana et al. (2018), is that students' level of mathematical courage to ask mathematical questions is still low. This is especially true when students are given the chance to ask non-routine, open-ended questions. This reflects that students' free, holistic, comprehensive, innovative, critical, creative, and literal thinking habit to render thinking results has been sub-optimal and that the opportunity for them to practice this thinking habit has been non-existent. Habituation must be performed routinely and continuously by both the teacher and students so from the internalization process there will form a habit, from which a need and eventually a culture will also rise in the mathematics instructions at school. It is, thus, needed to take a mathematics classroom instructional approach that is fun based on students' culture, way of thinking, and contributions over the course of the instructional process. This approach has double purposes of building students' hard skills, soft skills, and mathematical courage and of giving students to think metaphorically, hence producing humanist, nationalist human beings of innovation and creativity who are able to take on the challenges and changes in this era.

It would be improbable to implement this idea without an underlying theory, so this research emerges to build a theoretical framework for this learning approach in order to promote students' mathematical hard skills and soft skills. This theoretical framework is constructed through systematic review, synthesis, critical analysis, and integration of several pieces of literature on mathematical hard skills and soft skills, humanist mathematics learning approach, ethnomathematics, metaphorical thinking, teacher's professional competences, and problem-posing ability. Results of this research are to contribute as a theoretical foundation for further research during the implementation process in the field.

Research methods

This research uses an integrative literature review as the research method to build a theoretical framework on humanist ethno-metaphorical mathematics learning approach to improve students' mathematical hard skills and soft skills and thus enable them to take on the challenges and changes in this era. The integrative literature review carried out in this research lays a foundation on which a theoretical or conceptual framework is to be built by reviewing, criticizing, and synthesizing literature that is representative of a certain topic in an integrated manner, allowing a new theoretical framework and perspective to be produced (Torraco, 2005). This review is unlike two other kinds of review—systematic literature review and semi-systematic literature review. The two functions as sources for identifying and reviewing critical investigations to ensure the trend and impact of major studies on a certain topic rather than as means for developing or building a theoretical framework on a learning approach (Baumeister and Leary, 1997; Torraco, 2005; Liberati et al., 2009; Wong et al., 2013; Snyder, 2019). Integrative literature review, meanwhile, has a unique contribution to the reconceptualization of an established topic, which in turn can be used to develop a new framework and perspective by providing an overview or description of research trend and effect (Snyder, 2019). Therefore, it was deemed fitting and effective to be used in this research for the purpose of making a theoretical framework on the humanist ethno-metaphorical mathematics learning approach. The role this method assumes is to promote a solution to the need for improved hard skills and soft skills in order to build human beings who are innovative, creative, humanist, and nationalist and who are capable of dealing with the challenges and changes in educational revolution.

Integrative literature review is to be practiced in four stages, namely to design, conduct, analyze, and write a literature review (Torraco, 2005; Snyder, 2019). In the first stage, literature is designed by determining seven key points such as the topics, reasserting the study reasons and objectives, formulating certain research scope and questions, and collecting the literature to be reviewed. The next stage is carried out by conducting an analysis in steps that include determining when the review is to be conducted, examining the reviewing process, and criticizing and synthesizing literature. Literature criticism is performed by a critical analysis which involves close examination of a main idea and its relationship with a problem and by criticizing the existing literature to support our construction framework. Meanwhile, synthesis is conducted by integrating the existing ideas with new ideas to make a new formula for the topic under discussion. In this research, synthesis takes the form of an alternative model or theoretical framework as well as a new way of thinking on the problem under study with an integrative review, which is directly laid down from a previously conducted critical analysis and synthesis (Torraco, 2005).

Our review of publications that addressed the theoretical framework of Humanist Ethno-Metaphorical Mathematics Learning focused on seven topics:

1. Mathematical hard skills
2. Mathematical soft skills
3. The humanist mathematics learning approach
4. Ethnomathematics
5. Metaphorical thinking
6. Teacher's professional competencies
7. Problem-posing ability

Using keywords of these seven issues, we searched Google Scholar, ScienceDirect, and SpringerLink, for articles published between January 1, 1973, and October 30, 2021.

We used journal's articles, books, theses, dissertation, and proceeding's articles to cite the sources. We also conducted a manual search of specialist publications and citations from the papers found during the initial investigation. After we had all the documents, we went over them to ensure we could use them to accomplish the research goals. The papers that have been chosen are those that address at least one of the seven research topics.

The third stage is review analysis. In an integrative literature review, data analysis is replaced by a clear logic and conceptual reasoning as a foundation for argumentation and explanation. Both are major features that are used to develop a framework or model proposed and to enable readers to see a link between the research problem, literature criticism, and theoretical findings in a theoretical framework. The last stage is to write a review in a complete, structured manner. The motivation and need of the study are to be delivered. Besides, the reviewing process is explained transparently in aspects such as how literature is identified, analyzed, synthesized, and reported by the researcher. Review results in an integrative literature review are not measured and evaluated as strictly as in empirical studies. Nonetheless, the quality of such research is seen from the depth, accuracy, and substantial contributions that are truly valuable and new in a certain field or topic (Snyder, 2019).

The literature of hard and soft mathematical skills, and problem-posing ability focusing on the indicators and their types of skills are studied in detail and comprehensively to construct the characteristics of the learning targets to be achieved. Furthermore, ethnomathematics and metaphorical thinking literature are explored to design the framework of this learning model. Lastly, teachers' professional competencies are discussed to determine what competencies and characteristics are needed by teachers who will implement this learning model.

Results

Humanist ethno-metaphorical mathematics learning is a theoretical framework on humanist mathematics learning with metaphorical thinking culture that improves students' mathematical hard skills and soft skills that are necessary to face the challenges in this era. Its urgency in mathematics learning has been growing, given that, over the time, mathematics has been perceived as daunting to students, in which case learning at school that follows a drilling and memorization system oftentimes gives students only the knowledge of formulas rather than the understanding of the meaning and benefit of learning mathematics and mathematics' relationship with their daily life.

Metaphor itself is here meant to refer to another way of expressing a supposed or actual meaning based on students' understanding and experience. In humanist ethno-metaphorical mathematics learning, metaphors are used to express the meaning of a mathematical concept or idea ethnomathematical or mathematically that exists in, or possibly is practiced in, students' culture and daily life, allowing students greater ease to understand the mathematical concept and to find its meaning and understand its benefit in daily life. Using metaphors will also connect mathematical concepts to ethnomathematical ones that have been known in students' everyday life.

In humanist ethno-metaphorical mathematics learning, metaphorical thinking is used to conceptualize abstract mathematical concepts into concrete ones, while ethnomathematics is used to set up a learning context that makes the conceptualization process from abstract to concrete easier. Undertaking mathematical idea construction will involves three forms of conceptual metaphors: first, grounding metaphors, which lay the basis for understanding mathematical ideas that are connected to daily experience; second, linking metaphors, that are present in the process of constructing a link between two things by selecting, asserting, giving flexibility to, and organizing the characteristics of the main topic, with support from a subsidiary topic, in the form of metaphorical questions; and third, redefinition metaphors, that arise when redefining the metaphors and selecting the most suitable one among them with the topic to be taught.

Several metaphorical thinking strategies can be used in mathematics learning, and these involve the following: first, comparing the meanings of metaphors in illustrating mathematics; second, giving students a chance to convey their own metaphors; and third, comparing the meanings of the metaphors across various cultures. The use of cultural contexts and metaphorical thinking will take students' learning beyond just formulae memorization.

With ethnometaphors, students will be able to connect mathematics to their daily life and the cultures that exist around them. They will also be able to take meanings from mathematics learning and understand and communicate them with metaphors or expressions that are closely related to their everyday life and culture, making it easier for them to understand and communicate mathematics. However, enabling students to extract meanings is not the only thing that ethnometaphors can do. They also enable students to apply mathematics in their daily life because ethnomathematics essentially departs from the notion and concept that mathematics is a culture-based human activity that originates in the way in which society responds to mathematics-related phenomena.

Using ethnometaphors in tandem with students' cultural contexts and daily life in learning allows students to learn not only mathematics, but also ethic, moral, social, and nationalist values that come within the culture and daily life that are used as the learning context, enabling the shaping of students' character as humanist individuals. These things are important for students to deal with the changes that are rendered by educational revolution, which is rife with IoT, and AI uses that may both be advantageous and disadvantageous to the civilization and the world. It is thus vital to build character and imprint ethical, moral, social, cultural, and nationalist values on students to direct the changes in this revolution toward a greater benefit for the civilization and the world.

Some things that characterize humanist ethno-metaphorical mathematics learning lay a foundation for improving students' mathematical hard skills. These skills include mathematical understanding ability, mathematical reasoning ability, mathematical problem-solving ability, mathematical communication ability, mathematical connection ability, mathematical logical thinking ability, mathematical critical thinking ability, and creative mathematical thinking. Furthermore, humanist ethno-metaphorical mathematics learning also improves students' mathematical soft skills. They include habits of mind, learning activeness, learning interest, motivation, mathematical resilience, self-concept, self-confidence, self-ability, and appreciation of science.

Further research should specifically improve each mathematical hard skill and soft skill using humanist ethno-metaphorical mathematics learning based on the theoretical framework of this study's humanist ethno-metaphorical mathematics learning. In implementing this learning approach, teachers should assume the role of facilitators who can design humanist learning innovatively. They should have soft skills that are of two categories: personality competencies and social competencies. Falling to the first category are as follows: maturity, virtuous character, wisdom, charisma, and fitness to be a role model for students; understanding of the professional rights and obligations of a mathematics teacher; understanding of the professional tasks and functions of a mathematics teacher; and understanding of the impacts of educational innovations on the development of the nation's character. Meanwhile, the second category includes the following: upholding of norms, values, morality, religion, ethics, and professional responsibilities; practical communication ability; understanding of problems in mathematics education and contemporary mathematics; teamwork and rapid adaptation to the skills needed in a work environment; mastery of educational interactions between teacher, student, parent, and society; understanding of consultative communication between mathematics education, regulator, and societal needs; and ability to use and apply information and communications technologies in mathematics learning.

Teachers must have the innovativeness to design mathematics learning that is interesting, fun, and innovative based on students' ways of thinking and contributions during the learning and teaching activities. This learning design must be set off from the students' needs, conditions, and innovative ideas, which are the product of their learning methods to achieve better learning outcomes. Besides, they must also make use of appropriate learning aids and strategies to motivate students, including the environment, as a learning source to create enjoyable, fun learning.

In humanist ethno-metaphorical mathematics learning, it is imperative for teachers to be able to encourage the students to find their own ways to solve the problems presented, express their own opinions both orally and in writing, and participate in creating and shaping a comfortable learning environment for themselves. In this way, student-centered learning will be created, in which case students will be able to actively develop their own knowledge through the innovative learning that has been designed by the teachers. Hence, strong will be the students' conviction that what they master is not only the materials, but also how they learn those materials meaningfully.

The characteristics of humanist ethno-metaphorical mathematics learning are identical to those of humanist learning in general, as follow:

1. It places students as inquirers rather than just recipients of facts and procedures.
2. It gives students an opportunity to interact to understand and solve problems in depth.
3. It accustoms students to learn problem-solving in various ways.
4. It presents open-ended problems that are interesting and challenging.
5. It uses evaluation or assessment techniques that are not based solely on procedures.
6. It develops understanding and appreciation of student-generated mathematical ideas.
7. It helps students develop self-confidence, independence, and curiosity.
8. It presents learning by drawing a link to daily life.

Humanist ethno-metaphorical mathematics learning has a role in promoting students' mathematical hard skills and soft skills with which students will find it easier to deal with the challenges and changes in this era. However, one does not simply implement this approach, and by doing so improve students' mathematical hard skills and soft skills. Further research that is greater in specificity and implementativeness based on the theoretical framework that has been established in this study will be necessary. In other words, the empirical contribution of the theoretical framework developed here sets up a foundation for developing the humanist ethno-metaphorical mathematics learning approach and its implementation in the learning and teaching activities in the classroom.

Discussion

Mathematical hard skills

Mathematical hard skills refer to knowledge, technology, and technical skills mastery related to a field in the science of mathematics (Hendriana, 2017a). They are derived and explained from the existing core competences and basic competences for each grade. These skills are divided into several categories, namely mathematical understanding ability, mathematical reasoning ability, mathematical problem-solving ability, mathematical communication ability, mathematical connection ability, mathematical logical thinking ability, mathematical critical thinking ability, and mathematical creative thinking ability. The indicators of each category are as follows:

1. Mathematical understanding ability

Mathematical understanding ability is a basic competence in mathematics learning that includes the ability to absorb a material, remember and apply a mathematical formula and concept, estimate the truth of a statement, and apply a formula and theorem in solving a problem (Hendriana, 2017a; Louie, 2017). NCTM (1988) puts forth several indicators of mathematical understanding, namely being able to identify a concept verbally and in writing, being able to identify and make examples and other things, being able to use a model, diagram, and symbol to represent a concept, being able to turn one form of representation to another form of representation, being able to recognize various conceptual meanings and interpretations, being able to identify the properties of a concept and recognize the prerequisites to determine a concept, and being able to compare and contrast various concepts.

2. Mathematical reasoning ability

Mathematical reasoning ability is defined as a thinking process that seeks to link known facts to draw a conclusion (Saleh et al., 2018; Hawes and Ansari, 2020). Mathematical reasoning is classified into two categories, namely mathematical inductive reasoning, and mathematical deductive reasoning (Siswono et al., 2020; Kaplan et al., 2021). Mathematical inductive reasoning is based on some conclusion-drawing characteristics: transudative reasoning, or the ability to draw a conclusion from one case with another case; analogical reasoning, or the ability to draw a conclusion based on similarities of processes or data; generalization reasoning, or the ability to draw a general conclusion based on some limited data under scrutiny; the ability to estimate answers of solution and trend, interpolation, and extrapolation; the ability to provide explanation on an existing model, fact, property, relationship, or pattern; and the ability to use a relationship pattern to analyze a situation and establish a conjecture (Hendriana, 2017a). Indicators of mathematical deductive reasoning, meanwhile, include the following: the ability to perform calculation based on a certain rule or formula; the ability to draw a logical conclusion based on rules of inference, appropriate proportion, probability, correlation between two variables, and combination of multiple variables; and the ability to formulate direct evidence, indirect evidence, and evidence with mathematical induction (Hendriana et al., 2014, 2017b; Bruckmaier et al., 2021; Shodikin et al., 2021).

3. Mathematical problem-solving ability

Problem-solving ability is defined as the ability to formulate a new answer or solution beyond simple application of previously learnt rules to achieve a goal. Hendriana (2017a) explains that the indicators of mathematical problem-solving ability include the following: being able to present a problem in a clearer form; being able to state a problem in an operational form; being able to formulate a hypothesis and work procedure to solve a problem; being able to test a hypothesis (by collecting data, processing data, and drawing inference from data); and being able to re-examine the results obtained. There are several strategies that can be used to solve a problem: trials and errors; making a diagram; experimenting with a simpler problem; making a table; finding a pattern; breaking down a goal (detailing a general goal into actual goals); performing calculation; thinking logically (using reasoning and conclusion drawing); analyzing how to achieve a desired goal; and ruling out improbable (Pólya and Conway, 1973).

4. Mathematical communication ability

Mathematical communication ability is defined as the ability to deliver a mathematical idea both in speaking and in writing (Hendriana, 2017a; Hendriana et al., 2017b). The indicators of this mathematical ability include being able to reflect and clarify thoughts on mathematical ideas, being able to connect everyday language and mathematical language using symbols, being able to use the skills to read, listen to, evaluate, and interpret mathematical ideas, and being able to use mathematical ideas to form an assumption and devise a convincing argument (Hendriana et al., 2014; Hendriana, 2017a).

5. Mathematical connection ability

Mathematical connection ability is defined as the way to solve interrelated mathematical problems, situations, and ideas into a mathematical model and to apply the knowledge gained from solving a problem to solve another problem (Lappan et al., 1996). This ability is critical to the mastery of conceptual understanding and to problem-solving. Additionally, this ability allows an individual to connect some mathematical ideas to have a deeper mathematical understanding and to see associations of mathematical topics to contexts outside mathematics and to daily experiences. The indicators of mathematical connection ability include being able to draw on connections between mathematical topics and between a mathematical topic and other topics and being able to use mathematics in other subject matters and/or in daily life (Hendriana, 2017a).

6. Mathematical logical thinking ability

Mathematical logical thinking ability is the ability to think inductively and deductively according to the laws of logic and the ability to understand and analyze numerical patterns and solve problems using the thinking ability (Hendriana, 2017a; Demetriou, 2020). The indicators of mathematical logical thinking ability are as follows: being able to draw a conclusion based on analogies; being able to examine or test the validity of an argument; being able to connect facts as problems involving logical thinking; and being able to be building and fixing an assumption (Hendriana et al., 2014, 2017b; Hendriana, 2017a).

7. Mathematical critical thinking ability

Mathematical critical thinking ability is the ability to use the thinking ability actively and rationally with full awareness and to consider and evaluate information (Hendriana, 2017a; Han et al., 2021; Van Peppen et al., 2021). The indicators of this ability include the following: the ability to identify and justify concepts or the ability to provide rationale for conceptual mastery; the ability to generalize or the ability to complete supporting data or information; and the ability to analyze an algorithm or the ability to evaluate or examine an algorithm.

8. Mathematical creative thinking ability

Mathematical creative thinking ability is the ability to find a variety of unprecedented solutions, which are acceptable in their correctness, to open-ended mathematical problems with ease and flexibility (Hendriana, 2017a; Apiola and Sutinen, 2021). Creative thinking ability is inclusive of fluency, flexibility, authenticity, and elaboration. The indicators are as follows: fluency, by which to generate a lot of relevant ideas or answers and have a smooth flow of thinking; flexibility, by which to generate a great variety of ideas, alternate ways or approaches, and have diverse thinking directions; authenticity, by which to offer answers unlike others' or rarely presented by many; and elaboration, by which to develop, improve, and enrich an idea, go into greater details, and expand thoughts (Hendriana, 2017a; Dunstan and Cole, 2021).

Mathematical soft skills

Mathematical soft skills refer to habits of mind, learning activeness, learning interest, motivation, mathematical resilience, self-concept, self-confidence, self-ability, and appreciation of science (Hendriana, 2017a; Hendriana et al., 2017b). They have a vital role in building an individual's character. In education, learning strategies should optimize the interactions of teacher to student as well as the interactions of student to teacher or student to student. This is necessary to create a healthy, conducive, productive environment and to propagate multidirectional interactions.

The indicators of several mathematical soft skills are outlined below:

1. Habits of mind

The indicators of habits of mind include having the habits to be persistent and insistent, managing what the heart says, empathizing with others' feelings, thinking flexibly, being reflective, confident, and open-minded, practicing metacognitive thinking, working carefully and properly, achieving high standards, posing questions, presenting problems effectively along with some supporting data, drawing on former experiences, making analogies, thinking and communicating clearly and correctly, using the senses keenly, thinking intuitively, estimating solutions, creating, fantasizing, and innovating, showing passion when making responses, having the courage to assume responsibility and take risk, showing some sense of humor and thinking interdependently, and learning continuously (Costa and Kallick, 2005; Jacobbe and Millman, 2009; Hendriana, 2017a).

2. Learning activeness

The indicators of learning activeness include being able to pay attention to the teacher's explanation, being able to understand the problems presented by the teacher, being active in posing and answering questions, being able to cooperate in groups, being able to express opinions, being able to give group mates an opportunity to express opinions and being able to present the work of the group.

3. Learning interest

The indicators of learning interest include taking some joy in learning, showing interest in learning, being engaged in learning, learning diligently, completing mathematics assignments, being committed, and disciplined, and having a studying schedule (Hendriana, 2017a).

4. Motivation in mathematics

The indicators of motivation include showing self-confidence in using mathematics, being flexible in doing mathematical work, showing willingness in setting aside other obligations and tasks, being committed to doing mathematics, being able to defend opinions, and showing insistence and perseverance in completing mathematics assignments.

5. Resilience in mathematics

The indicators of resilience in mathematics include industriousness, self-confidence, hard work, persistence in the face of problems, failures, and uncertainties, desire to socialize, helpfulness, discussion with peers and adaptation to the environment, curiosity, reflection, researching and using various resources, language proficiency, and self-control and awareness of feelings of one's own (Johnston-Wilder and Lee, 2010; Hendriana, 2017a).

6. Self-concept

The indicators of self-concept include showing willingness, courage, insistence, earnestness, seriousness, and interest in learning mathematics, believing in one's ability and success, recognizing one's strengths and weaknesses in mathematics, showing cooperativeness and tolerance to others, appreciating the opinions of others and of one's own, forgiving of others' and one's own mistakes, showing communication ability and knowing one's place, and having perspective on, deriving benefits from, and taking a liking in the subject matter and the learning of mathematics (Hendriana, 2017a; Hendriana et al., 2017b).

7. Self-confidence

The indicators of self-confidence include the following: believing in one's own abilities; showing no anxiety, feeling free, and taking responsibility for one's own deeds; being independent in decision-making; having the courage to express opinions and feeling driven to make achievements; and recognizing one's own strengths and weaknesses (Hendriana et al., 2014, 2017b; Hendriana, 2017a).

8. Self-ability

The indicators of self-ability include being able to deal with the problems that arise, being convinced in one's success, having the courage to take on challenges, having the courage to take risks, being aware of one's strengths and weaknesses, being able to interact with others, and being resilient and persistent (Hendriana et al., 2017b).

9. Self-appreciation

The indicators of self-appreciation include believing in one's abilities, being confident in oneself during communication, being confident in one's strengths and weaknesses, taking pride in the results that are achieved, and being confident that others are in need of one's self (Hendriana, 2017a).

Ethnomathematics

Ethnomathematics etymologically uses three Greek roots, namely *ethno* for a natural or sociocultural group, *mathema* for explaining and learning, and tic for ways, arts, and techniques (D'Ambrosio, 2016). Thus, ethnomathematics is defined as a program that learns and combines the mathematical ideas, ways, and techniques practiced and developed by diverse sociocultural or members of cultural groups. It emphasizes exploring the science developed by a cultural group on ideas, ways, and techniques to develop a knowledge system. It acknowledges that there are a variety of ways of doing mathematics that are developed by numerous cultures (D'Ambrosio, 2001). The main foundation that underlies ethnomathematics is the awareness of the vast range of ways to have knowledge of and to do mathematics in relation to values, ideas, notions, ways, techniques, and practices in a diversity of cultures (D'Ambrosio, 2001; D'Ambrosio, 2007). Ethnomathematics represents the ways in which a multitude of cultures make their own mathematical realities through mathematical ideas, notions, ways, techniques, and practices that are used in daily life.

Ethnomathematics is a program to create new knowledge, so it is a must for mathematicians to regard society as a whole, including in perceiving its constituent cultural dimensions (D'Ambrosio, 2016). This is to take into consideration the expectations of each member of society and the traditions that contain high moral values such as appreciation, tolerance, acceptance, awareness, dignity, integrity, and peace, among others. As a result, it allows to keep the ethics of the mathematics users in check, make them human, and prevent the use of mathematics as a basic instrument for conquest, colonization, subordination, absorbance, and even elimination of other civilizations.

Ethnomathematics is associated with the motif by which a certain culture (*ethno*) in its history develops steps to calculate, infer, compare, and classify techniques and ideas (tics) that enable the society within to model the natural and social environment and context to explain and understand mathematical phenomena (*mathema*) (Rosa and Orey, 2016). It is also easier to accept to indigenous peoples of certain populations as the contexts used are easier to access and reach, particularly to those living in rural and coastal areas. Mathematics in traditional practices become more interesting than formal mathematics, given that the latter is conducted in a rigid, cold fashion.

Ethnomathematics is dynamic, holistic, transdisciplinary, and transcultural (d'Ambrosio, 1985; D'Ambrosio, 2016). Its evolution will benefit academic mathematics, especially since in ethnomathematics the way in which mathematics is done is closer to real contexts and the mathematical agents are immersed in reality. Thus, it is deemed necessary to modernize resources that are rich in cultural heritage so that both ethnomathematics and academic mathematics can be well-positioned in the world today.

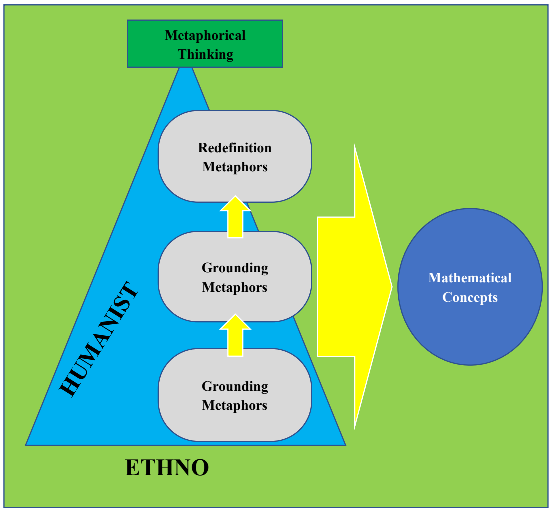

FIGURE 2
Humanist ethno-metaphorical mathematics learning model.

Metaphorical thinking

The studies on metaphorical thinking in mathematics learning in Indonesia were pioneered by Hendriana's work (Hendriana, 2002) that concerned problem-posing in reciprocal teaching, which was preceded by an inquiry into peer-learning at the remediation stage. Globally, they were first introduced by Carreira (2001) through his work that was entitled "Where there's a model, there's a metaphor: Metaphorical thinking in students' understanding of a mathematical model", which was subsequently presented in Indonesia by Hendriana (2009). Back then, there was no single work that used metaphors in answering mathematical problems in the form of non-standard answers as a treatment that could promote students' mathematical hard skills and soft skills. Thus, a learning design was established using several elements known as metaphorical thinking (Carreira, 2001) to improve hard skills (mathematical understanding and mathematical communication abilities) and soft skills (self-confidence) in students (Hendriana, 2009).

Metaphors are classified as connotations in the traditional rhetoric, that is, as a depiction that classifies the presence of a variety of meanings in word use and more precisely in the denotation process (Carreira, 2001). A metaphor is accounted for as the application of a name that belongs to something else proportionately by means of comparison as marked explicitly by a comparative theme. It then gives a unique character to the wholeness of the relationship between the explicit and implicit meanings of a concept. Simply put, a metaphor is said to be a comparison that bridges the relationship between literal meaning and figurative meaning (Ricoeur, 2002).

The fact of a part of a human thinking process and its understanding system is metaphorical (Ricoeur et al., 1977). Metaphors lie in their central role in understanding the relationship between the language of human knowledge and the world of desire (Carreira, 2001). It is also fair to say that they are linguistic expressions whose meanings are out of the direct reach of the existing symbols as the intended meanings predicate the linguistic expressions (Ricoeur, 2002). Cognitive paradigms perceive metaphors as tools to conceptualize abstract concepts into more concrete concepts (Hendriana et al., 2018). Thus, metaphors are another way of expressing meanings that supposedly or actually are based on students' understanding and experience, as is illustrated in **Figure 2**.

At the other end of the spectrum, we can also see that a metaphor is a direct comparison of two things with different meanings, whether they are related or unrelated (van Poppel, 2020; Steines et al., 2021). Metaphors can open up a new horizon for one's concrete understanding, thereby able to promote students' communication ability in shedding light on difficult concepts through a combination of some concepts they are already familiar with.

The thinking process that makes use of metaphors in gaining an understanding of a concept can also be referred to as metaphorical thinking (Ricoeur et al., 1977). A metaphor starts off from a concept student have recognized all the way to another concept they have no knowledge of, or they are presently learning. It relies on some properties of the concept and object metaphorized. Metaphorical thinking in mathematics is used to make clear of one's thinking way that is related to his/her mathematical activity (Carreira, 2001; Hendriana et al., 2018). Abstract concepts that are organized through metaphorical thinking are stated in concrete things based on structure and reasoning way on the foundation of a sensorial-motor system called conceptual metaphor (Carreira, 2001).

Some of the metaphorical conceptual forms employed to construct a mathematical idea are as provided below (Ricoeur et al., 1977; Carreira, 2001; Hendriana, 2009):

1. *Grounding metaphors*, which are the basis for understanding mathematical ideas that are linked to everyday experience.
2. *Linking metaphors*, which establish a relationship between two matters by selecting, asserting, giving flexibility to, and organizing the characteristics of a primary topic with the support of a subsidiary topic in the form of metaphorical statements.
3. *Redefinition metaphors*, which redefine metaphors and select the most suiting one to the topic to be taught.

Metaphorical thinking in mathematics starts with modeling a situation mathematically, followed by giving meaning to the models through an approach from a semantic point of view (Ricoeur et al., 1977; Carreira, 2001; Hendriana, 2009). In mathematics learning, metaphor use by students are one way to link mathematical concepts to the concepts they are familiar with in daily life, in which case they express mathematical concepts in their own language to demonstrate their understanding of such concepts (Hendriana, 2009).

Carreira (2001) explains metaphorical thinking in a diagram form as is seen in **Figure 3**.

Some strategies in metaphorical thinking that may be helpful to students in understanding a mathematical topic are as provided below (Carreira, 2001; Hendriana, 2009):

1. Use metaphors to illustrate a concept in steps including identifying first the main concepts to be taught, thinking of possible metaphors to illustrate the concepts, choosing one among several possible metaphors that is most suitable, and planning ways for discussing that metaphor/analogy to ward off confusion from the students. In this case, we must believe that the students have adequate knowledge and experience to think metaphorically.
2. Give students a chance to express their own metaphors. This is important to prevent misunderstandings that arise from the diversity in cultures and customs, which may lead also to differences in the means and foundations of student understanding in making an analogy of a topic. Then, give the students an opportunity to exchange analogies so they have a chance to discuss with one another.
3. Discuss the understanding foundation in metaphorical thinking by analyzing the reasons for which analogies/metaphors are chosen.
4. Compare the significances of the metaphors across various cultures.

Thus, metaphorical thinking can be defined as a thinking process to discern and communicate abstract concepts in mathematics into more concrete concepts by comparing two things with different meanings.

Metaphorical thinking in mathematics is unlike metaphorical thinking in traditional contexts, with the differences lying in the conceptual understanding and in the application to solve the problems encountered (Hendriana, 2009). In the case of ordinary metaphorical thinking, students are required to describe a concept using the concepts they have formerly recognized without having to completing it in detail.

Teacher's professional competences

The professional competences of a mathematics teacher cover the following: understanding of mathematics theories and mathematics learning theories; mastery of the implementation of mathematics theories and mathematics learning theories; mastery of the selection, formulation, designing, and delivery of mathematics theories and mathematics learning theories; and mastery of the principles, rules, and concepts of mathematics theories and mathematics learning theories in learning environment contexts (Hendriana, 2017b). A mathematics teacher must also possess some mathematics pedagogic competences, which include the following: understanding of the curriculum and development of mathematics learning plans; understanding of the approaches, methodologies, and techniques in mathematics learning and their implementation in the classroom; understanding of the implementation of mathematics learning and mathematics learning evaluation systems in the classroom; mastery of the skills to assess students' level of understanding and potential in mathematics learning; and mastery of the skills to conduct research in mathematics learning.

A teacher is expected to have some soft skills, which consist of personality and social competences (Caggiano et al., 2020). Personality competences here are comprised of 4 aspects: maturity, virtuous character, wisdom, charisma, and fitness to be a role model for students; understanding of the professional rights and obligations of a mathematics teacher; understanding of the professional tasks and functions of a mathematics teacher; and understanding of the impacts of educational innovations on the development of the nation's character. Meanwhile, the social competences a teacher must have include the following: upholding of norms, values, morality, religion, ethics, and professional responsibilities; effective communication ability; understanding of problems in mathematics education and contemporary mathematics; teamwork and rapid adaptation to the abilities needed in a work environment; mastery of educational interactions between teacher, student, parent, and society; understanding of consultative communication between mathematics education, regulator, and societal needs; and ability to use and apply information and communications technologies in mathematics learning.

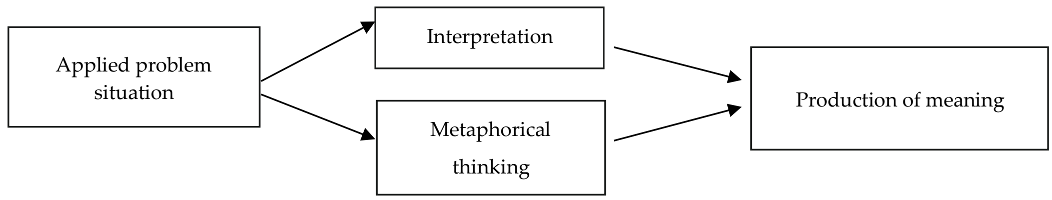

FIGURE 3
Metaphorical thinking concept.

To coordinate all the above mentioned, a teacher is demanded to have the ability to innovate through interesting, fun, and innovative mathematics learning activity designs based on students' ways of thinking and contributions over the course of the learning and teaching activities (Hendriana et al., 2019). Innovative learning is learning which is designed based on the needs, conditions, and innovative ideas of the students and is the product of their ways of learning to have better learning outcomes (Hendriana and Rohaeti, 2017). In innovative learning activities, it is expected that students be able to participate actively in various activities that are aimed to develop their skills and understanding with a focus on learning by doing (Hošková, 2010). The teacher is expected to be able to use a string of relevant learning aids and methods to motivate students, including the environment, as a source of learning to create interesting, joyful learning. On the other side, it is also demanded of the teacher to be able to encourage students to find their own ways to solve the problems presented, express their ideas both orally and in writing, and participate in creating and shaping a comfortable learning environment for themselves (Hendriana, 2012). As a result, students who serve as the learning subjects are able to actively develop their own knowledge through innovative learning that has been designed by the teacher. During the learning process, the teacher solely acts as facilitator.

There are several types of innovative learning that are capable of promoting students' hard skills, including the following: indirect learning that can positively contribute to students' creative and critical thinking abilities; learning using games that are based on flash macromedia software that can improve students' mathematical reasoning and communication skills; problem-based learning that can stimulate students' mathematical reasoning, understanding, and communication skills; and discovery learning that can exert a positive effect on students' mathematical communication ability and achieved understanding (Hendriana, 2012, 2017a). Innovative learning of these types can also inspire several soft skills in students, including mathematical disposition and learning independence.

There is another sort of innovative learning that puts a stress not on mechanistic learning, but on humanist learning, in which case mathematics learning has formerly been productive merely in the cognitive aspect but now its productivity has expanded into the affective aspect as well. This learning type is believed to be capable of tackling the hard skill and soft skill problems frequently encountered by students. Learning of this type is also known as humanist mathematics learning (Hendriana, 2012, 2017a).

Humanist mathematics learning is a preliminary essential in giving stimulus to students, hence reducing negative responses to mathematics (Hendriana, 2002, 2009, 2012, 2017a; Hendriana and Rohaeti, 2017). Through pleasure in mathematics, it is hoped that the habit of thinking mathematically can be well-trained. Therefore, students will learn to appreciate and have fondness for mathematics as they have developed a belief on how to formulate and use mathematical means should a need arise.

Such a learning system will be oriented toward the students rather than the learning materials or the learning process and outcomes. Hence, strong will be the students' conviction that what they master is not only the materials, but also how they learn those materials meaningfully. There are several things that can be performed in humanist mathematics learning to give impacts and meanings to students, including the following (Hendriana, 2009):

1. Teacher's creativity in devising strategies around the applied curriculum. Not only can he/she teach according to the curriculum implementation direction and technical direction, but the teacher can also develop some strategies around the curriculum to sort and select the materials important to the students and deliver the materials sustainably, even also discard materials of no import.
2. Teachers' innovations in learning. The variety of learning methods hold a pivotal role in attracting students' interest in mathematics learning. Innovations of various learning methods according to the teaching materials will keep students from boredom when participating in learning.
3. Relating the teaching materials to events or happenings in daily real life. Demonstrating the link between mathematics to realities in life will make mathematics learning more meaningful to students. They may apply the concepts or theories they have learned to solve real problems that they encounter in their daily life, making mathematics more humanist in nature.

Conducting mathematics learning in a humanist manner will surely allow students to take pleasure and interest in learning mathematics. They will put some efforts to let the joy they take in mathematics to grow, and it is expected that such efforts would lead to excellent achievements. Although it is impossible to force all the students to take a liking in mathematics, it is still deemed necessary to motivate them for them to be able to master the concepts in mathematics. Humanist mathematics learning in itself is characterized by the following (Hendriana, 2009):

1. it places students as inquirers as opposed to just recipients of facts and procedures;
2. it allows students to interact with each other in order to understand and solve problems in depth;
3. it accustoms students to learn to solve problems in a variety of ways;
4. it presents open-ended problems that are interesting and challenging;
5. it uses evaluation or assessment techniques that are not based solely on procedures;
6. it develops understanding and appreciation of student-generated mathematical ideas;
7. it helps students develop self-confidence, independence, and curiosity; and
8. it presents learning by drawing a link to daily life.

Problem-posing ability

In the practice in the field, teachers typically face difficulties in eliciting expected responses despite the various stimuli that have been created. Of the questions posed by teachers regarding the materials delivered, Widodo and Pujiastuti (2006) states, approximately half are close-ended questions that require only short answers out of memory rather than understanding. In relation to this statement, Japa (2014) recommends that teachers should pose problems that are more of the open-ended type in the learning process. This is necessary to allow students to express their opinions in the form of both questions and statements (as a stimulus form), which is expected to inspire responses out of other students that may be used as alternative solutions.

With, one of the weaknesses that students have in presenting problem solutions is the lack of questioning ability on the part of the students themselves. The questioning ability in the mathematics subject will be considered excellent when it covers aspects of quality, relevance, language, and frequency. Widodo and Pujiastuti (2006) opines that, in an analysis, questions will be classified based on certain considerations. The first consideration concerns academic and non-academic questions. While academic questions are related to the subject's materials, whether discussions on them have been complete or still underway, non-academic ones are questions that are related to social, organizatory, and material aspects, all of which are non-academic. The second consideration is about closed- and open-ended questions. The former are questions that elicit limited responses and typically are direct toward a single conclusion, whereas the latter are questions that invite multiple answers. The last consideration is associated with cognitive processes that fall into Bloom's taxonomy, namely, to remember, to understand, to apply, to analyze, to evaluate, and to create.

Regarding mathematical questioning ability, Hendriana et al. (2017a) define it as the ability to ask mathematical questions, or one's ability to pose problems, out of a statement considering the relationship between the questions to the questions' contexts, in which case the questions posed are either routine or non-routine, close-ended or open-ended. The categorization of mathematical questioning ability is broken down as follows:

1. The mathematical questioning ability is categorized as very low if the questions one raises are incompatible with the contexts of the questions and if the questions are considered routine, close-ended questions.
2. The mathematical questioning ability is categorized as low if the questions one raises are incompatible with the contexts of the questions and if the questions are considered routine, open-ended questions.
3. The mathematical questioning ability is categorized as moderate if the questions one raises are compatible with the contexts of the questions, but the questions are routine and close-ended.
4. The mathematical questioning ability is considered as high if the questions one raises are compatible with the contexts of the questions, but the questions are non-routine and close-ended.
5. The mathematical questioning ability is considered as very high if the questions one raises are compatible with the contexts of the questions and if the questions are non-routine and open-ended.

Questioning ability development in mathematics is encouraged for students to have the courage to express opinions. Affectively speaking in mathematics learning at school today, students tend to have little courage to say their opinions in their own language. On this, Hendriana et al. (2018) state that the mastery of the mathematical questioning ability has not reached a favored mark in the indicator of non-routine, open-ended problem-posing when seen from the mathematical courage perspective.

This review attempts to combine the said ability with the metaphorical thinking approach. The aim is to enable all students to convey their opinions throughout the learning process, irrespective of the questions given, whether the opinions have been expressed faithfully in appropriate mathematical terms or just through metaphors that describe them. Students would initially find it difficult to express their opinions due to a lack of self-confidence, mathematical anxiety, and other negativities, but a little bit of "cognitive conflict" in relation to their activeness in saying their opinions during the learning process will then be introduced. Afterward, a "reward" is given to those who are able to let their opinions heard during the learning process, allowing the learning process to run joyfully. Such is supported by a learning atmosphere that is built to appreciate every opinion that comes out of the students, making them feel appreciated while they are learning.

Conducting learning in such a way would make students who initially are shy, anxious, and lacking in self-confidence during the learning process find more joy. After taking some comfort, students will gradually become more accustomed to such a way of learning. A few lecturers in an educational institution in West Java, for instance, have conducted, and made it a culture to conduct, learning activities in this manner. For a positive result to be obtained, one may first face some difficulties. Some force and rewarding may be required for a habit to be established. Once a good habit is formed, those around us my feel some positive impacts. It is not an impossibility for the habit to evolve into a culture to which we belong. This will lead us to what we know as humanist, ethno-metaphorical mathematics learning, a pleasurable approach to mathematics learning to students that is based on the culture of thinking metaphorically and appreciation of every student-made contribution during the learning process in the classroom.

Conclusion

Humanist ethno-metaphorical mathematics learning that has a basis on ethnomathematics and metaphorical thinking is one of the learning approaches that offer a promise in mathematics learning to improve students' hard skills and soft skills, thereby helpful for students to face the challenges and changes in this era. Learning is conducted in the form of conceptual metaphors following humanist mathematics learning strategies. In learning of this sort, the teacher takes an active role as facilitator who must have soft skills that consist of personality competences and social competences. He/she must also could design learning in an innovative, student-centered fashion for the students to be able to take meanings of the mathematics learning and find their own ways to solve the mathematical problems they are presented with as well as to express their own ideas. Therefore, this situation may help students improve their hard and soft skills during the learning process.

Numerous constraints must be considered when interpreting the findings of this integrative literature review study. This study reviews a variety of sources to develop a theoretical framework for a promising learning model in mathematics education, emphasizing ethnomathematics and metaphorical thinking. This promotion model is based on metaphorical thinking, indicators of soft and hard skills, and ethnomathematics learning syntax. As a result, literature that does not discuss the other literature must be excluded from this study and its model and its implementation in the learning process. However, this study thoroughly examined the literature that supports the constructed learning model.

Finally, we have seen an increase in alternative learning approaches since the pandemics began 2 years ago. Most of them operate optimally in areas with robust internet infrastructure, enabling proper online course-based blended learning. There are—however, few studies focusing on rural areas with limited internet connectivity but a rich cultural heritage. As a result, the findings of this study can be used to implement humanist ethno-metaphorical mathematics learning as a promising alternative learning approach for improving mathematical skills in a city of culture through direct teaching and learning. The future researcher can conduct additional research through the collection of empirical data during the learning process. This is to demonstrate the model's efficacy in mathematics teaching and learning activities.

Data availability statement

The original contributions presented in this study are included in the article/supplementary material, further inquiries can be directed to the corresponding author/s.

Author contributions

HH: conceptualization. HH and RP: methodology and writing—original draft preparation. MR and ER: validation and data curation. WH and RP: formal analysis. HH, WH, and RP: investigation and writing—review and editing. MR, ER, and WH: visualization. All authors have read and agreed to the published version of the manuscript.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Improving students' ability in learning mathematics by using the science, technology, engineering, and mathematics (STEM) approach

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The science, technology, engineering, and mathematics (STEM) approach is a leading and important learning approach to analyze thinking ability and learning motivation. Accordingly, this study attempts to elaborate a STEM approach to analyze the critical thinking ability and motivation of high school students in Indonesia, especially in Palopo City, South Sulawesi, Indonesia. The current research applied pre-experimental treatment on research objects involving a group of experimental classes. Pre-experimental was used in testing the STEM approach in an experimental class with a one-group pretest–posttest design with 176 students divided into five classes. The results show: (1) improvement in students' critical thinking ability indicated by an average pretest score of 13.90 and posttest score of 70.67; (2) an increase in student learning motivation shown by an average of 71.57–80.83. The analysis results show an increase in students' critical thinking ability and learning motivation after applying the STEM approach. Conclusively, STEM functions as one of the practical learning methods for improving students' critical thinking skills and learning motivation.

KEYWORDS

STEM approach, critical thinking ability, learning motivation, South Sulawesi, Indonesia

Introduction

This study is aimed at analyzing and measuring the science, technology, engineering, and mathematics (STEM) approach by elaborating on the ability to learn mathematics to improve critical thinking and student learning motivation in Palopo City, South Sulawesi, Indonesia. STEM is a modern approach used as a communication and information technology applied to mathematics learning (Changtong et al., 2020).

The approach taken by integrating STEM aspects is carried out to see the extent of students' critical thinking ability and learning motivation toward effective learning methods (Carlson et al., 2016). The STEM approach is a current approach taken to change students' abilities (Blecking, 2018). As a result, this study elaborates on the implementation of mathematics learning methods through a STEM approach to optimally improve students' critical thinking skills and learning motivation.

The change in optimal ability intended by the STEM approach can ideally change the critical ability and motivation of student learning, so that students have incredibly fast and varied latitudes for learning mathematics (Blecking, 2018). Students in educational institutions, mainly formal education, certainly have a significant role in educating their students with the right approach (Graham et al., 2013). Consequently, a STEM approach is needed to encourage basic literacy and students' main competencies, namely critical thinking skills and learning motivation in solving problems. Therefore, educational actors, especially teachers at schools, must be able to formulate a STEM approach to instill good character values in the students (Theobald et al., 2020). Teachers should try to find various approaches so that can provide students with good basic literacy and the ability to solve simple and more complex problems once they graduate from school (Logan et al., 2019).

In the Indonesian context, especially in Palopo City, South Sulawesi, a learning method that teachers can implement to improve students' critical thinking skills and learning motivation is the STEM approach (Wahono et al., 2020). Burke et al. (2020) states that STEM approaches can make STEM a more effective learning method. In addition, critical thinking skills and high learning motivation are among the critical aspects that students need to have (Li and Schoenfeld, 2019). Therefore, this study will have a considerable impact and substantially contribute to the application of STEM approaches in Indonesia, especially the South Sulawesi region.

South Sulawesi was chosen as a case study on account of the fact that the quality of education in South Sulawesi remained low compared to other regions in Indonesia (I PATTA, 2012). It is essential to investigate the effectiveness of STEM approach in the Sulawesi region, which consists of several different regions (Hasbi, 2013). Nonetheless, many of the education related problems faced in South Sulawesi are similar to the western regions of Indonesia. In addition, it is important to know whether the STEM approach is a fundamental tool for improving learning outcomes in Indonesia (Harun, 2018).

An effective learning program is temporarily introduced to teachers through educational institutions to prepare quality students through various approaches, one of which is using a STEM approach (Hora and Oleson, 2017). All students need the learning program to develop self-capacity and participate positively in society (Theobald et al., 2020). Educational programs, teachers, and stakeholders in the field of education are oriented to improve students' ability to achieve learning success according to the standards of the national assessment component (Suchman, 2014). This learning is in line with improving critical thinking skills and learning motivation. Students must have literacy and numeracy competencies (Sanders, 2008). Both competencies are closely related to students' critical thinking ability and learning motivation (Kelley and Knowles, 2016). Thinking critically is not an ability that students can instantly have as it requires process and habituation (Erdmann et al., 2020).

Implementing process and habituation for learning mathematics at schools builds critical thinking skills and fosters student learning motivation (Freeman et al., 2014). Applying STEM approaches to learning methods makes students not only understand the content (Wahono et al., 2020), but it also helps them have applicative skills mainly used to solve problems. Learning that merely entails mastery of content would not be able to develop students' critical thinking skills. Students may even feel bored and disinterested because they only continuously learn about theories (Wang et al., 2017). These questions can serve as a basis for teachers to create more innovative learning plans that can improve students' critical thinking skills and learning motivation.

In addition to developing students' critical thinking skills, having more meaningful learning at schools is crucial to foster student learning motivation. Motivation is fundamental in learning (Li and Schoenfeld, 2019). Motivation directs learning activities correctly. Motivation provides students the zeal to carry out their learning activities (Dziuban et al., 2018). By driving the students' learning motivation, they should be able to learn well without having to feel compelled to carry out their learning activities. Especially in learning mathematics, given the student's motivation to learn both internally and externally, mathematics would no longer be considered an intimidating subject but an exciting one instead (Falco and Summers, 2019).

Science, technology, engineering, and mathematics has an important role in student learning outcomes because this is a central topic in the field of education in general (Silvia and Simatupang, 2020). Studies argue that research in STEM education is increasing globally and is becoming an international field (Wang et al., 2017). Asian regions with challenging educational problems require new teaching and learning changes (Erdmann et al., 2020). Therefore, it is no surprise that over the past decade, researchers and teachers in Asia have been conducting numerous studies, mainly related to the application of STEM in the classroom (Wang et al., 2017). However, no studies have revealed the effectiveness of STEM applications in the Asian sphere with existing characteristics, including in Indonesia, especially in Palopo City, South Sulawesi.

The statement above shows that the key consideration is that local governments, especially in Palopo City, South Sulawesi Province, has not shown interest in designing, implementing, and evaluating the distribution of curriculum in Asia with methods that accommodate STEM approaches. This review is the fundamental reason for carrying out the research, reviewing effective learning methods in integrating STEM approaches for various purposes, including student learning outcomes (Trevallion and Trevallion, 2020). On the other hand, this study emphasizes aspects of learning mathematics associated with critical thinking ability and motivation to learn mathematics (Manzanares et al., 2020).Therefore, the current research attempts to see how students' abilities can be improved by considering that a study needs to be carried out by implementing a particular approach, especially in mathematics learning to improve students' critical thinking skills and motivation in Palopo City, Sulawesi Selatan, Indonesia. As such, this study employed a student-centered learning model, namely a project-based learning model with a STEM approach.

Literature review

Science, technology, engineering, and mathematics approaches to effective learning methods

Science, technology, engineering, and mathematics are taught in schools to help students understand how to solve problems to improve human life. STEM-based learning helps students understand how to design a method (technique) through analyses and based on mathematical data calculations (mathematics) to find solutions to problems (Akiha et al., 2018). STEM approaches refer to a framework that includes (Carlson et al., 2016; Jensen et al., 2017; Blecking, 2018): (1) identify learning and (2) predict student behavior. Both can be modulated by various interventions and multiple STEM retention initiatives. Accordingly, STEM can be assumed to be most successful at paying attention to both elements. In addition, student learning and behavior improve critical thinking abilities and motivation, which spurs student learning success. The improvement of ability is seen against both factors in student learning success, indicating that students experience an adequate learning condition (Graham et al., 2013).

Some researchers suggest that through STEM learning, obtained analysis results indicate that students' critical thinking skills could develop well. Developing critical thinking is a skill students should have for compiling systematic practice plans and solving contextual problems (Margot and Kettler, 2019). Other studies argue that implementing STEM learning approaches can improve students' critical thinking skills (Erdogan and Stuessy, 2015; Kelley and Knowles, 2016; Changtong et al., 2020; Trevallion and Trevallion, 2020). In addition, an educational journal written by Akiha et al. (2018) states that implementing student worksheets developed using a STEM approach can improve students' critical thinking skills.

Mu'minah (2021) states that STEM could support and implement several things in learning, including 21st century (4C) skills, namely collaboration, critical thinking, communication, and creativity. Based on this statement, it is acceptable to say that students' critical thinking skills can be developed through a STEM approach. Other studies (Erdogan and Stuessy, 2015; Margot and Kettler, 2019) state that STEM learning collaboration helps students collect, analyze, and solve occurring problems and understand the relationship between one problem and another. The ability to collect, analyze, and solve problems is part of the critical thinking process (Erdogan and Stuessy, 2015; Margot and Kettler, 2019). This means that efforts to improve student's critical thinking skills can be carried out through a STEM approach.

Besides improving critical thinking skills, STEM approaches can also improve students' learning motivation. As shown in research articles that examined the development of STEM-based student worksheets, the use of STEM-based student worksheets was found to be able to increase students' learning motivation (Burke et al., 2020). In another educational journal article by Farwati et al. (2021), it was revealed that in STEM-based learning, overall, students are highly motivated to learn science. According to the article, the researchers consider that the STEM approach can be a solution to increase student learning motivation.

Armaludin et al. (2021) posit that motivation could be driven by external stimulation. However, motivation comes from within, as we can observe in various activities. In learning activities, teachers have a vital task of making various efforts to encourage students to actively engage in learning or carry out their learning activities (Li and Schoenfeld, 2019; Erdmann et al., 2020). This is in line with the STEM approach, which, in its learning activities, focuses on how students can execute problem-solving skills in real life (Armaludin et al., 2021). If students are encouraged to conduct an activity while learning, they will not feel bored, and learning becomes more meaningful. The higher a person's motivation, the higher the interest in learning. Puspita et al. (2020) in their research, revealed that with a STEM approach, students' interest in learning mathematics is categorized as very high. This fact supports efforts to increase student learning motivation by using a STEM approach.

Effective learning methods are used in the learning process in today's era, wherein teachers have various selections of learning methods they can use on the students in order to effectively and efficiently achieve the learning objectives (Carlson et al., 2016; Theobald et al., 2020). One of the key aspects is the issue of how teachers create an active atmosphere. This STEM method has proven to be effective in optimizing student learning activities in high school (Margot and Kettler, 2019). Practical methods are needed to meet the requirements for achieving optimal learning (the feasibility of ideal learning methods) with teaching materials that are compiled to improve critical thinking skills and student learning motivation in the field of study or subject of mathematics (Gao et al., 2020; Manzanares et al., 2020).

A practical learning approach through STEM is oriented toward increasing the effectiveness of learning implementation to improve students' critical thinking skills and motivation (Manzanares et al., 2020). The effectiveness of learning implementation triggers the achievement of high learning outcomes (Wahono et al., 2020). Through STEM effectiveness, students are also required to be able to solve problems, become inventors of science, be technologically literate, understand techniques, and think mathematically (Freeman et al., 2014). The integration of STEM in effective learning is used as the dominant source of learning (Dischino et al., 2011).

Science, technology, engineering, and mathematics education approach

There are, currently, three methods or approaches of teaching in STEM education frequently carried out. These approaches are believed to be capable of meeting STEM content, supporting proper execution of STEM learning, and making STEM learning useful for facing industrial revolution 4.0 (Kelley and Knowles, 2016; Akiha et al., 2018; Erdmann et al., 2020). The STEM education approaches are as follows.

The silo approach

Carr et al. (2012) state that the silo approach is a STEM education approach in which STEM subjects are taught separately or are not integrated. This approach allows students to understand each subject's content in depth (Erdogan and Stuessy, 2015). The silo approach emphasizes how STEM education are in the design of school curricula (Jensen et al., 2017). Harahap et al. (2019) outlines the weaknesses associated with the silo approach as follows: (a) has a tendency of minimizing the benefits of STEM learning due to the possibility of students' lack of interest in one of the STEM areas (e.g., female students like science and mathematics subjects but have no interest in engineering); (b) without practice, students may fail to understand the natural integration between STEM lessons in the real world, hindering academic growth because, in this approach, teachers only prioritize mastery of each STEM field content; and (c) only focus on mastering the content, which, consequently, leave students unaware of the relationships among each STEM field in real life applications.

The embedded approach

Bahrum et al. (2017) state that an embedded approach teaches each stem discipline by focusing more on one or two STEM disciplines. The embedded approach is an educational approach in which knowledge is obtained through an emphasis on real-world situations and problem-solving techniques in social, cultural, and functional contexts (Dischino et al., 2011). This approach focuses on one area of science or primary material by relating it to other embedded materials, but the other materials are not assessed or evaluated (Margot and Kettler, 2019). The disadvantage of the embedded approach is that it can result in splitting student learning into several pieces (Bahrum et al., 2017). Suppose a student is unable to associate embedded content with the main content. In that case, the student risks only learning part of the lesson rather than benefiting from the whole (Karimah et al., 2022).

The integrated approach

An integrated approach focuses on integrating different STEM fields and making them one subject (Sanders, 2008). This approach combines various cross-curricular contents such as critical thinking skills, problem-solving, and scientific information that can lead to a solution to a problem through the combination of materials taught in the classroom (Tanjung and Aminah Nababan, 2019). Rossalia et al. (2019) state that an integrated approach to STEM learning can be applied in schools and society by combining two, three, or all aspects of STEM (Burke et al., 2020). In this integrated approach, STEM learning occurs when two aspects of STEM have been integrated in learning (Wang et al., 2017). For example, if mathematics is integrated with physics in learning, then such learning can already be considered STEM learning (Akiha et al., 2018). Here is an overview of the integrated approach model. Introducing students to the interrelationships among all STEM subjects from a young age and inviting students to apply those linkages for solving problems in the real world will require students to work more actively (Carlson et al., 2016). Therefore, supporters of STEM education are increasingly enthusiastic about successfully supporting and continuing to develop the nature of interrelationships among all STEM subjects.

Research methods

To answer the research question, a field study was designed with a pre-experimental approach. The researchers subsequently describes the design, sample, instrument, and data analysis used in this study. The research method used is able to answer the research hypothesis by using the statistics of the one-sample t-test and the Pearson correlation test (Ilyas et al., 2015).

This study used the STEM approach to learning mathematics by employing a pretest–posttest one-group design using an experimental class to evaluate students' critical thinking abilities during the learning process. Accordingly, the STEM learning stages—reflection, inquiry, discovery, application, and communication—were included in the classroom intervention.

The STEM method was implemented over around 6 weeks. In the first 4-weeks, the STEM approach intervention took place while the students were learning. Two observers attended each meeting to monitor how lessons are being taught and how students participate in class activities. The other 2 weeks were used to review the pretest and posttest results to see how have the students' critical thinking abilities improved. In a sense, students responded to questions assessing their critical thinking abilities before and after the intervention (Utami and Yuliyanto, 2020). This type of research is pre-experimental by applying a treatment on the object of study involving only one group of classes as an experimental class. The treatment refers to the application of a STEM approach to learning mathematics (Ma'rufi et al., 2021).

This research involved a total of 176 students. They are mentioned as participants in various classes. Most of them were 16 years old. According to statistical data, 46% of them were enrolled in science programs. The tool we offered was suitable for evaluating the STEM approach to critical thinking abilities since they were at the time learning trigonometry-related content. Most of the background information of the research participants is summarized in **Table 1**.

Table 1 shows the Participant Demographic Information used in this study. In addition, 35 of the 176 students were selected to take the STEM test in the classroom. The 35 students with an average math score of 76 were enrolled in the same class. Additionally, the class was selected based on the advice of the mathematics teacher, due to the consideration that some of the students were capable of expressing their thoughts during the learning process. This type of research is pre-experimental by applying treatment on the object of study by involving only one group of classes as an experimental class. The treatment in question is the application of STEM approaches in learning mathematics (Ilyas et al., 2018). This study used one treatment, the STEM approach, in one experimental class. The design of the present study was in the form of One Group Pretest–Posttest Design, as presented in **Table 2** (Utami and Yuliyanto, 2020).

TABLE 1 Demographic information of participants.

Item	Total
Participants	176
Gender	
Male	57
Female	119
Program	
Science	81
Social studies	96
Ethnicity	
Bugis	112
Toraja	29
Makassar	35
Age	
15 years old	23
16 years old	119
17 years old	34

This study employed three research instruments. First, the learning implementation observation sheet, which is intended to measure the implementation of the learning implementation plan. The observer filled in this observation sheet during the learning process. The learning implementation observation sheet contains statements allowing the observer to check the answer choices under the ongoing learning activities. The number of statements on this observation sheet was adjusted to the learning implementation plan. The second instrument is the critical thinking ability test, which consisted of a pretest (initial test) and a posttest (final test) in the form of a description or essay. This test measured students' critical thinking skills in learning mathematics. The critical thinking ability test was made as a test for solving math problems. Third, three questionnaires were used in the study, namely: student activity questionnaires (for the purpose of determining how students' activities during mathematics learning with the STEM approach are used); student response questionnaire (for the purpose of finding out how students describe their response after taking part in learning mathematics); and student learning motivation questionnaire (aimed at finding explanation about and improvement in students' learning motivation after participating in the learning process). Each questionnaire was given with a STEM approach before and after the learning process.

The current research was conducted in the Mathematics and Science class (*MIA-Matematika dan Ilmu Alam*) of 10th grade students at Senior High School-*Sekolah Menengah Atas (SMA) 6 Palopo* City, South Sulawesi. This study used data collected from surveys and studies of students enrolled in all 10th grade classes (also mentioned as class X) who served as the population in this study, located at *SMA 6* in the *Palopo* City area of South Sulawesi Province (Winda Fronika, 2019). The study was conducted using one treatment group with two measurements of research data (Permatasari et al., 2018). Pretest: measurement of the Y variable of the treatment group taking place in the 2020/2021 academic year. The subjects or objects of study consisted of five homogeneous classes (class *X MIA-1*, class *X MIA-2*, class *X*

TABLE 2 Frequency distribution of students' critical thinking ability.

Interval	Category	Pretest		Posttest	
		f	Percentage (%)	*f*	Percentage (%)
$85 \leq x \leq 100$	Very high	0	0.00	4	11.43
$75 \leq x < 85$	High	0	0.00	5	14.29
$60 \leq x < 75$	Moderate	0	0.00	23	65.71
$55 \leq x < 60$	Low	0	0.00	3	8.57
$x \leq 55$	Very low	35	100.00	0	0.00
Sum		35	100.00	35	100.00

Source: Primary data after processing (2022).

MIA-3, class *X MIA-4*, and class *X MIA-5*). Since the population is considered homogeneous, one class was randomly selected (simple random sampling) from five existing classes as a sample in this study. The selected class was an experimental class that was taught using a STEM approach. A total of 176 experimental unit students as research subjects with a total of 35 selected students who's each class can be seen based on the following percentage.

Figure 1 showcases the primary data used in the study, which were obtained from pretest data and posttest data. Pretest data consist of the scores or results obtained before applying STEM in learning, and posttest data refer to the scores or results obtained after applying the STEM approach in learning (Dywan and Airlanda, 2020). Meanwhile, data collection was carried out using: (1) testing tools to collect data on the critical thinking ability of high school students; and (2) questionnaires to find out the learning motivation of high school students. In this study, observation, administering exams, and questionnaires were the primary methods of data collection. Observations were made to gather information on the execution of the instructions and student learning activities. Two observers examined the learning process and recorded their observations. Additionally, test results were used to gather information on students' critical thinking abilities. The tests were administered twice, once before the STEM-based learning process (pretest) and another after the STEM-based learning process (posttest). Two professionals with expertise in teaching mathematics verified the tests that were given. Indicators of critical thinking skills from this study were used to create a modified scoring grid. For interpretative purposes, the students' critical thinking ability level was categorized based on the scores they obtained, which were divided by the highest score the students achieved.

Data were collected from the testing instruments developed to measure students' critical thinking ability. The testing instruments we used, both pretest and posttest, were the same. A questionnaire was developed to measure student learning motivation. This data collection was developed based on a previously described conceptual framework that describes the framework of (1) identifying learning and (2) predicting student behavior (Ilyas et al., 2020; Ma'rufi et al., 2020). Both can be modulated by various interventions and multiple STEM retention initiatives. The framework describes the application of STEM factor approaches in learning mathematics, including critical thinking ability and student learning motivation factors related to the application (Dywan and Airlanda, 2020).

The SPSS software package ver. 25 was used for all data analyses. Two stages were employed in data analysis: (1) prerequisite analysis test; and (2) hypothesis testing. The feasibility and reliability test of the instrument involved testing the validity and reliability (Tamur et al., 2021). Since the acquired data was ordinal, we performed the Method of Successive Interval (MSI) to transform ordinal data into interval data as a prerequisite for inferential testing (Kutner et al., 2004). In this case, MSI used Microsoft Excel software to transform the variable data in the study. Furthermore, the first research question refers to the extent of students' critical thinking skills in learning mathematics with the STEM approach. Thus, the one-sample t-test analysis was used to determine the students' improvement in critical thinking skills before and after implementing the STEM approach.

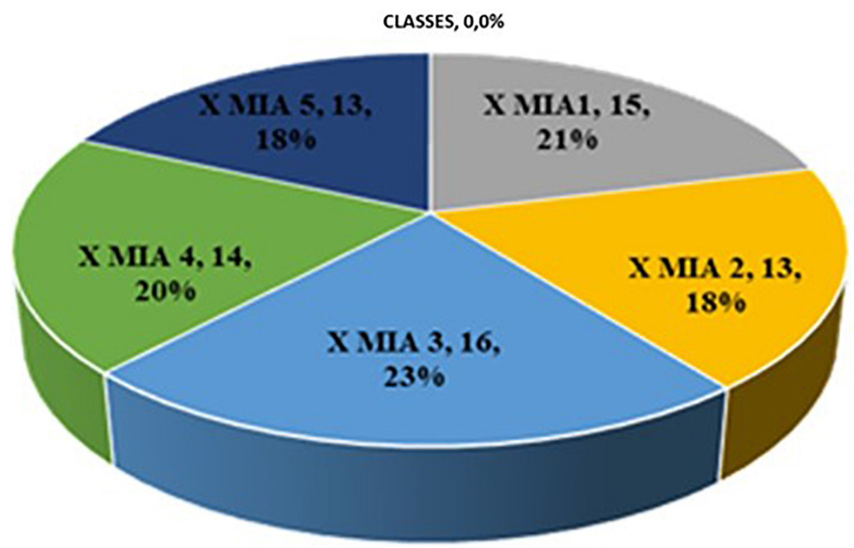

FIGURE 1
Data of 10th grade *mathematics and science* students at Senior High School-*SMA Negeri 6* Palopo. Source: Primary data after processing (2022).

Furthermore, the second research question was raised to assess the extent of student motivation before and after implementing the STEM approach. In this case, a one-sample t-test analysis was also used. As a prerequisite, a normality test was carried out by referring to the residual value, whether it has a normal distribution or otherwise, by identifying the Normal P–P Plot of Regression Standardized Residual graph and the significance value on the Kolmogorov–Smirnov test. A good regression model has an average residual value or is at least close to normal. Finally, we used a hypothesis test (t-test) to determine the effect of the independent variables (critical thinking skills and motivation), whether they have partially significant effect on the STEM approach.

Descriptive statistical analysis was carried out using the percentage of learning implementation achievement in this research based on certain categories (Ilyas et al., 2018). Inferential statistical analysis was applied by testing analysis requirements and hypothesis testing. Data analysis in this study consists of the results of analysis prerequisite test and hypothesis test. The analysis prerequisite test consists of a normality test on pretest and posttest data. The hypothesis test used t-test to determine whether any differences in pretest and posttest data were apparent to demonstrate differences in students' critical thinking ability and learning motivation before and after application of the STEM approach (Wahono et al., 2020).

Results

Students' critical thinking ability through learning methods using a science, technology, engineering, and mathematics approach

Based on the results of data analysis, an overview of students' critical thinking skills taught using a STEM approach is presented in **Table 2**.

As shown in **Table 2**, 35 out of 35 students (100%) were lacking critical thinking skills before the STEM approach was applied. The STEM approach resulted in the identification of 4 students (11.43%) with very high critical thinking ability, 5 students (14.29%) with high critical thinking ability, 23 students (65.71%) with moderate critical thinking ability, and 3 students (8.57%) with low critical thinking ability (Theobald et al., 2020).

Students' critical thinking ability scores after being taught by applying a STEM approach had changed. This can be seen in the change in scores that occurred in each value from pretest to posttest. The results of the pretest of critical thinking ability show that the lowest score was 3, while the highest score was 25. A total of 100% of students were able to think critically in the lower task. As for the posttest results, the lowest score was 55, while the highest was 100. Conclusively, the students' critical thinking ability was in the students that's categorized middle and above. Given an average pretest of 13.90 indicates that the students' critical thinking ability was in the deficient category. Meanwhile, the average posttest score was 70.67, which is in the high category. The median score ranged from 14 to 70. According to the category of students' critical thinking ability, it can be stated that before being given treatment, the average student's critical thinking ability was in the deficient category, with scores ranging from 0 to 20 (Ma'rufi et al., 2021). After the students were given treatment, the average student's critical thinking ability was in the high category ranging between 60 and 80. The rate of the increase in students' critical thinking skills after being taught using a STEM approach is shown in **Table 3**.

As presented in **Table 3**, the average gain from the low, medium, and high classifications, showing 0.65 points, is in the medium category, implying that the average increase in students' critical thinking ability after the application of the STEM approach lies in the medium category.

Student learning motivation through learning motivation using a science, technology, engineering, and mathematics approach

Based on the results of data analysis, an overview of the learning motivation of students taught with a STEM approach can be seen in **Figure 2**.

As shown in **Figure 2**, there was an increase in student learning motivation following the application of the STEM approach. The average student learning motivation prior to the application of the STEM approach was 141.14, with 115.00 as the lowest score and 178.00 as the highest. After the application of the STEM approach, the average student learning motivation increased to 162.17, with 124.00 as the lowest score and 193.00 as the highest. In addition, the frequency distribution of learning motivation of students who were previously taught using the STEM approach is specified into five categories as shown in the following table.

As showcased in **Table 4**, before the application of the STEM approach, out of 35 students there were 13 students (37.14%) who had high learning motivation and 22 students (62.86%)

TABLE 3 Normalized acquisition classification of students' critical thinking ability.

Acquired normalization coefficient	f	Percentage (%)	Classification
$g < 0.3$	0	0.00	Low
$0.3 \leq g < 0.7$	26	74.29	Medium
$g \geq 0.7$	9	25.71	High
Average	0.65		Medium

Source: Primary data after processing (2022).

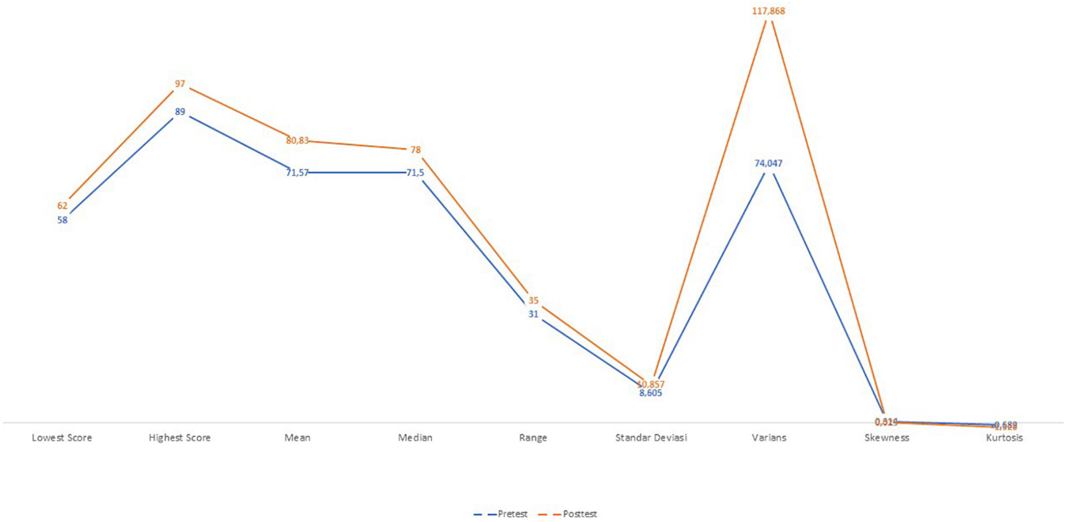

FIGURE 2
Recapitulation of student learning motivation using a STEM approach. Source: Primary data after processing (2022).

who had very high learning motivation. Meanwhile, after the application of the STEM approach, out of 35 students, there was 1 student (2.86%) who had high learning motivation and 34 students (97.14%) who had very high learning motivation (Blecking, 2018).

Hypothesis testing

In the current study, two hypotheses were tested, hypothesis 1 is aimed at finding out whether there is an increase in students' critical thinking skills after being taught using a STEM approach (Ilyas et al., 2020). Meanwhile, hypothesis 2 is aimed at finding out whether there is an increase in student learning motivation after being taught using a STEM approach.

Hypothesis 1

> H_0: There is no improvement in students' critical thinking skills after being taught using a STEM approach.

> H_1: There is an increase in students' critical thinking skills after being taught using a STEM approach.

Hypothesis 1 was tested using one sample *t*-test. However, before conducting a hypothesis test, a prerequisite test was carried out, namely the normality test. The results of the normality test showed that the probability value of students' critical thinking ability obtaining data after the application of the STEM approach was 0.118 > 0.05, this means that the data acquisition of students' critical thinking ability came from a normally distributed population (Logan et al., 2019).

The results of the prerequisite test show that the data acquisition of critical thinking skills was at a normal distribution. Furthermore, a hypothesis test was carried out. The results of hypothesis test 1 are presented in the following table.

As shown in **Table 5**, it is apparent that the *P*-value of the (two-tailed) test hypothesis 1 is 0.001 < 0.05, subsequently, H_0 is

TABLE 4 Frequency distribution of student learning motivation.

Interval	Category	Pretest		Posttest	
		f	Percentage (%)	*f*	Percentage (%)
40.00≤ X< 53.33	Very low	0	0.00	0	0.00
53.33≤ X<80.00	Low	0	0.00	0	0.00
80.00≤ X<106.67	Moderate	0	0.00	0	0.00
106.67≤ X<133.33	High	13	37.14	1	2.86
133.33≤ X<200.00	Very high	22	62.86	34	97.14
Sum		35	100.00	35	100.00

Source: Primary data after processing (2022).

TABLE 5 Hypothesis test results 1.

One-sample test						
	Test value = 0.29					
	t	df	Sig. (two-tailed)	Mean difference	95% confidence interval of the difference	
					Lowest Score	Highest Score
Gain	19.437	34	0.001	0.36219	0.3243	0.4001

Source: Primary data after processing (2022).

rejected and H_1 is accepted. This means that there is an increase in students' critical thinking skills after being taught using a STEM approach.

Hypothesis 2

> H_0: There is no increase in student learning motivation after being taught using a STEM approach.

> H_1: There is an increase in student learning motivation after being taught using a STEM approach.

Hypothesis 2 was tested using paired sample *t*-test. However, before conducting a hypothesis test, a prerequisite test was carried out, namely the normality test. The results of the normality test showed that the probability value of student learning motivation data before the application of the STEM approach was 0.200 > 0.05 and the student learning motivation data after the application of the STEM approach was 0.200 > 0.05. This implies that the student learning motivation data before and after the application of the STEM approach came from a normally distributed population (Ilyas et al., 2018).

The results of the prerequisite test show that students' learning motivation before and after the application of the STEM approach was at normal distribution. Furthermore, a hypothesis test was carried out. The results of hypothesis test 2 are presented in the following table.

As indicated in **Table 6**, the *P*-value of the (two-tailed) test of hypothesis 2 is 0.001 < 0.05, subsequently, H_0 is rejected and H_1 is accepted. This implies that there was an increase in students' learning motivation after being taught using a STEM approach.

Discussion

Based on the results of the study, learning using a STEM approach can improve students' critical thinking skills, as observed from the average increase in students' thinking ability in the moderate category. Improvement in students' critical thinking skills was due to the application of the STEM approach wherein students are directed to integrate STEM in solving problems to train students' critical thinking skills (Alzen et al., 2018). The STEM approach to learning provides space for students to ask critical and relevant questions about the materials they study, thus training students' critical thinking skills. According to Tamur et al. (2021) and (Supardi et al., 2021), the STEM approach can produce student thinking activities that help bring out students' critical thinking, which is characterized by the capacity to solve problems, make decisions, analyze assumptions, evaluate, and conduct investigations. This causes students to think more critically and understand the study materials because students solve the problems they face by linking scientific knowledge with technology, mathematics, and engineering (Putri et al., 2020).

The results of the study also indicate that using the STEM approach increases student learning motivation; as observed, the average student learning motivation before the application of the STEM approach was 141.14, while after the application of the STEM approach, the average increased to 162.17. This increase in learning motivation was afforded to learning using a STEM approach linking STEM in learning. Consequently, learning became interesting for students, the materials taught were not only limited to theory but also practice (Johnson and Elliott, 2020). This is in line with the argument posited by (Erdmann et al., 2020) stating that in learning using a STEM approach, students are taught both theory and practice in the form of project work. As a result, the students experience the learning process firsthand. Further, according to (Purwaningrum and Faradillah, 2020), using technology in mathematics can increase student engagement and learning motivation.

This study's STEM integrated approach was designed to promote mathematics learning in compliance with curricular requirements. Accordingly, STEM was prioritized in the production of instructional materials (Graham et al., 2013). Such an integrated approach to STEM learning is more accessible to implement than a thematic approach. An integrated STEM strategy eliminates the dividing wall between the various STEM disciplines (Carlson et al., 2016). Indirectly, the integrated application of STEM necessitates a STEM methodology to determine the amount to which students' critical thinking abilities and learning motivation grow when utilizing an

TABLE 6 Hypothesis test results 2.

Paired samples test								
	Paired differences					*t*	df	Sig. (two-tailed)
	Mean	SD	SEM	95% confidence interval of the difference				
				Lowest Score	Highest Score			
Pretest–posttest	−21.02857	17.09229	2.88912	−26.89998	−15.15717	−7.279	34	0.001

Source: Primary data after processing (2022).

integrated approach (Blecking, 2018). Therefore, an integrated STEM strategy is aimed at providing students with inter-disciplinary knowledge to fulfill the demands of the workplace (Johnson and Elliott, 2020). The stem integrated approach is an interdisciplinary method for understanding the effect that critical thinking capacity has on student motivation.

This technique mixes diverse cross-curricular knowledge, such as critical thinking abilities, problem-solving, and scientific information, to provide a solution to a problem by combining classroom-taught material (Freeman et al., 2014). Trevallion and Trevallion (2020) claim that an integrated approach to STEM education may be implemented in schools and society by merging two, three, or all STEM components. In this integrated method, STEM learning occurs when the two STEM parts interact in learning. For instance, if the subjects of mathematics and physics are incorporated into learning, the learning is already considered STEM learning. The following is a summary of the integrated approach model (Manzanares et al., 2020).

The integrated closeness of STEM that was used in the learning in the current study, the ideas paired with critical thinking abilities, and student learning motivation facilitated students comprehension of the material (Falco and Summers, 2019). Consequently, the improvement in learning outcomes attained by students in this research is substantial. This integrated approach to STEM education has resulted in increased learning, implementation, and reaction levels and enhanced mathematics learning outcomes based on parameter criteria (Li and Schoenfeld, 2019). Therefore, it can be asserted that STEM is an excellent learning tool for enhancing students' critical thinking skills and motivation, resulting in an integrated method for enhancing student's math learning results (Erdmann et al., 2020). The influence that the application of STEM involving critical thinking ability and student learning motivation has on the improvement of student learning outcome is represented by the research results relating to the measurement of differences, correlations, and effectiveness based on student worksheets, questionnaires, and instrument tests of STEM as an integrated research criteria.

Limitation and future research

Using an integrated STEM strategy eliminates the barriers between each STEM subject. The integration of STEM disciplines implicitly necessitates a STEM mindset. The integrated STEM approach is an endeavor to provide students with the multidisciplinary knowledge necessary to meet workplace demands. In this study, the combination of ideas, critical thinking abilities, and student motivation facilitated pupils in comprehending learning materials, particularly while studying mathematics.

The present study's limitation is that it focused on applying the STEM approach to mathematics education. It was anticipated that the findings of this study would encourage students and researchers to adopt a method that encourages students to solve mathematical issues they encounter while studying. However, we also believe that to accomplish this, students must approach the learning process through the lenses of STEM. This has not yet transpired in its entirety, as the student learning process detailed in this study contained limited material. STEM functions as an effective learning tool that supports students' critical thinking abilities and motivation and an integrated method that enhances students' mathematical learning results. This research has implications on the creation of mathematics education curriculum and enhancing students' mathematics learning results.

Conclusion

The STEM approach is regarded as the primary and most essential method for assessing cognitive ability and learning motivation. The results of the current research indicate that the application of a STEM-based method to learning mathematics with 10th grade students in Mathematics and Science class (*MIA-Matematika dan Ilmu Alam*) at Senior High School-*Sekolah Menengah Atas (SMA) 6* Palopo could increase students' critical thinking skills. Students were taught to solve issues by integrating STEM. With a pretest average of 13.90 and a posttest average of 70.67, the pupils' ability to think critically improved. The results also revealed that a STEM-based strategy enhanced student learning motivation by an average of 71.57–80.83 points. This study demonstrates that the use of a STEM approach to mathematics learning methods can enhance critical thinking skills and learning motivation, hence making STEM an effective learning method that can be implemented across the board in student education.

Data availability statement

The original contributions presented in this study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

MI developed the first draft and data analysis. MM helped to get the data and develop literature review. PK supported the method section and final manuscript. EM supported the final analysis. All authors contributed to the article and approved the submitted version.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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How to promote STEM competencies through design

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Introduction: This study explored the impact of a community of inquiry on Science, Design and Technology and Mathematics curriculum competencies of 159 Year six students as they carried out a design task.

Methods: A quasi-experimental design was employed with both qualitative and quantitative analyses. A community of inquiry approach was adopted by the teachers ($n = 3$) in the experimental group but not by teachers ($n = 4$) in the comparison group. Both groups participated in a learning sequence on electricity culminating in a design challenge in small collaborative groups.

Results: The results showed that the experimental group ($n = 65$) demonstrated significantly greater instances and a broader range of Science, Design and Technology and Mathematics competencies across the design task as well as significantly higher learning gains than their comparison group ($n = 94$) peers.

Discussion: The cognitive shifts towards higher competency development in the experimental group is stronger as a result of the reflection and reasoning required to engage in a community of inquiry.

KEYWORDS

community of inquiry, design, discourse analysis, STEM competencies, dialogic inquiry

Introduction

The introduction of design and technology to the Australian curriculum for primary and secondary schools signals the recent focus on new pedagogies to address this age of technological advancement (Kimbell and Perry, 2001) and to address calls for a stronger focus on science, technology, engineering and mathematics or STEM education (The Australian Industry Group, 2015). The addition of this subject area is also mindful of the argument put forward by several scholars (Bereiter and Scardmalia, 2006; Collins and Halverson, 2010; Brown et al., 2011) that greater emphasis in education on design is required in order to emphasize creating as a way of knowing given "design epistemology is concerned with generating useful, practical ideas to resolve existing real-world problems" (Koh et al., 2015, p. 9).

With increasing complexity of global issues and the world of work, education systems are trying to equip students with 21st century skills that include thinking critically and creatively, solving complex problems, making evidence-based decisions, and working collaboratively (Weldon; 2017). We are currently experiencing what has

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been termed "the skills movement" (Care et al., 2016). Since the beginning of the 21st century, curriculum documents have increasingly focused on the changing skills required for employment. There is rising interest amongst education authorities in these skills, with UNESCO reporting that "almost 90 countries… refer to generic competencies in their general education curricula" (Tedesco et al., 2013, p. 11). As recently as 2017 it was shown that specific skills are advocated within national policy documents in 117 countries (Roth et al., 2017).

Given this period of focus of the school curriculum on skills and competencies, it is important to understand the distinction. Skills are "doing or acting in practice, involving motor skills as well as cognitive skills" (Baartman and de Bruijn, 2011, p. 127). Competence or capability is generally understood to comprise sets of knowledge, skills and attitudes and the capacity to use them (Baartman and de Bruijn, 2011, p. 126). While a disposition is having knowledge and skills and a sense of when to use them.

Curriculum subject areas are often represented as competency frameworks (Yates, 2017). And as is the case for the Australian Curriculum, competency frameworks often include 21st century skills as a subset of the competencies students are expected to achieve. In a review conducted for the New South Wales Department of Education, Lamb et al. (2017) question whether these skills and competencies have found their way into teaching and learning in Australian schools and whether they can be taught or assessed. This study addresses these questions with a focus on the competency frameworks specified in Science, Design and Technology and Mathematics (STEM) subject areas of the Australian Curriculum as shown in Figure 1. The design and technology curriculum competency framework is considered to describe technology and engineering competencies. A glance across these competency frameworks shows an emphasis on 21st century and inquiry skills including identifying questions and problems, analyzing, comparing and contrasting information, conducting investigations, interpreting evidence, assessing arguments and drawing conclusions.

Given the emphasis on inquiry skills in these competency frameworks, we hypothesized that an inquiry pedagogy like community of inquiry that engages students in active and dialogic inquiry would improve STEM competencies. There is a need for more intentional and explicit research around the instructional environment and how it contributes to supporting students' engagement with these competencies through inquiry work. This study also proposed that STEM competencies can be assessed using discourse analysis when students are actively involved in dialogic open-ended design tasks. Tasks such as these make visible student thinking, subject matter knowledge, intellectual skills and dispositions. This analytical approach will be described following a discussion of community of inquiry pedagogy and its impacts on teaching and learning in the classroom.

Theoretical and conceptual framework: Learning in a community of inquiry

Community of inquiry (CoI) is a dialogic inquiry pedagogy for the implementation of philosophy in the primary and secondary school classroom. It engages students in deep thinking through collaborative dialogue about critical concepts with the main objective of improving reasoning abilities (Reznitskya and Gregory, 2013). The pedagogical practice known as community of inquiry has distinctive philosophical underpinnings. It was framed by Charles Sanders Peirce and based on his conception of communities of discipline-based inquiry involved in knowledge construction. The community of inquiry (CoI) pedagogy was developed by Matthew Lipman as part of his Philosophy for Children program to guide classroom discussion through the introduction of philosophy into the school curriculum (Lipman, 1991). It is espoused to "develop students' ability to think for themselves through the internalization of social practices which in turn develops their social and intellectual dispositions and capacities for active citizenship" (Burgh and Nichols, 2011). The CoI method has the potential to foster capacities to become acquainted with the conventions of disciplines through active participation in the practices of discipline-based communities of inquiry where not only disciplinary competence can be developed but also habits of self-correction. These habits then allow the reconstruction of those conventions when confronted with new problematic situations. These theoretical suppositions are empirically explored in this paper.

Matthew Lipman believed that children were capable of critical, creative and caring thinking (Lipman, 2002) and that these forms of thinking were mutually reinforcing. This is an important point of distinction to other dialogic inquiry pedagogical approaches discussed in the literature such as Collaborative Reasoning (Waggoner et al., 1995), Accountable Talk (Wolf et al., 2006) and Thinking Together (Dawes et al., 2003). CoI is the only approach that espouses the essential need to focus on caring thinking in order to solicit, stimulate and engage critical and creative thinking.

Lipman developed this dialogic inquiry educational approach to allow students to philosophize, problematize, and psychologize the curriculum. He coined the term educational philosophy to mean

> "a discipline that promotes thinking in other disciplines. It is philosophy that has been developed for practical use in the classroom to get students to think in other subject areas by employing concepts, ideas and reasoning skills; skills borrowed from philosophy in order to facilitate thinking about the subject matter under examination" (Lipman, 2008, p 152).

Lipman's program is founded on the tenets of pragmatism espoused by John Dewey and Charles Sanders Peirce. Pragmatism holds to the notion that "knowledge is the product of inquiry, that

Science			Design and Technology				Mathematics	
Science Understanding S1	**Science social/ethical endeavours S2**	**Science inquiry S3**	**Investigating and defining T1**	**Generating and designing T2**	**Producing and implementing T3**	**Evaluating T4**	**Mathematical understanding M1**	**Mathematics inquiry M2**
Selects and integrates appropriate science knowledge to explain and predict phenomena Apply knowledge to new situations (Science knowledge refers to facts, concepts, principles, laws, theories and models that have been established by scientists over time)	Understanding and explanation of the world Construction of explanations and improving knowledge with emerging evidence Making connections between science and social and ethical priorities	Identifying and posing questions Planning, conducting and reflecting on investigations Processing, analysing and interpreting evidence Communicating findings Exercising scientific thinking	Critiquing, exploring and investigating needs, opportunities and information for innovations Evaluating social and environmental implications of innovations	Developing and communicating ideas Creating change, make choices, rate options, and consider alternatives, Documenting design ideas and possibilities focusing on high-quality designed solutions.	Applying techniques to make products, designed to meet specific purposes and user needs Selecting and using apt materials, components, tools and equipment Applying accurate production skills and using appropriate work practices to achieve sustainability.	Making judgements throughout a design process and about the quality and effectiveness of their designed solutions Determining effective ways to test and judge designed solutions Reflecting on processes and transfers learning to other design opportunities	Building and relating basic conceptual knowledge Connecting concepts to develop new ideas Identifying commonalities and differences Thinking and interpreting information mathematically	Make choices, interpret, formulate, model and investigate problems using mathematical strategies to represent unfamiliar or meaningful situations Communicate solutions effectively

FIGURE 1
Science, Design and Technology and Mathematics competency frameworks.

knowing is not merely the acquisition of facts external to the knower, but comes through a problem-solving exercise that moves from doubt to belief on the basis of evidence and inference" (Millett and Tapper, 2012, p. 3).

CoI has three critical elements. It is collaborative with a built-in social dimension involving communal dialogue with the requirement that students listen carefully and respond respectfully to the ideas of others. It is philosophical in that students clarify concepts, explore meanings and work towards a shared understanding approaching knowledge with an understanding that it is fallible. The third element is inquiry where students engage with open-ended or divergent questions and intelligent agreement and disagreement through a community of inquiry process. CoI is a practice that brings together collaboration and inquiry using a philosophical approach. It permits students to engage in a disciplinary inquiry where they are able to "problematize or transform commonly accepted facts into problems to be explored, thereby opening knowledge to thinking" (Lefstein, 2010, p. 176).

The CoI process is initiated by presenting students with a problematic situation within the context of the subject under study that engages them in thinking about what is unclear or in conceptualizing the problem. Based on what they find problematic, students generate a list of questions – that guide the conceptualization of the problem. A central question is chosen and students then offer their opinions, explore ideas, state conjectures and generate hypotheses in order to seek solutions or explanations. Finally, students engage in analysis, reasoning and argumentation to achieve a deeper understanding or conceptualization of the problem into which they are inquiring.

Making thinking an explicit focus in science lessons requires pedagogical strategies that provide students with opportunities to engage in communal dialogue about how science and technology impacts society. Sprod (2014) argues that pedagogies that make thinking more visible, like CoI, are not widely implemented at a system level. However, there is good evidence for such an approach impacting on students' learning and cognitive abilities. Research on CoI has shown that teachers use significantly more open-ended questions when trained (Trickey and Topping, 2004, 2006; Baumfield, 2016; Nichols et al., 2017). Students that engage in CoI show improved cognitive abilities to conceptualize problems, sustained for several years, increased student–student dialogue characterized by prolonged length of student utterances/elaborations (rather than increased total student utterances), enhanced student reasoning and justification skills (Topping and Trickey, 2014) and significantly higher student substantive questioning and other inquiry behaviors (Nichols et al., 2017).

Given these impacts of CoI and the problem conceptualization students' encounter through CoI, we asked the following research question. What is the effect of embedding the CoI process in inquiry science curriculum on the development of the Australian Curriculum's identified STEM competencies demonstrated during a design problem solving task? Although studies have shown improvements on psychometric measures of cognition, reasoning and argumentation as a result of participating in dialogic inquiry or

CoI (Reznitskya et al., 2012; Topping and Trickey, 2014), these measurements have limitations. They were not designed for exploring subject-specific skills and competencies and so lack the appropriate subject-specific context. Performance-based subject-specific dialogic assessment in the form of an authentic open-ended task is more appropriate for exploring gains in STEM-specific competencies. As Chinn et al. (2011) argue, to gain a more contextual understanding of diverse aspects of students' epistemological development, studies need to utilise more situated and refined measures. De Liddo et al. (2011) have shown that the quality of student discourse in the classroom provides key insights into learning and skill development. Drawing on Niel Mercer's socio-cultural discourse analysis and argumentation theory they identified patterns of activity in students' discourse that corresponded to learning processes and knowledge construction. They also refer to the use of discourse to relate learning outcomes to learning processes as discourse-centric learning analytics. This study employed sociocultural discourse analysis and discourse learning analytics to explore the relationship of CoI and/or a 5E's inquiry learning sequence, learning outcomes and visible STEM competencies.

Materials and methods

Procedure

This study, that was part of a larger project (Nichols et al., 2022), employed an intervention approach. Teachers attended a two-day workshop on implementation of a researcher-designed Year 6 Science inquiry learning sequence on energy that aligned with the Australian science curriculum. The learning sequence culminated with assessment in the form of an inquiry design problem solving task that required students to engage with Science, Design and Technology and Mathematics subject area competencies. We modelled how to open the learning seqeunce through a CoI with an approach to problematizing the topic under study that would be revisited by teachers and students throughout the learning seqeunce.

Participants and design

Participants included 159 Year six primary school students and seven teachers across five schools with similar socio-demographic profiles (full range of school size was from 600 to 800 students, with an age range of 10 to 12 years, 45–60% of students were female and 40–55% were male) in municipal and regional areas of Brisbane, Australia. Teacher participants included six females and one male that ranged in years of teaching experience from less than 1 year to 12 years with two first year graduates, three who had worked for six to 8 years and two that worked anywhere from eight to 12 years. There were 87 female students and 72 male students. Ethical clearance was acquired for this study and participants were recruited through several inclusion criteria such as.

1. The teachers were intending to teach Year six in the year of the study.
2. The teachers consented to participate in professional learning around implementation of a Year six curriculum learning sequence on electrical energy.
3. Both teachers and students were fully informed about and consented to participating in classroom observations, tests and interviews.

A before and after convergent mixed methods approach (Cresswell, 2012) was utilized with all teacher participants participating in 2 days of professional learning around CoI and the implementation of an inquiry science learning sequence (Figure 2) designed with the 5E's (Figure 3; Bybee, 2014). However, while implementing the intervention in their classrooms, four of the teachers in the study chose not to engage their students in CoI as they perceived there was a sufficient inquiry emphasis with the learning sequence design. All other aspects of the intervention were conducted in their classrooms, the only difference was that they did not start the learning sequence off with a CoI, they started with where electricity comes from activity (see Figure 2 for the intervention activities). As a result, the study design became a two-by-two pre-post intervention and comparison approach. This inherent shift in study design due to participant decisions around implementation has been validated in the literature (Topping and Trickey, 2014). The CoI group consisted of three teachers and 65 students from two schools and the Non-CoI group comprised four teachers and 94 students from three schools.

Intervention phase

The intervention activities are outlined in Figure 2. During the professional learning all teachers were introduced to embedding a CoI approach in a learning sequence of work on electricity and energy that culminated in a design task. As part of the professional development around the CoI pedagogical process, a collaborative community of inquiry on human rights for access to electricity was a way to problematize the learning sequence content. The CoI was modelled for the teachers by showing two stimuli (a creative commons image of a classroom in a developing country without electricity and a short video that provided some detail about where electricity comes from and what happens in a blackout). Dialogue was facilitated by exploring the question "Is electricity a basic human right?" Teachers were encouraged to justify their perspectives. An additional question based on the opening question being a plausible truth was posed; "If electricity is a basic human right, then why are so many people disadvantaged?" In order to gauge depth of understanding, foster deeper thinking about and problematize the learning sequence topic, additional substantive questions were explored around considering if electricity is a need or a want, thinking about the implications of having no electricity, the ethical implications of the prohibitive expense of

Activity (5E's Phase)	Resources
Day 1	
Community of Inquiry (Engage)	Stimulus image
Where does energy come from? (Engage) Torch deconstruction activity (Explore) Lemon battery investigation (Explain)	Cooperative Learning Torch worksheet Incandescent torches Simple circuit Lemon battery materials Lemon battery assessment task
Switch activity (Explain) Conductors and Insulators activity (Explore/Explain) Fair Test – conductors and insulators	Conductors & Insulators worksheet Conductors & Insulators experiment
Day 2	
Electrical circuits Series and Parallel circuits with Electrolab (Explain)	Circuit materials Electrolab kits Laptops
Power sources comparison solar/battery (Elaborate) Poster mind-map renewable and non-renewable (Explore/Explain) Group challenge design task (Evaluate)	Solar and battery circuits WorldBook posters Group assessment task Generators

FIGURE 2
Professional learning/intervention sequence of activities and 5E's phases.

Phase of 5E Learning Cycle	Description
Engage	Learning experiences in this phase seek to capture students interest and curiosity, introduce them to the topic and evaluate prior knowledge and gaps in understanding.
Explore	Each new concept introduced is actively explored through hands on experiences, or through video, computer software or other materials to support understanding.
Explain	In this phase students explain what they have explored in the explore phase in their own language. The teacher can then explicitly teach how to explain the concept with scientific terminology to support students to explain the concept using accurate scientific language.
Elaborate	Students can apply their new knowledge in a new context in this phase to deepen their conceptual understanding.
Evaluate	Student understanding can be assessed through diagnostic, formative or summative assessment throughout the cycle. Self- and peer-assessment is also useful.

FIGURE 3
Description of the 5E's phases.

electricity, accessibility of renewable energy, where the responsibility lies in using energy more efficiently and what would happen if no one took responsibility.

The process focused on building a culture of respect through a collaborative shared dialogue concerned with providing examples and counterexamples, seeking clarification, reason giving, making distinctions and intellectual progress through thinking, reasoning and conceptual analysis. A deliberate goal of the discussion was to test generalizations and uncover assumptions. The process was concluded with reflection considering how the teachers perceived their contributions and engagement in the community, respect and the value of thinking about others.

This collaborative inquiry process encourages the development of ethical perception by fostering the ability to discern any situation's critical features and relationships and then utilize these to make judgements (Sharp, 2017). Students develop concern for the implications of motives, judgements, actions for others and for themselves. In identifying these implications, students must imagine the varied permutations that are feasible and in so doing position themselves critically and creatively within a context consciously relating to its diverse aspects. Students learn to make judgements within a set of circumstances and from particular positions. In this way, the concern or caring thinking that is activated within a CoI is inextricably linked to, and fuels critical and creative thinking.

The learning sequence: The intervention aimed to endow teachers with physical resources and skills to deliver a Year six learning sequence of work around electricity and energy. The learning sequence activities were designed to employ cooperative learning approaches and the 5E's inquiry model (Bybee, 2014). This instructional model is underpinned by a constructivist learning theory with the notion that conceptual understanding of science concepts and their meaning are constructed through experiences. These experiences occur in a learning cycle over a number of phases known as Engage, Explore, Explain, Elaborate and Evaluate. Figure 3 provides a description of the 5E's phases that were used to plan the learning sequence. The learning sequence included an emphasis on design tasks including the building of switches, exploring lemon batteries and constructing circuits to identify energy transformations. This prepared students to complete the final assessment task where cooperative groups were challenged to design and construct a device that would provide electricity to a third world community using recycled materials provided to them.

This study focuses exclusively on the design phase where students worked in small groups to brainstorm the main features of their device, exploring what their generator would require. Groups comprised four students provided with specific roles. The roles included a project manager to oversee the group work, a drafts person to draw sketches, a photographer digitally capture the final design sketch, and a materials manager to encourage the group to consider and discuss the materials that would be used for construction of the device. While students each had a role to perform they were encouraged to also provide ideas for the design.

Data corpus and analysis

Figure 4 lists and describes the data corpus for the study and the associated analyses that were conducted. A test was provided to students prior to and immediately after the learning sequence. The test included questions that related to the content of the learning sequence (Figure 5). The total test score was 26. Overall learning gain was calculated for the CoI and Non-CoI groups (see Figure 4; McDaniel et al., 2007). Mann–Whitney U test was used to compare pre-test scores, post-test scores and learning gain across the CoI and Non-CoI groups. A non-parametric statistical test was carried out given the CoI group scores were not normally distributed.

Two small student groups per classroom conducting their power-generating device design were video-recorded for up to 40 min (group task recordings ranged from 15 to 40 min). Video recordings, totaling approximately 240 min, were transcribed and parsed into turns (Johnstone, 2007). A turn was initiated by a student talking and completed by another student talking or when talking ceased. We then identified episodes with verbal demonstrations of STEM competencies shown in Figure 1. Two or more turns of talk initiated by a student with demonstrations of STEM competencies was identified as an episode. When a question had been addressed or a design issue had been resolved or the topic shifted this was identified as the end of an episode. Episodes provided the units of analysis to which the codes for the competencies applied. We applied discourse analytics (De Liddo et al., 2011) where we coded episodes for the competencies. We also applied sociocultural discourse analysis (Mercer, 2004) to summarise the nature of the talk.

A method for analyzing student talk in the classroom that incorporates qualitative and quantitative methods is sociocultural discourse analysis (Mercer, 2004). Neil Mercer describes this analytical approach as analyzing collective thinking in the classroom given that when students work together they not only interact, they interthink. This type of discourse analysis takes a sociocultural perspective on learning where the classroom dialogue (teacher-student and/or student–student interactions) can provide insights into educational success and failure. It is a contextual approach to analyzing the relationship between dialogue processes and outcomes. Mercer's analysis of student's talk in groups over time resulted in the development of a typology. He describes three types of student talk based on the degree to which students are showing cooperative or competitive behaviors and whether or not they display reciprocal acceptance of ideas or critical reflection. Disputational talk is characterized by quick exchanges such as assertions and counter assertions or challenges. Decision making tends to be on an individual basis and there is obvious disagreement but there is little attempt to reconcile ideas, offer suggestions or engage in constructive criticism. Cumulative talk is characterized by the construction of common ideas that are built in an uncritical way. This talk is evident when there are repetitions, positive confirmations and elaborations. Exploratory talk is evident when group members are all contributing their ideas, and opinions are clearly considered before the group builds to a particular decision. This form of talk will consist of critical and constructive engagement with shared ideas and suggestions put forward for everyone to consider. Challenges and counter

Data corpus	Data Analysis
Pre-Post test	Pre-test and Post-test scores Overall learning gain for all students in CoI and Non-CoI groups where Learning gain = (Post-test score – pre-test score) / (Total score – pre-test score) Mann-Whitney U test comparing the CoI and Non-CoI group Pre-test score, Post-test score and Learning gain
Discourse analysis of transcribed video recordings - students working in small groups on inquiry design task	Digitally recorded discussions transcribed and parsed into turns Segmentation through episodes Coding of discourse within the episodes for STEM competencies Mann-Whitney U test was applied to measure relative demonstrations of competencies across CoI and Non-CoI groups
Students Focus Group Discussion (FGD)	Qualitative analysis to support the overall findings

FIGURE 4
Data corpus and analyses for the study.

challenges may be evident but they are justified and alternative ideas or hypotheses are provided. Reasoning is more evident in this form of talk and forced accountability of claims is visible. Sociocultural discourse analysis was used in this study to explore and describe the nature of the talk demonstrated by student groups as they worked on their design challenge.

Learning analytics using discourse as a source of the analysis (De Liddo et al., 2011) was used to apply a coding scheme approach for a systematic observation in which utterances were assigned to defined categories and relative frequencies of occurrence of these categories were calculated. The categories used for this study were the STEM competencies defined by the Australian Curriculum competency frameworks for Science, Design and Technology and Mathematics subject areas shown in Table 1. These two approaches to discourse analysis were used to compare learning outcomes and demonstrations of competencies in a group of students that engaged in CoI and their peers that did not engage in CoI.

In order to standardize across the different timeframes for the CoI and Non-CoI group discussions, percentage of coded lines of transcript were calculated. The proportion of coded lines in the entire transcript of lines was compared between CoI and Non-CoI groups using a Mann–Whitney U test. Inter-rater reliability scores were determined for each of the coded competencies using two researchers across 25 percent of the episodes. Cohen's kappa calculation (Cohen, 1960) was utilized to compare scores. Where disagreements arose, they were resolved through discussion until agreement reached 81 to 90 percent.

Following completion of the learning sequence, teachers were asked to select a group of 6 to 8 students to participate in a student focus group semi-structured interview. During the focus group discussion, students were asked to reflect on their learning and compare how the completed learning sequence was different from previous learning sequences in science earlier in the year in their school. Audio recordings of focus group discussions totaled approximately 210 min. The responses from groups that had participated in CoI were separated from responses of those groups that did not participate in CoI. Student focus group discussions were used as qualitative evidence to support overall findings.

Results

Table 1 shows that there was no significant difference between the CoI and Non-CoI groups in their pre-test scores indicating that the groups were similar at the start of the learning sequence. However, there was a significant difference in post-test scores and learning gain across the two groups.

Table 2 shows overall the CoI group has a significantly higher proportion of their discussion coded for STEM competencies suggesting that CoI does promote engagement with these competencies and to a greater extent than in the Non-CoI group. This comparison is based on the proportion of coded STEM competencies relative to the total lines of transcript and so normalizes for any differences in the length of the student small group discussions. A finer grained discourse analysis shows how students in the CoI and Non-CoI groups demonstrated and utilized STEM competencies.

The stacked bar graphs in Figure 6 show coded demonstrations of competencies in the discourse for a CoI and Non-CoI group in three-minute intervals as they worked in their small group on the design of their generator. This data representation reveals that the CoI group engages a broader range of coded STEM competencies then the Non-CoI group. Note also that the CoI group spend 33 min designing their generator while the Non-CoI group discussion is 15 min long. These two groups are representative of other group discussions because these findings were consistent across all CoI and Non-CoI groups in the study. Teachers

Pre- and Post-test Questions:

1. Use the items below to help you **draw** a circuit diagram using circuit symbols.

   Images of a wire, switch, light bulb and battery here

2. a) **Look at** the circuit below and the list of materials. **Circle** which materials will complete the circuit when put between "A" to make the lights work.

   Image of a circuit with two light bulbs (glowing bright) and a battery with 'A' designating a place to insert a circuit component from the list.

   Materials: rubber duck, chalk, paddle pop stick, elastic band, metal spoon, copper necklace, battery, aluminum foil

   b) **Explain** why you circled the materials above.

3. **Look at** the two circuits below.

   Two images side by side showing a simple circuit with 1) one light bulb and a battery and 2) two light bulbs and a battery.

   a) What is the difference between the two circuits?

   b) How would the bulbs look different in these two circuits?

4. **a) Write** down the different types of energy shown in the picture at points A, B and C.

   Image showing the main features for creation of hydroelectric power A) a reservoir, B) a generator and C) above ground power lines.

   b) Use these three types of energy to make an **energy transfer diagram**

   potential energy → kinetic energy → electrical energy

5. How are wind power and coal power the same and different? Show this by putting points in the Venn diagram below.

   Images showing wind power and coal power.

   Venn diagram compoaring differences and similarties of wind and coal power.

6. A student has come up with a great idea! She wants to make a piece of clothing that uses a soft solar panel to do "SOMETHING". She needs a creative idea. Help the student **design** the item of clothing that uses a solar panel and **draw** a simple circuit diagram so that she can make the circuit.

End of test

FIGURE 5
Pre–/post-test questions.

TABLE 1 Mann–Whitney U test comparison of median scores and interquartile ranges (in parentheses) for CoI and Non-CoI groups.

Variable	CoI (N = 65)	Non-CoI (N = 94)	U	Z value	p
Pre-test Score	3.0 (2.0–4.25)	3.0 (1.5–4.13)	2770.0	−0.002	0.316
Post-test Score	12.00 (9.5–14.00)	9.00 (6.50–12.00)	2000.0	−3.701	<0.0005
Learning gain	0.41 (0.32–0.52)	0.29 (0.19–0.42)	1958.0	−3.84	<0.0005

TABLE 2 Comparison of CoI and Non-CoI group proportion of total lines of transcript coded for STEM competencies.

Variable	CoI (N = 48)	Non-CoI (N = 43)	U	p	Effect size
Proportion of discussion showing coding for STEM competencies	77	40	475.5	0.0005	0.46

confirmed that there was nothing procedural they did to influence the time students spent in group discussions conceptualizing their design.

Figure 6 also shows that the CoI group engages with the Mathematical competency understanding while the Non-CoI group does not engage with this competency. Other notable contrasts between the two groups is the higher relative engagement with the science inquiry and social/ethical competencies as well as the Design and Technology competency evaluation by the CoI group.

If we express the same data from Figure 6 as time trend graphical representations we see more clearly in Figure 7 different patterns of competency recruitment over time and across the discussion between the two groups. The trend line for

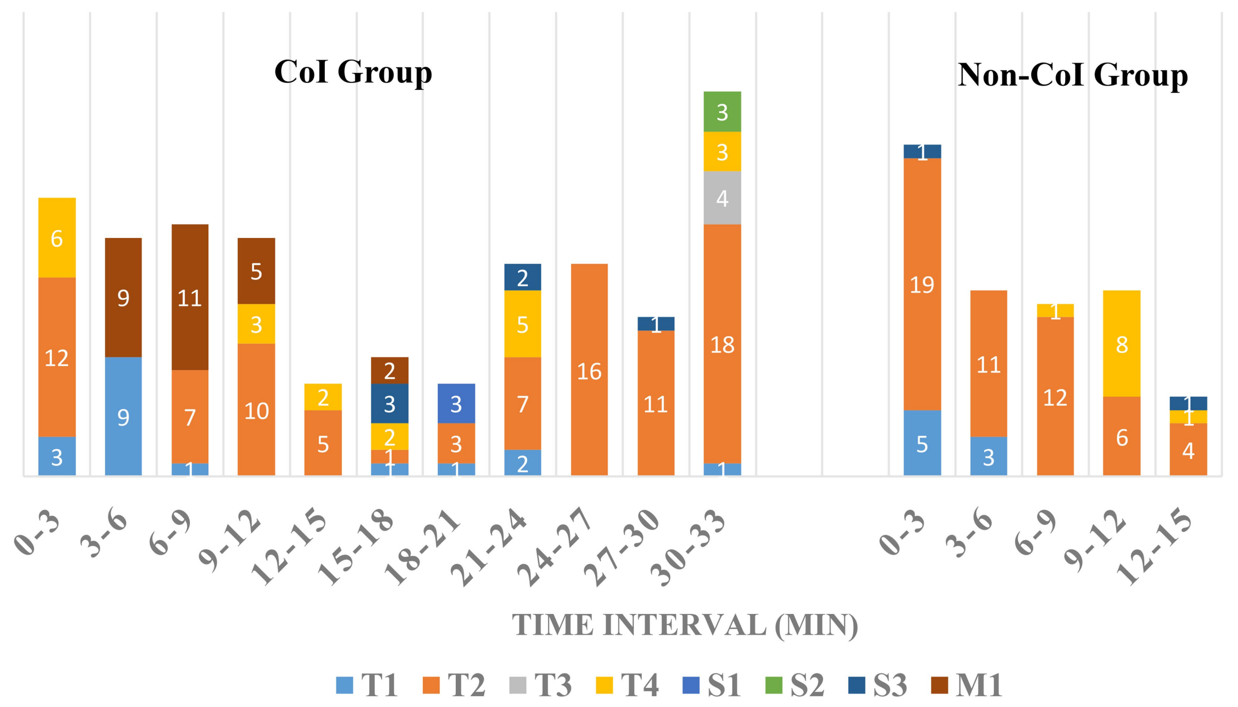

FIGURE 6
Student discourse STEM competencies in a CoI and Non-CoI group task. T1=investigating and defining, T2=generating and designing, T3=producing and implementing, T4=evaluating, S1=science understanding, S2=science social/ethical, S3=science inquiry skills, M1=mathematical understanding.

the Design and Technology competency generating/designing across the discussions of the two groups shows a different approach to the task. The Non-CoI group launch into generating/designing their generator in the first 3-min interval (2 min into the discussion) and engagement with this competency steeply declines across the short discussion. The same trend line in the CoI group shows a different approach to generating/designing that begins in the third 3-min interval (7 min into the discussion), generally declines up to the 15–18 min interval and then steeply increases over the next five 3-min intervals. There is a biphasic nature to the discussion within the CoI group evident through this competency trend line with an overall positive slope compared to a negative slope evident in the Non-CoI group discussion.

Engagement with the other competencies across the discussion provides a richer picture of the different approaches to the problem-solving task across the two groups. The Non-CoI group draws on the Design and Technology defining and Science inquiry competencies in the first two 3-min intervals and then in the last three intervals draw on the Design and Technology evaluating and Science inquiry competencies. The shorter discussion time and the lack of engagement with the Science social/ethical, Design and Technology implementation and Mathematical understanding competencies in this group suggests a more rigid approach with procedural tactics applied to the task. The CoI group open their discussion by engaging with Design and Technology defining and evaluating competencies as well as Mathematical understanding competency before they launch consistently into designing. The second surge of designing from 18 to 22 min happens after 7 min of evaluating their initial design phase. The initial period (from 17 to 23 min) of the second design phase shows engagement with many competencies including Mathematical understanding, Science understanding, Science inquiry competencies as well as Design and Technology defining and evaluating competencies. The CoI group finish their discussion by further engaging with Design and Technology defining and implementing as well as Science social/ethical competencies. In other words, the CoI group enter into two designing cycles recruiting a wider range of competencies. This group shows a more flexible and engaged approach to the task.

Vignettes of the CoI and Non-CoI discussions showing how they conceptualize the design of their generators elucidate the contrasts of competencies across the two groups and how they are employed in the discourse. Student names are pseudonyms.

CoI group conceptualizing the design

Phase 1

(Example showing instances of mathematical understanding (6–9 min interval)

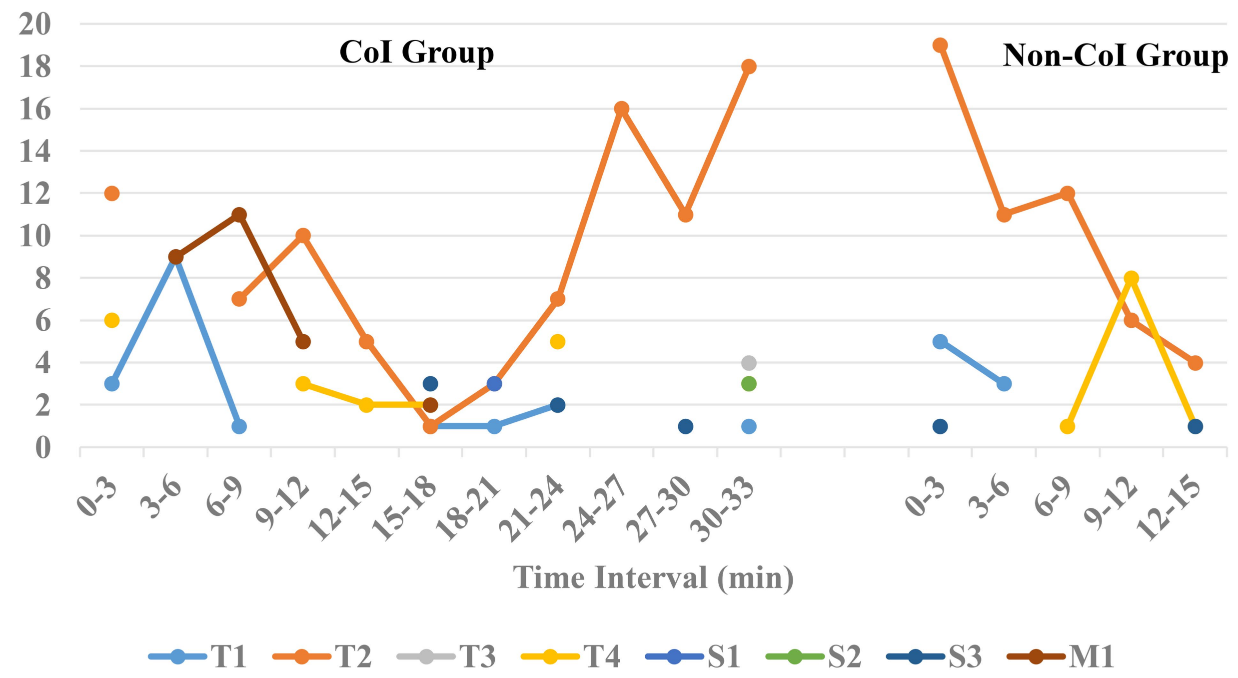

FIGURE 7
Time trends showing STEM competencies in discourse across a CoI and Non-CoI group. T1=investigating and defining, T2=generating and designing, T3=producing and implementing, T4=evaluating, S1=science understanding, S2=science social/ethical, S3=science inquiry skills, M1=mathematical understanding.

Josh: That's a cylinder *(M1: Thinking and interpreting information mathematically)*.

Suraya: Teacher said it's a semi-circle *(M1: Thinking an interpreting information mathematically)*.

Ali: I call it a long semi-circle because this is what it is meant to be, like that (showing the shape with a curved sheet of paper) *(M1: Thinking and interpreting information mathematically, Connecting concepts to develop new ideas)*.

Suraya: It is long *(T2: Developing and communicating ideas)*.

Ali: Long semi-circle. It is a cylinder fully solid inside of it. *(M1: Thinking and interpreting information mathematically, Connecting concepts to develop new ideas)*.

Phase 2

(18–21 min interval)

Ali: Sticky tape it! Would the sticky tape hold that much sand and pressure? *(S1. Applying science knowledge to the situation; M1. Identifying commonalities and differences)*.

Ellie: To move with paddle pop stick we need something else. Will think about it later, finish the design *(T2. Developing and communicating ideas)*.

Josh: I'll pour sand here. if I keep pouring over *(T2. Considering alternatives)*.

Ellie: This is the cup. It goes all the way around and tips out and it will stay there *(T2. Focusing on high quality design solutions)*.

Ali: It will keep the force, this will do the same but the cups will do it more efficiently. *(M1. Identifying commonalities and differences mathematically, S1. Applies knowledge to new situations)*.

Phase 3

Suraya: Where is it attached? *(S3. Identifying and posing questions)*.

Ali: This bit is attached from the center. This is the pin. The mill is attached to the pin. And the pin is attached to that. And this is inside the cup, this becomes taped to the wall. So these two will be the only ones spinning. *(T2. Communicating design ideas, S3. Exercising scientific thinking)*.

Suraya: Where does the sand come from? *(S3. Identifying and posing questions)*.

Ali: I do not like this idea about sand. *(T1 Critiquing needs and information)*.

Ellie: I agree, I feel it is confusing.

Ali: Like the sand pours down on the mill. Mill spins and while the mill spins there's also like a pin that's behind the mill. This was the mill [showing a ruler], there's a pin coming behind it. While the mill spins the pin spins with this [turning the ruler]. And because the pin spins this turns the turbine *(T2. Developing and communicating ideas, S1 Applying knowledge to new situations)*.

Suraya: So what if there are no pins? *(S3. Identifying and posing questions)*.

FIGURE 8
Design product for the CoI group showing the use of the milk bottle.

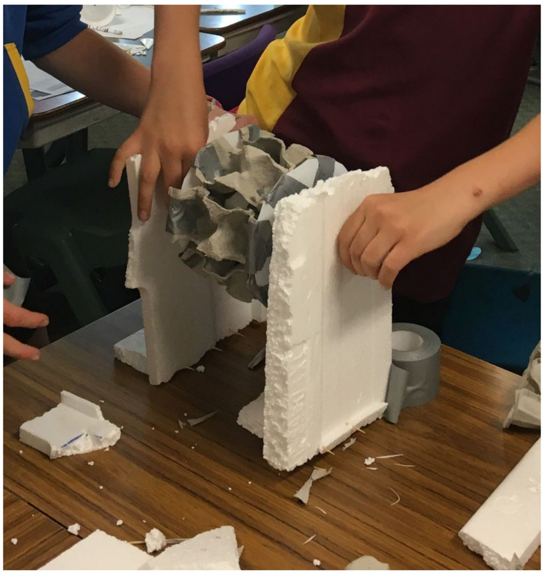

FIGURE 9
Design product for the Non-CoI group showing the use of the egg cartons.

Ali: Then we can use something else and tape it *(T2. Documenting design ideas and possibilities, focusing on high-quality designed solutions)*.

Ellie: How is the sand supposed to run in here go into that? *(S3. Identifying and posing questions)*.

Ali: There's a pathway where the sand comes, here *[S. demonstrates]. (T2. Developing and communicating design ideas)*.

Ellie: So just say a milk bottle right here *(T2. Developing and communicating ideas*; Figure 8*)*.

Ali: There's a pathway, pathway between the mill, because of the force of the sand from the potential energy this will turn *(S1. Applying knowledge to new situations, Integrates apt science knowledge)*.

Ellie: And it becomes kinetic? *(S1. Applying knowledge to new situations)*.

These transcripts provide evidence in the CoI group of Exploratory talk. It begins with Josh, Ali and Suraya disputing the 3D shape of their design and coming to a joint decision with inclusion of all ideas. They build on each other's ideas throughout the conceptualization of the design features with differing opinions being offered and the ideas are supported by reasoning (for example: *There's a pathway, pathway between the mill, because of the force of the sand from the potential energy this will turn.*)

Non-CoI group conceptualising the design

Phase 1

Example showing instances of investigating and defining (0–3 min interval):

Kai Wei: We have to create this. We can paste two plates together *(T2: Developing and communicating ideas)*.

Katie: We can use cups *(T2: Making design choices)*.

Kai Wei: What cups? We have paper plates.

Magda: OK.

Katie: Garbage bags? (T2: Making design choices)

St.2: Egg cartons *(T2: Making design choices*; Figure 9*)*.

Phase 2

Example showing instances of evaluating (6–9 min interval):

Katie: What about plastic cups cut in half? *(T2: Making design choices)*.

Magda: Use that as a paddle? *(T2: Consider design alternatives)*.

Brad: Yes and use two different paddles. You want to try that? *(T2: Developing and communicating design ideas)*.

Katie: And one is a bit bigger? I do not know how to draw it *(T2: Documenting design ideas)*.

Brad: We will still use a plate though. *(T2: Making design choices)*.

Katie: Yes we will use plates. *(T2: Making design choices)*.

Kai Wei: We will put little slits in a paper plate and use them *(T2: Making design choices)*.

These coded episodes reveal that students in the Non-CoI group tended to show Cumulative talk. Participants contribute ideas and these ideas are accepted without dispute. There are repetitions, confirmations and elaborations and there is evidence of cooperative interaction. But unlike the CoI group, a critical consideration of ideas is lacking. The discourse featured predominantly design and technology competencies with little integration of science or mathematics competencies, while students in the CoI group utilized their science and mathematical competencies to extend their design. In addition, students in the CoI group had longer individual utterances than the Non-CoI group and tended to provide justifications or explanations of their ideas.

Student focus group discussions provided opportunities to reflect on and share their perceptions of their learning experience.

CoI focus group discussions

St1*: We got to think and design first, like turn the turbine to create electricity because we need some energy or sand or water to power and turn the turbine to generate electricity or to turn on the LED light.*

St1: *I agree with St2. My knowledge has improved in science because I used to not understand much. But when we started to learn about electricity I started to understand more science … We were not really told much before.*

St3: *As a group we got to play and look at the generator – we never had one before.*

St4: *I also agree with these two (St1&St3) that my knowledge has improved because our teacher made us go step by step, using a process. She asked us what it meant and if we did not she went through it again, putting it into a scenario. She told us how the generator moved, and obviously we did not know. She said there are magnets inside the generator and wires wrapped around it, and she explained that. Some of us kind of got a little confused about how it is moving. So she explained it again. So the wind energy, moves the turbine, and it makes the generator turn.*

CoI students tended to build on each other's ideas and to explain the insights they gained using justifications and providing content examples. They were able to reflect and articulate how and what they learned. The FGD confirmed the Exploratory nature of the talk that we observed in the group work. This finding suggests that the skills learned in the CoI are transferred to other situations.

Non-CoI focus group discussions

St1: *You got to build stuff, in the other ones (science* learning sequences*) we did not. In this one we got to work with a lemon. We got 2.8 something.*

St3: *Volts.*

St2: *We got up to 3 point something. We learned the very first person to make electricity, and it was based on his last name. Volta or something.*

St4: *We enjoyed the circuits and, using the electro-lab, enjoyed them flying off.*

When asked the same questions about the science learning sequence compared to previous ones, Non-CoI group students tended to provide simple short answers that lacked detail. The use of 'stuff' and 'something' indicates that this group was not able to clearly articulate their learning. The answers are very short compared to the substantial and deeper reflections of the CoI group.

Discussion

This study explored the notion that science students who engage in a collaborative community of inquiry around the topic they are learning better develop curriculum-defined STEM competencies. The findings of this study where student development of STEM competencies was a focus, show that engaging in CoI across a science learning sequence promotes a disposition or habit or desire to engage in thinking and reasoning through Exploratory talk which more strongly fosters STEM competencies. The CoI group demonstrated a full range of STEM competencies. The Non-CoI group that did not engage in CoI, only tended to show Cumulative talk that unlike the CoI group, lacked a critical consideration of ideas. This group also did not demonstrate a full range of STEM competencies and applied more procedural tactics to complete the task.

Inquiry approaches not only elicit reasoning and help in making judgements (Reznitskya et al., 2012) but also develop creativity. A study by Hathcock et al. (2015) investigated the use of inquiry-based questioning as a means of supporting creativity within an engineering/design STEM activity. The aim was to determine the impact of inquiry question-based scaffolding on the observed product creativity in a design activity. The activity was to build a buoy that would not rest at the bottom or the sides of a tank using provided materials. Findings suggested that student groups facilitated by inquiry-based questioning strategies were better able to solve an ill-structured problem and achieved a more linear progression toward creative products than student groups who were not facilitated by inquiry-based questions. The questions were designed to encourage students to think and talk with their partners and cue them to issues related to their design. The authors concluded using inquiry-based questioning strategies with ill-structured tasks may assist teachers in scaffolding student success in STEM learning, both in terms of solving the task as well as cueing students toward translating their creative ideas into creative products. Our study adds to these findings and showed that engaging in a community of inquiry supports students to engage in deeper and more reasoned discussions about their design and exhibit a broader range of STEM competencies.

In addition to these findings our study showed that students that engaged in CoI demonstrated significantly higher instances of STEM competencies during their design task alongside of significantly higher learning gains. These findings are consistent with a recent study conducted by English et al. (2017). They examined Year six students' approaches to solving an engineering-based problem on earthquakes which drew on the Australian curriculum in Mathematics, Science and Design and Technology. Six teachers and 136 students from two independent schools and one government school from Queensland, Australia participated in the study. In small groups, students applied their preliminary learning about earthquakes to the design and construction of a building that could withstand earthquake damage. The problem involved the design of three-dimensional models that were constructed, tested, redesigned and further tested in generating final products that met given criteria and constraints. Analyses of group work for Year six students' engineering process competencies that comprised problem-scoping, idea creation, designing and constructing, assessing design, and redesigning and reconstructing revealed that students showed evidence of STEM disciplinary knowledge through development of these skills. In our study all students showed learning gains but the students that engaged in community of inquiry dialog, demonstrated significantly higher learning gains and a broader range of STEM competencies. This indicates that the thinking skills acquired through community of inquiry enhances both the STEM competency development and disciplinary knowledge. English and colleagues argue that the STEM inquiry, design task supported students to develop engineering habits of mind. We agree with English and colleagues and would argue that while these design tasks promote student engagement with STEM competencies, embedding CoI into the learning sequence significantly enhances these skills through development of habits of mind and dispositions to know when and how to apply reasoning alongside the competencies to create a design solution.

This good thinking that students in the CoI group demonstrated in this study and previous studies (Sprod, 2017) evolves over time and through collaborative, challenging and stimulating learning experiences (Adey et al., 2007). Sprod (2014) argues that "if we have the aim to teach good thinking in science, we need to be aware that the sort of thinking we are seeking to encourage and inculcate is quite a complex set of capabilities and dispositions, backed by sound judgment" (p. 1534). Engaging students in a community of philosophical inquiry that problematizes science content under study, encourages and models rigorous thinking in the discussions and through explicit consideration, the skills and dispositions of scientific thinking are addressed.

In a CoI, as students communally devise, defend, and analyze each other's perspectives, they adopt capabilities, dispositions and reasoned argumentation linguistic skills, which they can apply to solve complex problems. The dialogic discussions about open-ended questions that relate to and problematize the disciplinary content provides students with content-appropriate experiences, where the tenets of rigorous inquiry, enacted with their peers, become part of their overall cognitive performance. Through dialogic interactions with peers, students hone their skills to engage in reasoned argumentation, as they grapple with new language and thinking practices (Reznitskya and Gregory, 2013).

Thinking within science, design and technology and mathematics draws on both the general thinking capacities and dispositions that apply across all domains as well as more specialized subject thought processes or competencies. In CoI, students are able to engage in deep thinking about science topic-related issues. The cognitive shifts towards higher competency development is stronger as a result of the reflection and reasoning required to engage in CoI. CoI enhances students' competencies by positioning them in a community that utilizes, reflects on and cares about the epistemic criteria of thinking, problem solving and inquiry.

Students in the CoI group engaged more substantively in thinking and problem solving than their peers in the Non-CoI group. They were better able to articulate what they learned and how they learned. A fundamental part of problem-solving is the cognitive processes involved in conceiving problems. The problem conceptualization phase of problem solving is the period of cognitive processing occurring before the externalization of ideas using sketches, verbal communication or mathematical expression. In this dynamic process there is an active construction of thoughts, ideas and memories that are influenced by thinking, attitudes, emotions, and experiences (Delahunty et al., 2020).

Delahunty et al. (2018, 2020) have shown that providing experiences to support students to understand how to conceptualize a problem has profound benefits in developing problem solving skills in STEM education. Without support, students lack flexibility in problem solving evident in a rigid approach that often results in procedural and surface tactics (McCormick and Davidson, 1996). CoI provides students with content-specific rich experiences that engage them in problem conceptualization that they can recall from memory to apply in new situations. The students in the CoI group engaged deeply and flexibly with conceptualizing the design problem drawing on their CoI experience. The Non-CoI group did not have this prior experience and showed a shallow, procedural engagement with the task.

Finally, the CoI focus group discussions in this study revealed a capacity to reflect on, clearly describe and consider the epistemic benefits of their learning. The Non-CoI group were less able to reflect on their learning and were not able to articulate well what they learned or how they learned the content. The CoI method involves reflection on the process, learning and group interactions and contributions. This promotes the ability of students in the CoI group to reflect on learning and so students can call on their experience to more clearly articulate the content they learned and how they learned it.

Limitations of the study

It is noted that the findings of the study could be attributed to test effects, maturation or other confounders. The sample size could also impose limitations for making the findings generalizable beyond the contexts, students and participants presented.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Ethics statement

The study involving human participants was reviewed and approved by The University of Queensland's Human Research Ethics Committee. Written informed consent to participate in this study was provided by the participants' legal guardian/ next of kin.

Author contributions

KN contributed to conception, design of study, performed statistical analysis, wrote first draft of the manuscript, and approved the submitted version. RM contributed to conception, wrote sections of the manuscript, contributed to manuscript revision, and read and approved submitted version. MH organized the database, contributed to conception and presentation of data. All authors contributed to the article and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Effectiveness of in-class excel-based active learning activities for transportation engineering courses

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Recently, transportation engineering industry members showed concern that students lacked the skills to solve real-world engineering problems using spreadsheet data analysis. In response to the circumstances shown by industry members, this study investigated how to engage students in a better way by incorporating spreadsheet analysis during class and helping them learn the course topics. Helping students link theoretical knowledge to real-world problems can be a challenge. In this effort, in-class activities and worksheets were redesigned to integrate with Excel to solve example problems using built-in tools, including cell references, equations, data analysis tool pack, solver tool, conditional formatting, charts, etc. The effectiveness of this technique was investigated using students' evaluations of the course, enrollment data, and students' comments. Based on the data of those criteria, it is evident that spreadsheet activities may increase student learning.

KEYWORDS

engineering, active learning, transportation, excel, spreadsheet

Background

Industrial Advisory Board (IAB) members at the study university play a critical role in improving an engineering program by guiding the program's direction and ensuring the needs of their workforce are met. Encouraged by accreditation standards, many departments conduct an annual survey to receive feedback from IAB members on improving their program so that students are ready to work in the industry upon graduation. Recently, civil engineering IAB members specialized in transportation engineering showed concern that is graduating students lack the spreadsheet skills needed for solving real-world engineering problems. In response to this concern, this study investigated how to help students learn Excel to solve transportation engineering problems as a part of the lecture.

The primary objective of this study is to help students learn Excel spreadsheets for solving transportation engineering problems. The in-class worksheets were reshaped to achieve the objective, incorporating Excel spreadsheets to solve example problems and hand calculations. For the Excel activity, students are provided the data in an Excel spreadsheet. Students use that data to solve the same worksheet problem using built-in Excel tools, including cell references, equations, data analysis tool pack, solver tool, conditional formatting, charts, etc.

Literature review

Previous studies suggested that active learning is a standard method to foster students learning in engineering (Nickels, 2000; Douglas and Chiu, 2009; McCloskey and Bussom, 2013; Anitha and Rao, 2014; Ssemakula et al., 2018). Different active learning techniques include think-pare-share (TPS), group assignments, reciprocal questioning, the pause procedure, the muddiest point technique, the devil's advocate approach, group discussions, formative quizzes, and lecture summaries, etc. (Nickels, 2000; Douglas and Chiu, 2009; McCloskey and Bussom, 2013; Anitha and Rao, 2014; Ssemakula et al., 2018). Among the techniques, TPS is the most used technique in many engineering classes where solving example problems are a vital component of the lecture (Nickels, 2000). According to this technique, a specifiv topic is presented to the class, and students take notes. Then, an example problem related to the covered topic is ready to be solved. Sometimes, students are provided a handout known as an in-class worksheet listing the example problems that will be solved during class.

McCloskey and Bussom (2013) studied active learning in the business curriculum using an Excel spreadsheet. This study reviews how Excel spreadsheet was used in business classes to learn problem-solving techniques and the active use of spreadsheets. Several previous studies, from science to engineering to political science, investigated how to engage students better (Smith et al., 2005; Heller, 2010; Marshall and Nykamp, 2010; Peters and Beeson, 2010; Popkess and McDaniel, 2011). McCloskey and Bussom (2011) studied students' engagement in the learning process using an Excel spreadsheet. Uddin et al. (2017) learned how to use Excel to teach physics. In this study, Excel was used as a simulating tool. Several aspects of Excel were demonstrated in this article. All these studies suggest that Excel can be an excellent tool to enhance student learning. To the author's knowledge, no studies were found investigating the effectiveness of Excel on student learning in engineering classes. This study investigated student learning in civil engineering classes, especially in the transportation area.

Several papers were studied related to how to use Excel spreadsheets for solving engineering problems and financial analysis efficiently (Nickels, 2000; Douglas and Chiu, 2009; McCloskey and Bussom, 2013; Anitha and Rao, 2014). Microsoft Excel has many tools, including Visual Basic for Applications (VBA). VBA is developed explicitly for Excel and is currently used for many applications, including financial analysis, engineering problems, data management, etc. Sprego (Spreadsheet Lego) is a simplified version of VBA that helps to solve advanced engineering problems (Nickels, 2000; Douglas and Chiu, 2009; McCloskey and Bussom, 2013). McCloskey and Bussom (2013) conducted a case study on the effectiveness of teaching spreadsheet management using Sprego. Results indicated that Sprego could be used for solving advanced problems easily efficiently. Also, S. Abramovich studied students' ideas in the digital era (Anitha and Rao, 2014). The primary projective of this study was to contribute to Technology-immune Technology-enabled (TITE) mathematics education research efforts by using Wolfram Alpha and Microsoft Excel spreadsheet.

Methodology

The primary requirement to execute the activities related to Excel is that students need a computer to work on the activities during class. If the classes are taught in a traditional classroom, students must to bring their laptops, or the course must be taught in a computer lab. For this study, the methodology has two main steps: (1) Develop the worksheets; (2) Evaluate the effectiveness of the learning strategy. The overall methodology can be seen in **Figure 1**.

Students are provided with handouts and in-class worksheets at the beginning of a typical lecture class. In-class worksheets include the description of example problems, and handouts provide the tables, figures, and equations needed to solve the problems. The class starts with discussing a topic; then, students try to solve a problem provided in the in-class worksheet. After that, the instructor solves the problem with the students' help, followed by creating an excel spreadsheet to solve the same problem using built-in Excel tools. The spreadsheet should produce the outputs by only changing the inputs. At the end of the lecture, students must submit their in-class work, including a worksheet and an Excel spreadsheet. First, students are learn how to use Excel tools to solve engineering problems. Students' evaluation shows that students enjoy solving the problems using Excel spreadsheets, and most importantly, they mentioned that it helped them understand the problem better. Also, it was noticed that Excel activities help energize students to be active in the middle of a class. Students need to bring their laptops to class. A Wireless internet connection is also beneficial for downloading the necessary files for the class.

In this study, two courses were considered, transportation planning and transportation engineering. Both courses are very similar in terms of course assessment. The following section discusses only the transportation planning course as an example.

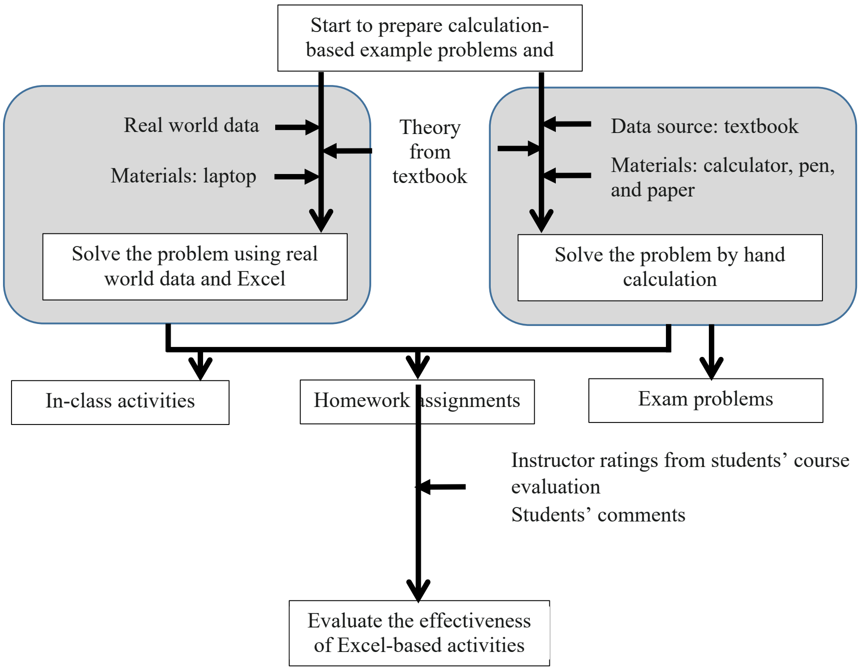

FIGURE 1
Study methodology.

In-class Activity: To illustrate the application of the gravity model, consider a study area consisting of five zones. The data have been determined as follows: the number of productions and attractions has been computed for each zone as shown in Matrices 1, 2, and 3. Assume *Kij* is the same unit value for all zones. Finally, the friction factor values are shown in Matrix 3 for each travel time increment. Determine the number of zone-to-zone trips through two iterations.

Matrix 1: Productions and Attractions

TAZ	Productions	Attractions
1	234	1080
2	76	531
3	602	76
4	432	47
5	472	82

Matrix 2: Travel Time Matrix

TAZ	**1**	**2**	**3**	**4**	**5**
1	4	12	8	15	21
2	6	3	9	23	14
3	20	7	4	10	25
4	12	18	8	4	17
5	24	19	23	15	8

Matrix 3: Friction Factor

Travel time (min)	**Friction Factor**
3	87
4	45
7	29
10	18
15	10
20	6
25	4

FIGURE 2
Sample in-class activity from the transportation planning course.

In the analysis section, the data from both courses are presented. The courses will be referred to as Transportation Planning and Transportation Engineering for discussion purposes. Both are junior/senior-level courses, respectively.

CE 401 transportation planning

This course was a small, technical elective class taught at a public university in the Midwest. As the prerequisite of this

TABLE 1 Solution to the in-class activity shown in Figure 2.

TAZ	1	2	3	4	5	Total
1	199	2	15	2	16	234
2	35	25	12	3	1	76
3	147	350	78	19	8	602
4	330	90	4	6	2	432
5	369	90	7	5	1	472
Total	1,080	531	76	47	82	

course is a junior-level transportation engineering course only senior-level students usually take this course, and is offered once a year in the fall semester. From 2018 to 2020, the enrollment was 6, 7, and 10 students, respectively. The course assessment included two exams (40%), weekly quizzes (5%), homework assignments (25%), course project (20%), and class participation (10%). Class participation comes from the in-class worksheets, and Excel spreadsheet analysis is a significant part of the in-class worksheets.

The CE 401 course structure included two 1 h and 20-min class periods per week and involved some active learning exercises in the form of calculation-based problems in every class. During a typical class, students learn a topic through lectures and then work on a relevant calculation-based example problem. Usually, the problems are iteration-based, which means the answer from each iteration will be close to the solution. As the number of iterations increases, the accuracy of final the answer increases. Because of the nature of the problems, it was observed that an Excel spreadsheet could be of great help in getting the final answer quickly and easily. In-class activities included hand calculations and then developing an Excel spreadsheet to get the same answer from hand calculation. At the end of the lecture, students must submit their in-class work. The whole in-class activities were graded out of 10%.

The instructor created the in-class activities involving Excel spreadsheet using real-world data on local transportation networks obtained from different transportation agencies, including city governments and metropolitan planning organizations. The activities were like the standard end-of-chapter problems regarding the steps and equations required. As the data used for the activities are on the local transportation network, students can relate to the problems better, as evidenced by the student's comments from the student course evaluations.

TABLE 3 Students' comments on the Excel spreadsheet.

Fall 2018, Transportation planning
"Continue to incorporate the assignments and activities using Excel, solver, statistical analysis, and other practical applications. Reserve a computer lab once a week."
Fall 2019, Transportation planning
"The lab portion was accommodating on seeing information we learned"
"Maybe labs every other week rather than every week."
Fall 2020, Transportation planning
"I like the idea of the lab building off of the lecture and vice-versa. I have had some classes in the past where the lecture and the lab were on separate topics so having it two connected is very nice." "Please maintain or even increase the amount of Excel-type lab work. I found this beneficial and have learned a lot." "step by step or posting the lab steps on how to do it would be SO HELPFUL. This would help me learn and recreate what I did on Excel because I have no idea how to recreate any labs we did."
Spring 2021, Transportation engineering
"I love that the material was all organized in a clear pattern. It made it easier to follow along when using multiple tools to aid in learning (Excel, PowerPoint, Textbook) that otherwise would have been a struggle to keep up with."

After the lecture, the solution to the Excel activities was posted on the course website.

Excel-based problems are also a significant part of homework assignments. Weekly homework assignments comprised of 3–5 homework problems. 1–3 problems were created by the instructor that requires an Excel spreadsheet, and those are very similar to the in-class problems.

In the exams, 70% of the exam grades are open books, and the remaining are closed books. The open book part consists of calculation-based problems like homework problems, but in a short version so that students can solve them during exam without an Excel spreadsheet. Students are not allowed to bring their laptops during exams to solve the problems, but they can use other course materials, including homework assignments, handouts, books, and lecture slides.

In transportation planning courses, sometimes example problems require several iterations to get the final answer. For instance, sample example problems can be seen in Figure 2. The solution to the problems can be seen in Table 1. In the solution matrix (see Table 1), 25 values (5 rows × 5 columns) needed to be calculated. The same set of equations is used to get each value of all 25. Using a spreadsheet, the solution can be obtained very quickly and easily.

The effectiveness of using Excel spreadsheets was divided into two categories: (1) instructor observations from a

TABLE 2 Summary of Students' comments for CE 401.

Semester	# of classes incorporated Excel activities	Total comments	Comments related to Excel activities	Comments in favor of Excel activities
Fall 2018	5	5	1	1
Fall 2019	15	2	2	1
Fall 2020	15	4	3	3

transportation planning course and (2) Before-after analysis of student data. These two categories are discussed and supported by the data below.

Instructor observations

The incorporation of Excel activities was seen to serve two benefits. First, students practiced learning to solve real-world problems from hands-on experience. Second, students expressed enthusiasm for working on Excel activities, as evidenced by in-class discussion, in-class engagement, and students' course evaluations, which will be discussed later.

Overall, creating Excel-based in-class activities appeared to motivate students. The instructor plans to continue this active learning technique in future semesters.

Before-after analysis of student data

Two primary indicators were investigated to assess the effectiveness of incorporating Excel activities, including (1) student comments and (2) overall instructor ratings. In the following subsections, these two indicators were discussed.

Student comments

Every semester, the university conducts an anonymous student course evaluation for every course in the final quarter of the semester. After submitting the final grades, the instructor receives the results, so the survey respons cannot impact grades. In the course evaluation, students rate their instructor by answering 11 questions and writing comments on four topics. One of the four topics was "Please identify and explain aspects of the course that you encourage the instructor to maintain in the future." For this study, the student's responses were investigated to identify those related to the Excel activities. Table 2 shows the quantitative summary of the comments for CE 401. In the fall of 2018, Excel activities were introduced in five lectures on CE 401 Transportation Planning. From the student's course evaluation, one student suggested adding more Excel activities in future semesters. The comment is: "Continue to incorporate the assignments and activities using Excel, solver, statistical analysis, and other practical applications. Reserve a computer lab once a week." Based on this comment, the instructor incorporated Excel activities once a week (50% of total meetings) for Fall 2019. In fall of 2019, two comments were received, and both were related to Excel activities. One favors of continuing Excel activity, and the other suggested having these activities every other week. In 2020, four comments were received, three of them were related to Excel activities, and all were in great favor of continuing Excel activities. The comments can be seen in Table 3. In 2021, Excel activities were also introduced in the CE 301 Transportation Engineering course. Only one comment on Excel activities was received (see Table 2). Overall, students liked the idea of the Excel activities building off the lecture and found this extremely helpful in enhancing their learning. As per the students' suggestion, the instructor also realizes that a handout providing step by step explanation of using an Excel spreadsheet to solve the problem would be helpful for future reference.

Overall instructor ratings

Overall instructor ratings was investigated to assess the effect of incorporating Excel activities from 2018 to 2021 (Appendix A1). Tables 4, 5 present two courses' enrollment data and overall student evaluation from 2018 to 2021. In the fall of 2018, the instructor started to teach CE 401 and incorporated Excel activities in only five lectures. Students' course evaluations may also indicate their effectiveness. Students' evaluations of CE 401 increased from 3.11/4.0 in 2018 to 3.6/4.0 (ratings on a Likert scale of Poor = 1 to Excellent = 4) in 2019, which may indicate the effectiveness of incorporating Excel activities during lectures. Similarly, for CE 301, student evaluations also increased from 2.89 to 3.9. It is important to note that no other major changes were made in instructing the course except the incorporation of Excel activities.

TABLE 4 Before-after comparison of implementing Excel spreadsheet, CE 401.

	Before implementing Excel activities	After implementing Excel activities	
	Fall 2018	Fall 2019	Fall 2020
Number of students*	6	7	10
Average student evaluation	3.11	3.6	3.39

*Number of students represents both the number of participating and the evaluating students.

TABLE 5 Before-after comparison of implementing Excel spreadsheet, CE 301.

	Before		After
	Spring 2019	Spring 2020	Spring 2021
Number of students	15	10	19
Average student evaluation	3.11	2.89	3.9

Conclusion

In this study, an active learning technique using Excel spreadsheet analysis was investigated in two transportation engineering courses to determine whether it fosters students' learning. A worksheet was developed by listing calculation-based example problems for every lecture. Students are assigned to work on those example problems by hand calculation during class time. Then, students created an Excel spreadsheet to solve the same problem using different built-in tools, including solver, cell referencing, data analysis, conditional formatting, charts, built-in functions, etc. The effectiveness of this technique was investigated using students' course evaluations and comments. Results concluded that the technique was very effective in fostering students learning.

Data availability statement

The original contributions presented in this study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Ethics statement

The studies involving human participants were reviewed and approved by Purdue IRB. Written informed consent for participation was not required for this study in accordance with the national legislation and the institutional requirements.

Author contributions

The author confirms being the sole contributor of this work and has approved it for publication.

Conflict of interest

The author declares that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Appendix

#	Question	Fall 2018	Fall 2019	Fall 2020	Spring 2019	Spring 2020	Spring 2021
2.3	Class content	3.2	3.6	3.25	3.27	2.88	3.7
2.4	The textbook	2	3.6	3	3.18	2.63	3.6
2.5	Film, other aides and lab facilities	2.6	3.6	3.5	3.36	2.86	3.8
2.6	Assignments related to course goals	3.2	3.8	3.5	3.18	2.75	3.6
2.7	Exams measured my understanding	3.2	3.6	3.38	3.09	2.63	3.6
2.8	Course overall	3.2	3.8	3.43	3.18	3.13	3.8
3.2	Instructor's knowledge of subject	3	3.8	3.63	2.73	3.13	3.7
3.3	Instructor's ability to present material	3.4	3.6	3.63	3.45	3	3.7
3.4	Instructor's concern for students	3.6	3.6	3.38	3.55	3.13	3.5
3.5	Instructor's enthusiasm for subject	3.4	3.4	3.25	3.27	2.63	3.9
3.6	Instructor overall	3.4	3.2	3.38	3.27	3	3.5
Average		**3.11**	**3.6**	**3.39**	**3.23**	**2.89**	**3.41**

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Teaching vaccine development in schools: Learnings from a survey and curriculum design for a course

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Although vaccines are being developed and administered to people for more than a century, the understanding of the steps involved in vaccine development is a relatively new subject to the general public. During the current pandemic, there has been an explosion of non-validated news about COVID-19 and vaccines. To enhance the understanding of this critical societal science, there is an urgent need to teach these topics in the early education systems. Defining the essential subjects and courses for high school and developing syllabi for undergraduate courses in immunology and vaccinology can be difficult, as students choose diverse career options after their studies. To define these curricula, understanding the current level of awareness regarding vaccinology and immunology among students becomes essential. Thus, we have undertaken an exploratory survey of 650 high school and undergraduate college students in India on their awareness of the processes of vaccine development. Our results confirmed our hypothesis that there is a very limited understanding of this topic among school-going students. In this article, we propose an outline for a course for teaching in high schools. We recommend that this course should be interdisciplinary and a mix and match of majors and minors. It should train students with soft skills and prepare them for their careers in biomedical research.

KEYWORDS

COVID-19 vaccines, toxicology, pharmacology, clinical trials, survey, awareness

Introduction

We routinely use easy-to-use medicines available at a local pharmacy for everyday ailments such as headaches and sores, and we rarely think about how these medicines are made. With the constant bombardment of news in public media about COVID-19 and vaccines, there is a huge amount of information and misinformation on how the COVID-19 vaccines were developed in <1 year (Dror et al., 2020). We, as high school and college students, are not aware of what it takes to develop these vaccines. These

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subjects are not taught in high schools, and it can be challenging to develop age/class-appropriate courses, as this field is rapidly advancing and expanding (Chatterjea, 2020). The multidisciplinary nature of the vaccine development process requires defining the key components of the curriculum. In this article, we have conducted an exploratory survey of high school and college students and teachers across India on the awareness of vaccine development processes. We have hypothesized that there is a very limited understanding of these processes among high school and college students as well as teachers. Using the data obtained through our survey and taking COVID-19 vaccines as an example, we have curated a novel course outline that can be utilized as a framework for developing a curriculum that can enable teaching the multidisciplinary aspects of vaccine development in high schools and colleges.

In December 2019, there was an outbreak of an unknown respiratory disease in Wuhan, China, characterized by dry cough, difficulty in breathing, loss of taste and smell, chest pain, and fever, which could potentially lead to multiple organ failure (Trojánek et al., 2020). The disease was caused by severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) and was later coined "COVID-19" by the WHO (2020). On 11 March 2020, the WHO declared it a pandemic. As of this submission, there are more than 590 million infected and more than 6.4 million dead. It is predicted that the virus originated in bats and was transmitted to humans *via* Pangolin, which are the intermediate hosts of the virus.

Severe acute respiratory syndrome coronavirus 2 is an enveloped RNA virus, with a ~30 kilobase long single-stranded RNA as a genetic material. It is capable of infecting a variety

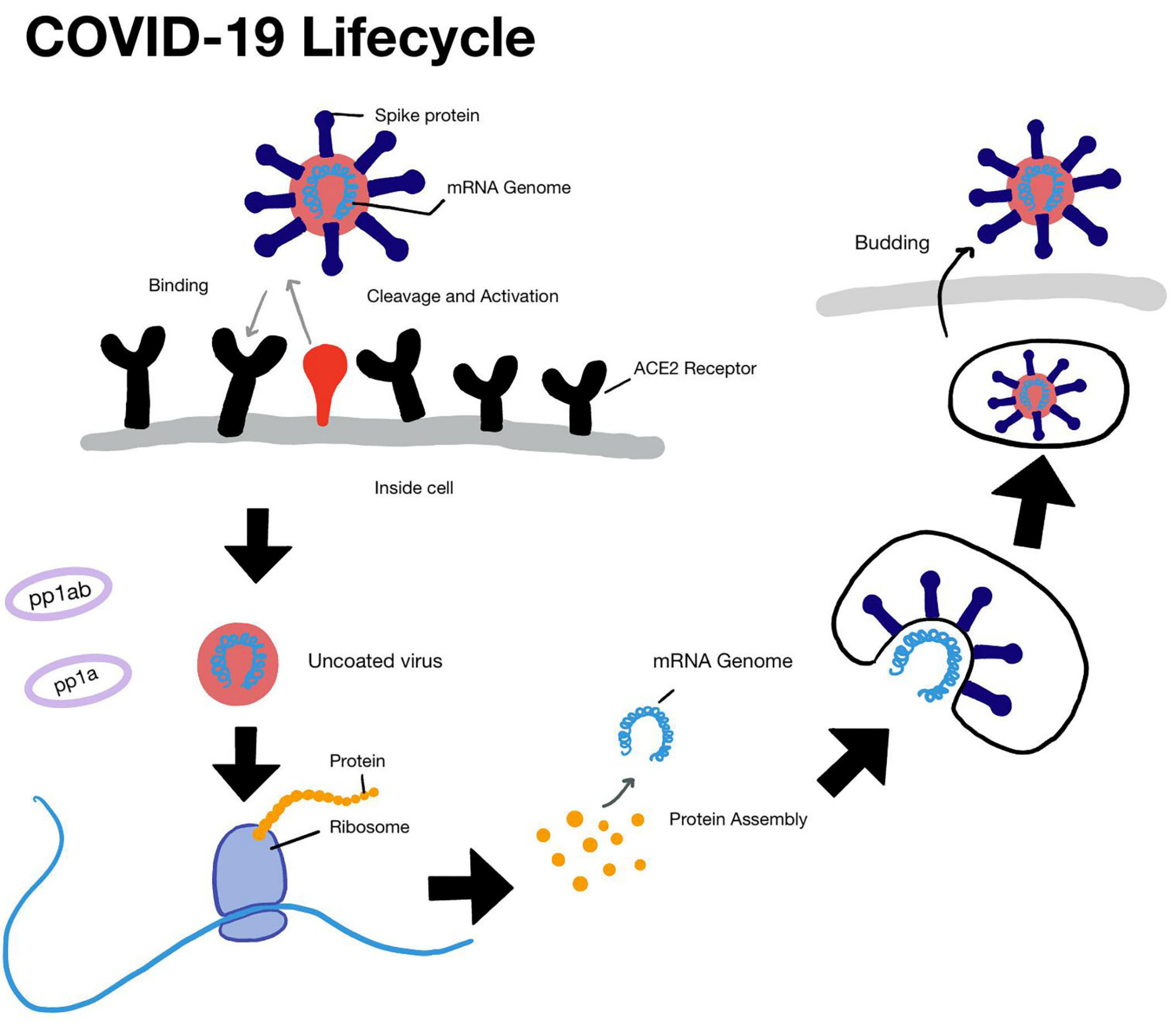

FIGURE 1
The life cycle of SARS-COV2. The steps involved from entry to replication and budding are shown in this figure.

of host species (Vabret et al., 2020). Most infected people recover from COVID-19 with mild-to-moderate symptoms and do not need any medical intervention. However, older patients, immunocompromised individuals, and those with underlying conditions including diabetes, chronic respiratory disease, or cancer experience more severe symptoms such as difficulty in breathing, chest pain, or pressure. SARS-CoV-2 infects host cells by the binding of its spike protein to the ACE2 and TMPRSS2 receptors present on various cells in the nasal cavity, trachea, and lungs (Hirano and Murakami, 2020; Hoffmann et al., 2020; Lukassen et al., 2020). Once the virus enters the cell, it uses the enzyme RNA-dependent RNA polymerase (RdRp) to transcribe viral proteins. These proteins assemble in the cell and new viral particles emerge, which infect other cells (Figure 1). Neutralizing antibodies to the spike protein can block viral entry (Poeschla, 2020). Drugs, such as remdesivir and molnupiravir, bind to RdRp and can block viral replication (Felsenstein et al., 2020). Several SARS-CoV-2 variants have been identified, which include Alpha, Beta, Gamma, Epsilon, Eta, Iota, Kappa, B.1.617.3, Mu, Zeta, and Omicron. The understanding of the pathogenesis of COVID-19 continues to evolve as new large-scale studies are being conducted, which will provide insights into the long-term effects of COVID-19 on human health (Lopez-Leon et al., 2021).

TABLE 1 Demographics of survey respondents.

	Students		Teachers	
	High school	College	High school	College
India	536	82	14	13

To combat the pandemic, several pharmaceutical companies began the development of novel COVID-19 vaccines as early as February 2020 (Cohen, 2021). Vaccines prepare the body to combat viral pathogens and significantly reduce the chances of infection and adverse effects. The major platforms to develop vaccines include mRNA, DNA, protein, viral vectors, inactivated viral proteins, and live attenuated viruses (Francis et al., 2022). Table 1 shows the characteristics of these platforms. Several reviews have summarized the efficacy and effectiveness of these vaccine platforms in preventing COVID-19 disease (Krammer, 2020; Cai et al., 2021; Fiolet et al., 2022; Francis et al., 2022).

Prior to the development of a vaccine, it is imperative to understand the pathogenesis of the disease, and hence, the first step involves research on how the disease is caused and progresses. We have described the vaccine development process in seven major steps (Stern, 2020) (Figure 2). (i) *discovery:* experiments that enable understanding the mechanism by which the vaccine can prevent the disease; (ii) *process development and scale up:* methods to manufacture the vaccine on a large scale; (iii) *pharmacology:* dose and frequency of immunization required to enable efficacy; (iv) *toxicology:* study the side effects

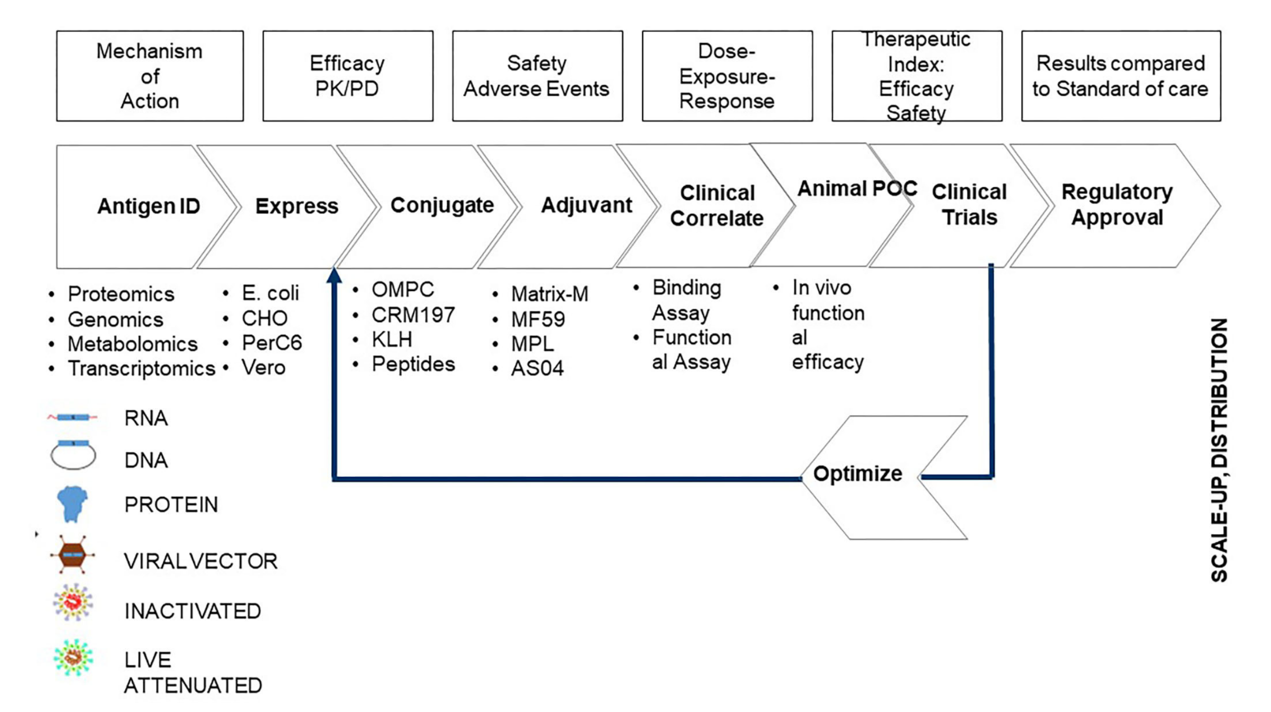

FIGURE 2
Steps involved in vaccine development. Chemistry, Manufacturing, and Controls (CMC) is the step that involves process development and scale-up of the method of developing the vaccine.

TABLE 2 Vaccine development course.

Books and other resources	
The Vaccine Book. Editors: Barry R. Bloom, Paul-Henri Lambert. eBook ISBN: 9780128054000 Peter L Stern. Key Steps in drug development. Annals of Allergy Asthma and Allergy. 125 (2020) 17–27	
Suggested point breakdown	
3 exams (10 pts each)	30 points
Homework	10 points
Team project	20 points
Final exam	30 points
Participation	10 points
TOTAL	100 points
An overview of the class	
Vaccine development is at a turning point in human medicine. Over the recent three decades, the development of vaccines has revolutionized the way we develop medicines. Efficiency and quality compliance are critical to achieving innovation and affordability. This comprehensive course will provide an overview of the basics and multidimensional nature of drug development-utilizing technology, statistical, and quality considerations. Risk assessment and mitigation will be discussed using a role-play process.	
Upon the completion of the course, the participants should be able to achieve the following outcomes:	
1. Become knowledgeable about the basic aspects of vaccine development, especially as it relates to application in various steps of the process 2. The process of sharing knowledge on applications of biotechnology with students 3. The ability to understand risk assessment processes 4. Understand the complex multidisciplinary nature of the drug development process, which intersects with several other biological processes 5. Have a shared understanding of academic and industry requirements	
Topics for lecture	
Pre-requirements: The course is aimed at providing an overview of the drug development processes. Attendees to the course should have the following criteria: • At least a gradation in an area of biology • Some knowledge of one of the areas involved —- • Desire to understand the application of research to drug development —-	
Learning objectives: • Become knowledgeable about the basic aspects of drug development, especially as it relates to the application in various steps of the process • The risks associated with the drug development process • The understanding of the social impact of the cost of drug development • Have the tools to develop methodologies for challenges faced during drug development • The ability to understand risk assessment processes • Understand the complex, multidisciplinary nature of the drug development process, which intersects with several other biological processes • Have a shared understanding of academic and industry requirements	

(Continued)

TABLE 2 (Continued)

Books and other resources
Learning outcomes: ● Navigate through the different regulations for drug research and development ● Understand the role of the regulatory affairs professional in drug development ● Conduct primary and secondary research to develop a regulatory strategy ● Understand the process for designing and running clinical trials on medical devices
1. The drug development and risk assessment workshop (A role-play exercise) ● Insights on drug development ● History and evolution of drug development ● Types of vaccines – live-attenuated, inactivated, mRNA, recombinant and conjugate 2. Design of vaccine ● Virus structure—parts of the virus ● Antigen target selection ● Optimal vaccine formulation ● Understanding statistical design of experiment 3. Pharmacology and toxicology ● Immune response—reactogenicity and immunogenicity ● Dosage study ● Understanding statistical aspects of variability 4. Process development and manufacturing ● Scale up studies ● Scale down studies ● Pilot scale ● Different manufacturing scales ● Understanding statistical aspects of trend analysis and process control
5. Clinical trials and regulatory approval process ● Phase I ● Phase II ● Phase III ● Phase IV ● Different regulatory agencies across the globe ● The difference in the approval system (basic) ● Understanding hypothesis testing 6. Risk assessment summary and conclusions ● Health risk ● Manufacturing risk ● Supply chain risk ● Financial risk ● Pandemic situation ● Understanding predictive statistics 7. A team presentation of a mock-vaccine development process ● Team development ● Defining the disease to treat ● Process development and manufacturing ● Pharmacology and toxicology ● Clinical trials ● Mock regulatory review and process audit

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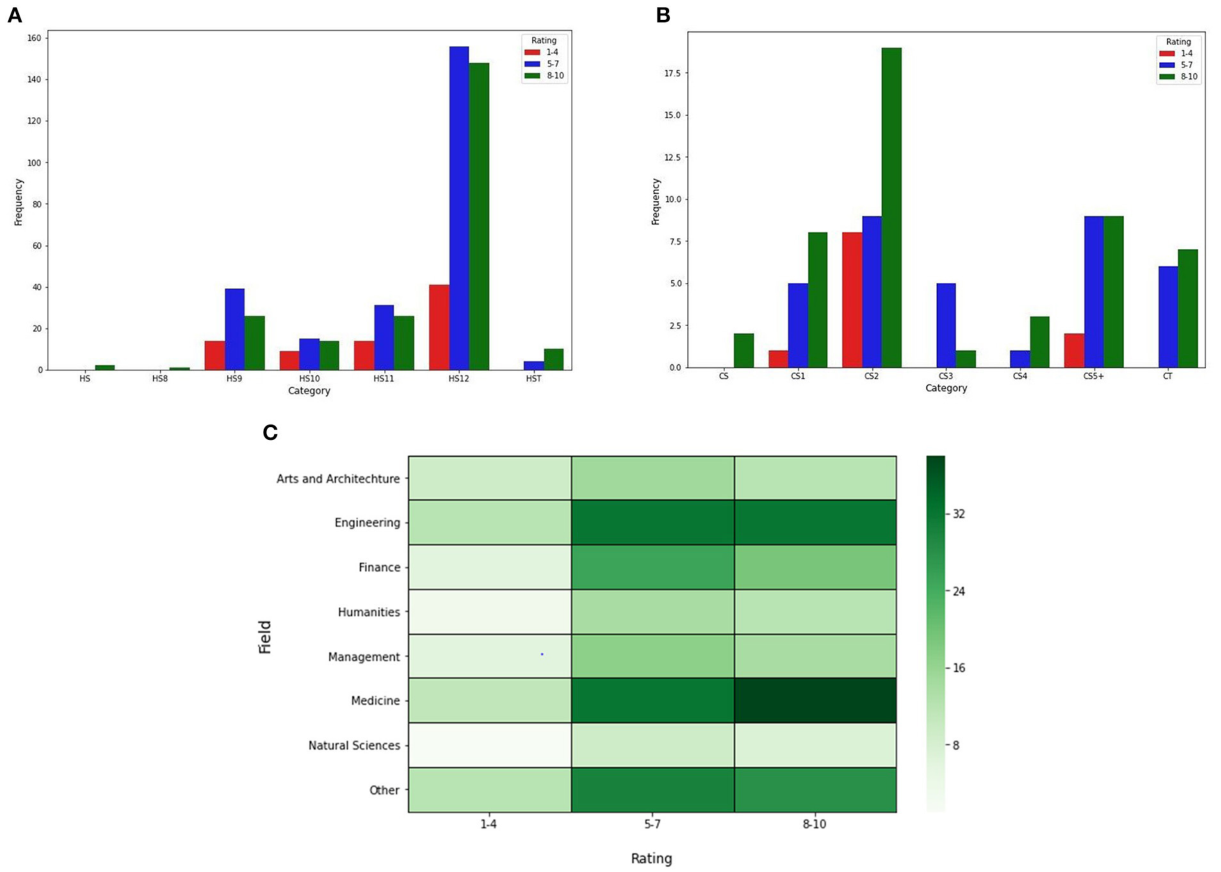

FIGURE 3
Awareness of vaccine development. **(A, B)** Bar graphs comparing the class level of high school (HS) students **(B)** year of college students (college) based on their education and rating of awareness of vaccine development. The bars correspond to the respondents' understanding of vaccine development on a scale of 1–10; by overall ranges. **(C)** Heat maps comparing the subject of interest of the individual with the rating of awareness of vaccine development.

of the vaccine; (v) *clinical trials:* phases 1, 2, and 3 stages of testing the vaccine in humans to define the efficacy and toxicity; (vi) *quality management:* processes involved in ensuring that vaccines manufactured are reproducible in terms of safety and efficacy, stable, and maintain potency through time; and (vii) *regulatory approval:* processes by which government bodies review and approve the vaccine to be administered to millions of people.

A survey to understand the awareness of vaccines in high schools and colleges

To understand the awareness of vaccine development processes among students beyond the student authors of this article, we conducted an exploratory survey among high school students, teachers, and administrators. The survey sought to examine several aspects of awareness of the processes involved in vaccine development, particularly COVID-19 vaccine development. We received a total of 645 responses through the authors' peer networks, colleagues, friends, and acquaintances. The dissemination was not random, and therefore, the authors do not claim that the data are representative of the population. The respondents included high school or college students or teachers in India (Table 2). Out of the total respondents, 83.1% were high school students and 12.7% were college students.

While examining and understanding the concepts of vaccine development among respondents, the pattern of responses from students and teachers pointed to the following key areas of teaching that could be implemented in high schools and colleges:

Awareness of vaccine development

The awareness of vaccine development was assessed by a rating score ranging from 1 to 10, with one having the least understanding (having taken 0 classes) to 10 being the higher (having taken three more classes). Figures 3A, B compare levels

FIGURE 4
Knowledge of vaccines. The word cloud demonstrates the frequency of people who responded to the mentioned diseases against which they knew how vaccines were approved. In the word cloud, the size of each disease (word) is proportional to its frequency.

of high school (HS) & college education (CS) for the rating of awareness about the development of vaccines. The response to the survey suggests that the students with a higher level of education scored lower on their awareness of the vaccine development processes, whereas students of lower classes scored higher. To further analyze their awareness, we evaluated their rating based on the subject they were studying. Students studying subjects such as finance, humanities, architecture, arts, natural science, and management scored lower than those studying engineering and medicine (Figure 3C). We find this observation intriguing; the data suggest that students pursuing engineering and medicine have a higher level of awareness for vaccine development compared to other subject groups.

Knowledge of vaccines approved

To ascertain the awareness of the students on vaccine development, the survey asked each respondent to list three diseases for which vaccines were approved. Figure 4 shows the list of the various diseases that the respondents listed for vaccines that have been approved. The results indicate that there is some understanding of vaccines and infectious diseases, which is an encouraging sign of knowledge awareness in schools.

Source of information

Finally, the survey also asked each respondent to provide the source of information on vaccines. Few students including both high school and college level selected more than two options for the question asked, and therefore, the responses were segregated, which were then considered as individual responses for the analysis. Figure 5 shows that 32.5% (351) of the students mentioned that communication with friends and family is the main source of information, whereas 20.89% (225) opted for headlines and news as a source of information, 18.9% (204) opted for newspaper articles, and 7.7% (83) did not put any efforts for collecting information. In total, 11.3% (122) read scientific articles.

These results indicate that majority of the students obtain their scientific information from newspapers, family and friends, rather than scientific articles. These observations indicate the

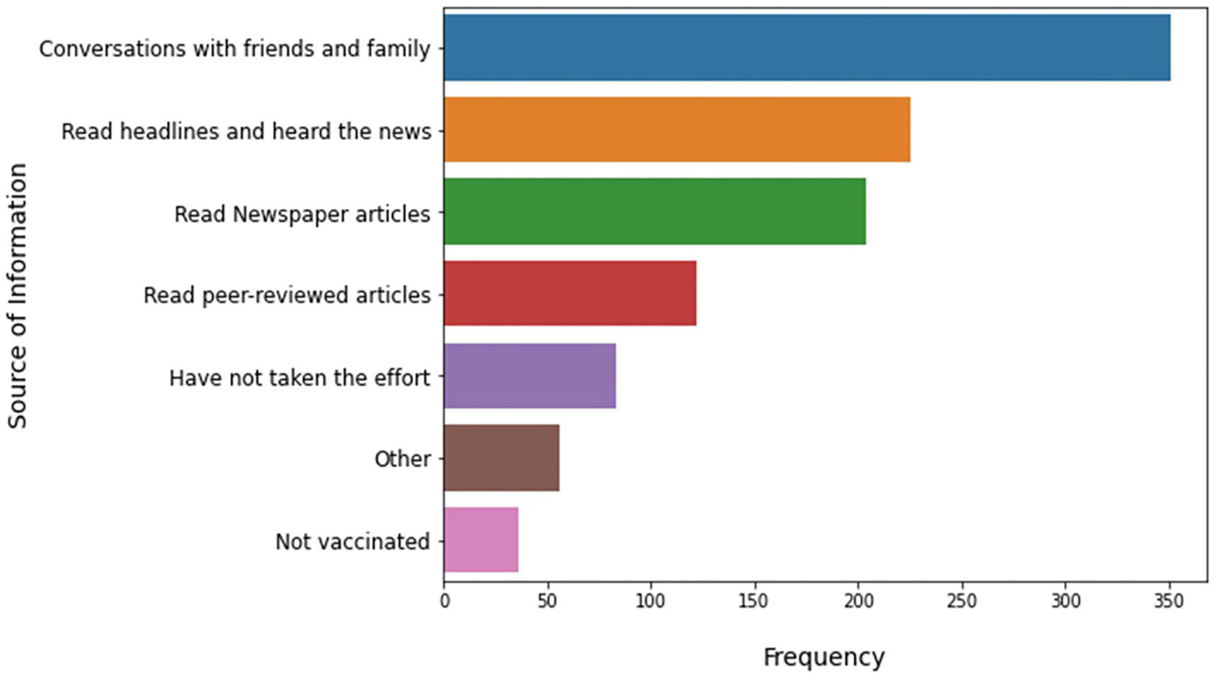

FIGURE 5
Sources of information. The bar graphs illustrate the various commonly used media through which respondents got their information about topics such as vaccines, vaccine development, and diseases. The list of sources was predefined in the survey.

necessity of the school systems to provide access to appropriate scientific journals and publications to students.

Developing a training and education system for high schools and colleges

The subject of biotechnology being taught in academia over the past decade has not been aligned with industry requirements. This gap has resulted in the formation of "finishing schools," which provide a bridge to the industry requirements. Having a detailed understanding of different processes of vaccine development in the pharmaceutical and biotechnology industry requires a multifactorial process that involves diverse subjects such as immunology, chemical engineering, pharmacology, veterinary sciences, and clinical and regulatory studies. Skill development in these areas is critical to the success of novel vaccine development in the future.

We have used a methodical approach to capture the key topics for inclusion in a course that can be curated to teach various aspects of vaccine development. The use of analogies in the pedagogy of education is a powerful tool for explaining complex concepts. The process of vaccine development can be quite similar to designing a car: from design, developing a prototype, scaling up, testing its performance, and ensuring that it is safe and efficient. It is a systematic process with numerous moving parts. Moreover, there is variability associated with this high-risk-high-reward product in terms of health and economic returns.

Since the understanding of the vaccine development process is multifunctional and involves several diverse activities, the course starts with a role-play workshop, in which three students are assigned the roles of CEO, CFO, and head of R&D of an industry. The goal of the team is to develop a vaccine from discovery, through process development, pharmacology, toxicology, clinical trials, and quality management of manufacturing to regulatory approval. At each key milestone of the development process, the team must make decisions based on an analysis of the cost, time, and risks involved prior to proceeding to the next step. A video recording of such a process is depicted in a YouTube video (Chirmule, 2020a). At the end of the workshop, there is a group analysis of the lessons learned during the vaccine development process. These lessons seek answers to questions such as (i) what could have been done to prevent the mistake? (ii) how could costs be reduced? (iii) why did the study not perform as predicted?

After the completion of the workshop, there will be a detailed presentation of the various steps involved in the drug development process, each of which should be studded with case studies and examples. Participants should be taught the key soft skills, such as the ability to ask important and meaningful questions (Chirmule, 2020b), a process to make decisions (Chirmule, 2020c), and several other soft skills important for various aspects of life. Table 2 shows a list of topics that can be considered to develop a curriculum. It consists of scientific and operational aspects of the steps and understanding the application of statistical concepts. The intent of this outline of the course is to provide administrators, teachers, and students with a framework to develop a course that can teach the multifactorial processes involved in the development of vaccines and, in fact, in the development of any medicine.

In summary, our exploratory survey confirmed the observation that there is extremely limited knowledge in the understanding of vaccine development in high schools and colleges. The limited information manifests in a lack of knowledge of drug development in society at large, resulting in the spreading of misinformation. Systematic education on the process of vaccine development will enable society to understand the multifactorial aspects, high degree of complexity, and risks. Understanding these processes can bring more awareness to the general population and provide informed decision-making that can ultimately provide high-quality informed debates on the risks and benefits of vaccines and drugs currently in use in society.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Author contributions

AG and SP researched and wrote the section on the pathogenesis of COVID-19 and participated in the survey planning and execution activities. PK and RZ researched and wrote the section on the COVID-19 vaccines and participated in the survey, planning, and execution activities. AL, SS, and NK conceived, planned, executed, analyzed the survey, and contributed to discussions on COVID-19 pathogenesis and vaccine. NC directed the concepts and oversaw all aspects of the manuscript. All authors contributed to the article and approved the submitted version.

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Conflict of interest

NC and SS are employed by SymphonyTech biologics.

The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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From stereotype to reality: A pilot study on the use of science, technology, engineering, and mathematics and STEAM in design education in Taiwan

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Currently, STEAM interventions in design education are a relatively new phenomenon. A design education system derives from three major ideas from the Bauhaus: (1) art and technology: a new unity; (2) human-centered design; and (3) interdisciplinarity, which is the essence and connotation of STEAM. In the transition from STEM to STEAM, the concept and mindset of art connect the four disciplines within STEM, elevating these tools and methods into a strategy. It is urgently necessary for design educators to restructure their curriculum using STEAM models and thought. However, there is no evidence that the integration of these disciplines will improve design education for the public. Consequently, this study examines the perception of educators and the public regarding the use of STEAM in design education. Using expert interviews, six design schools were selected as samples, and questionnaires were used to collect and analyze the views of different groups of people. According to the results, the expert group scored fairly high; and other groups will form stereotypes based on the characteristics of the school, resulting in a polarized assessment of STEAM. All groups displayed cognitive differences in many aspects. It is evident from this study that the STEAM model should be incorporated into design education; however, it is necessary to determine objectively the relationship between the five attributes and their relative importance within different design fields. Under the premise of complying with policies, regulations, and the actual situation of the school, the design of the curriculum planning needs to be adjusted and supplemented in a timely manner according to the STEAM model. Specifically, it cannot be arranged arbitrarily for STEAM, but it should also let students understand what STEAM is about so that they can understand why these courses exist. Furthermore, researchers should examine the effectiveness of these courses over time by conducting a phased retrospective.

KEYWORDS
STEM and STEAM, design education, humanities and arts literacy, interdisciplinarity cooperation, cognitive ergonomics

1. Introduction

Recently, the academic community has been interested in the concept, scope, and core theory of STEM and STEAM, and these successive publications provide strong theoretical support (Babaci-Wilhite, 2018; Culén and Gasparini, 2018; Milner-Bolotin, 2018; Khine and Areepattamannil, 2019; Videla et al., 2021; Anabousy and Daher, 2022). We live in a designed world. STEAM by design presents a transdisciplinary approach to learning that challenges young minds with the task of making a better world. STEAM by design develops designing minds. Designing minds work across STEAM fields developing social, cultural, technological, environmental, and economic responses to existing and future conditions. STEAM by design positions designing as world pedagogy that connects students as citizen activists in the communities in which they live and learn.

Back to field of design and creativity, since the 20th century, the German model has always occupied a pivotal position in the global design field, forming the Bauhaus–Ulm System (Bredendieck, 1962; Phelan, 1981; Harrington, 1988; Lerner, 2005; Ascher, 2015). The German design education model has become the benchmark in many countries. In Taiwan, modern design education was also influenced by the Bauhaus. It is constantly adjusted according to the development of the times, and has gradually formed a design education model suitable for Taiwan (Lu and Lin, 2010; Tsao and Lin, 2011; Wu et al., 2012). Since the 21st century, although the energy of design has flourished with the advancement of science and technology, and the style and type of design have also been constantly updated with the evolution of artistic and cultural concepts and trends, it is controversial whether the essence of design is implemented in so many new designs. Looking to the future, Bauhaus's three propositions for modern design education: (1) art and technology: a new unity; (2) human-centered design; and (3) interdisciplinarity, their goals and values remain unchanged. This coincides with the philosophy of STEAM (Haider, 1990; Marshall, 2014; Liao, 2016; MacDonald et al., 2019; Malele and Ramaboka, 2020; Anabousy and Daher, 2022).

The philosophy of modern design emphasizes the importance of benefiting people over products, and human-centered design is prevalent in the design of products. Therefore, whether it is "product," "design" or "evaluation," the focus is always on humans. We also follow the above principles when evaluating products or designs (Lin, 2007). Similarly, the above points apply to the development and application of the model of design education (Hanington, 2010). To achieve benign and sustainable development, it is important to continuously adjust the design education model to meet the needs of the times. As far as design education is concerned, the goal is to implement the essence of design, and to adjust how design responds to technological development and social change (Norman, 2010, 2011, 2018).

The design of the 21st century and its educational model also face challenges, which necessitate self-reform. The STEAM model is also seen as an effective way to intervene (Haider, 1990; Marshall, 2014; MacDonald et al., 2019; Malele and Ramaboka, 2020). The definition of industrial design by ICSID has also undergone many revisions, but its statement of the essence of design has stood the test of time (WDO, 2022a,b). Lin (2011) further refines those definitions and summarizes them into the following four points, which further demonstrates the rationality and necessity of applying the STEAM model to design education. They are briefly described below, and their relationship is shown in Figure 1.

1. Design is a creative act that expresses high-quality creative results through products.
2. Design is a form-making activity that applies technology to express the aesthetic effects of forming.
3. Design is an economic activity that meets the different needs of users and producers.
4. Design is also cultural creativity, which creates a daily life culture through products.

Therefore, based on the above reasons, as a theoretical framework for this study, STEAM was used, along with questionnaires and analyses, to examine the current state of STEAM in design education as well as to understand the cognitive differences between individuals and which STEAM attributes they valued. Thus, the following hypothesis is further proposed by this study:

1. The experts (who are familiar with both the target university and STEAM) gave the school a higher rating than other subjects.
2. The subjects who answered intuitively (who were unfamiliar with either the target university or STEAM) rated the lowest out of all subjects.
3. Other subjects (the general group) provided more relevant responses and may be closer to expert assessments.
4. The subjects rated their university higher than the others.

2. Theoretical framework: From STEM to STE(A)M

Although the core of design education is still influenced by the Bauhaus, it is worth paying attention to how design education should develop in the future, and the concept and mode of design education also need to be dynamically adjusted, so that the essence and spirit of design can be fully reflected (Norman, 2010, 2011, 2018; Kaur Majithia, 2017). Additionally, the revision and improvement of the design education model also need to find answers from the industry. If there is a disconnect between teaching and practical application of the knowledge and skills required, it will be difficult for design schools to train students to achieve the competencies required as designers (Cross, 2011; Chiang et al., 2021).

Science, technology, engineering, and mathematics (STEM) is a broad term used to group together these academic disciplines. This term is typically used to address education policies or curriculum choices. The acronym STEM was suggested by Rita Colwell, Ph.D., a bacteriologist who was the director of NSF in the 1980s (Marshall, 2015). The framework of STE(A)M derived from STEM, adding the category of art to the original STEM, emphasizing that future students should develop their humanistic and artistic literacy (Humart = Human + Art) and interdisciplinary ability (Interdisciplinary). In short, it is to integrate art and humanity into "rationality and objectivity" (Lin et al., 2015), and use art, culture, and humanity to connect the rational STEM to form a strategy and thought (see Figure 2). Many designs have diverse styles, types and forms, and this replicable beauty brings a lot of inspiration to design innovation and is more likely to resonate with most people. In this study, "Arts" is critical to connecting the other four attributes in STE(A)M, and becomes the core of this system. The concept of art has a very broad meaning, and this study believes that it also has cultural implications (Leong and Clark, 2003; Moalosi et al., 2008).

The STEAM model has been applied to education and training, and there have been many mature achievements and theories. For example, the formulation and application of STEAM education policies allow STEAM to be quickly promoted in teaching in related fields, and in turn examine the rationality and appropriateness of policies (Boy, 2013; Allina, 2017; Khine and Areepattamannil, 2019; Liao, 2019; Martín-Páez et al., 2019). A large number of specific application examples, or critical thinking on the STEAM model, provide a solid foundation for selecting STEAM as the core theoretical framework in this study (Land, 2013; Henriksen, 2014, 2017; Rolling,

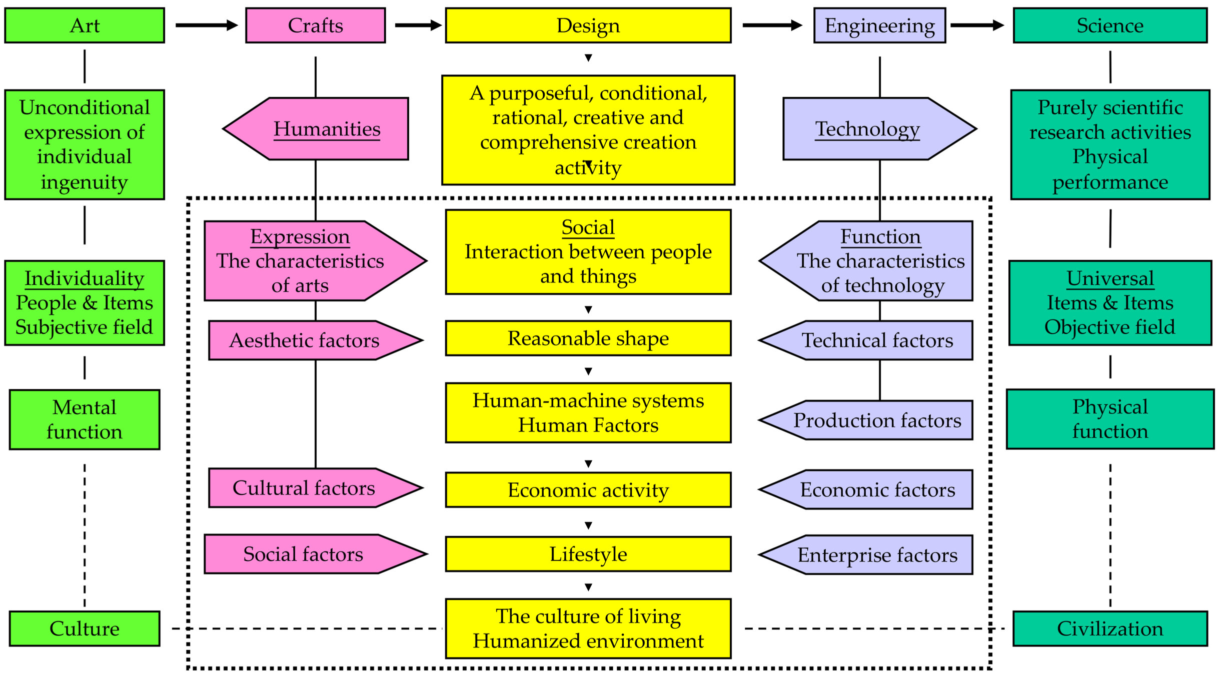

FIGURE 1
The essence of design: the balance between art and science (Source: this study).

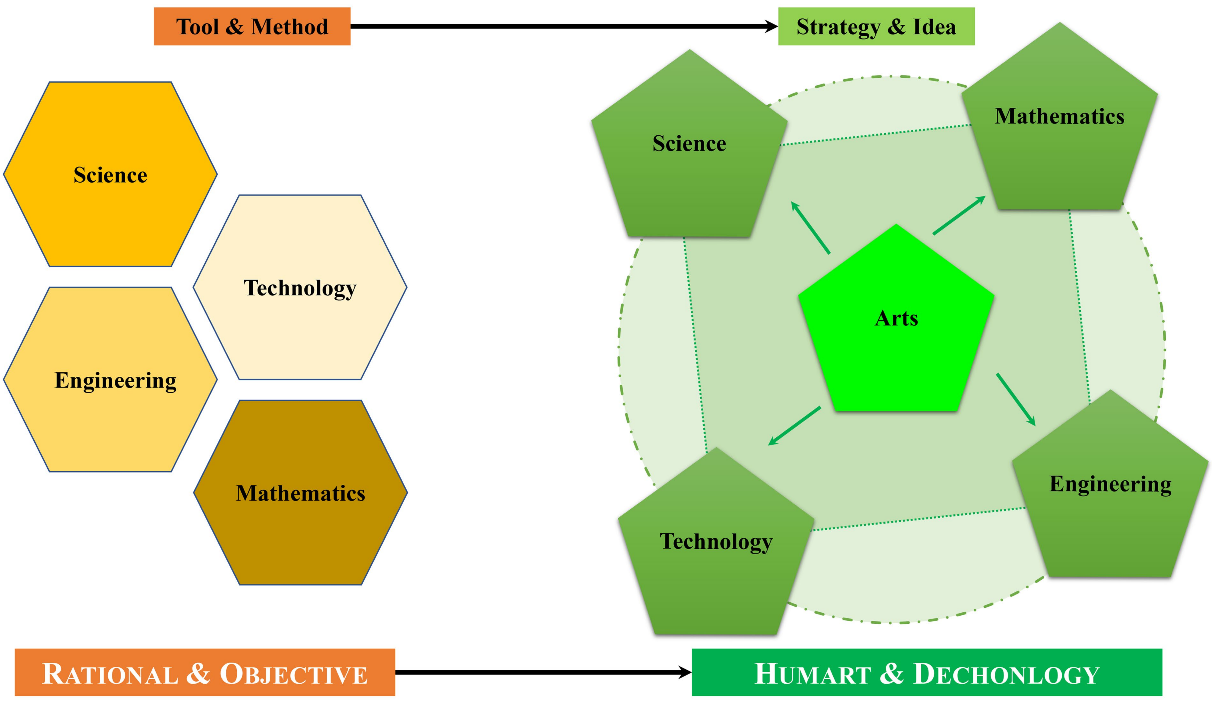

FIGURE 2
From STEM to STE(A)M: Humarts + Dechnology (Source: this study).

2016; Costantino, 2018; Colucci-Gray et al., 2019; Perignat and Katz-Buonincontro, 2019; Walshe et al., 2019; Li and Wong, 2020; Lin et al., 2021; Perales and Aróstegui, 2021).

Another reason for this study as a pilot study is to examine what are the cognitive differences between experts' and the public's perceptions of STEAM, and what is the relationship between the STEAM model and design education. How is the impact being made? STEAM, which is seen as a new driver, is also essential to ensure that it works as it is intended and can be corrected at any time based on audience feedback (Bequette and Bequette, 2012; Dahal, 2022).

In short, this study aims to understand the current status of the use of STEAM models in design education, further analyze the key points that need to be paid attention to when using STEAM models in design education by comparing the cognitive differences between subjects from different backgrounds, and provide a reference for the dynamic adjustment of STEAM models in design education in the future.

3. Methods

3.1. Procedures

Based on the previous studies, this study involved the use of questionnaire analysis to derive subjects' views on the use of STEAM in design education, as shown in Figure 3. The study can be divided into three sessions. In session I, a literature review is used to understand the difference between STEM and STEAM, and the relationship between STEAM and design education is explored. In session II, experts from the field of design were invited to conduct interviews, and design schools/laboratories from 6 universities around the world were selected as samples. The first draft of the questionnaire is analyzed and a small scale of forward testing is carried out to check the rationality of the questionnaire design. In session III, in addition to descriptive statistics, this study focuses on what is attributed to possible cognitive differences between subjects from two universities in Taiwan. Meanwhile, subjects' familiarity with the relevant university is regarded as self-variable, and the differences are analyzed after grouping, to better grasp the cognitive differences between different types of subjects.

3.2. Sample

This study argues that STEM focuses on the technical and methodological aspects, while STEAM is a strategy and idea, especially the formation of an art-centered theoretical framework. Therefore, we further selected six universities with design schools or laboratories as a sample for our studies: (1) Academic of Art & Design, Tsinghua University, (2) College of Design and Innovation, Tongji University, (3) College of Design, National Taiwan University of Arts, (4) College of Design, National Taiwan University of Science and Technology, (5) Rhode Island School of Design, RISD, and (6) MIT Media Lab (see Table 1).

Our selection of these six universities for this study is based on the fact that three of them concentrate on the arts, and the other three focus on the field of technology. This division will help this study better explore the use of the STEAM model and the current situation of design education in art or technical universities.

3.3. Questionnaire design and testing

In addition to the literature review, questionnaire was designed on the basis of several experts' insights. After the questionnaire was designed, we invited some scholars and students to fill it out and further revised the questionnaire based on their feedback. In this way, the validity and reliability of the questionnaire can be guaranteed. To better grasp their perspectives and facilitate data processing and analysis, we made copies of the questionnaires and provided them to the subjects from NTUA and NTUST. Additionally, we used online community to invite more subjects to participate. The questionnaire they filled out was named 'general edition'. Thus, 3 versions of the questionnaire were formed which are:

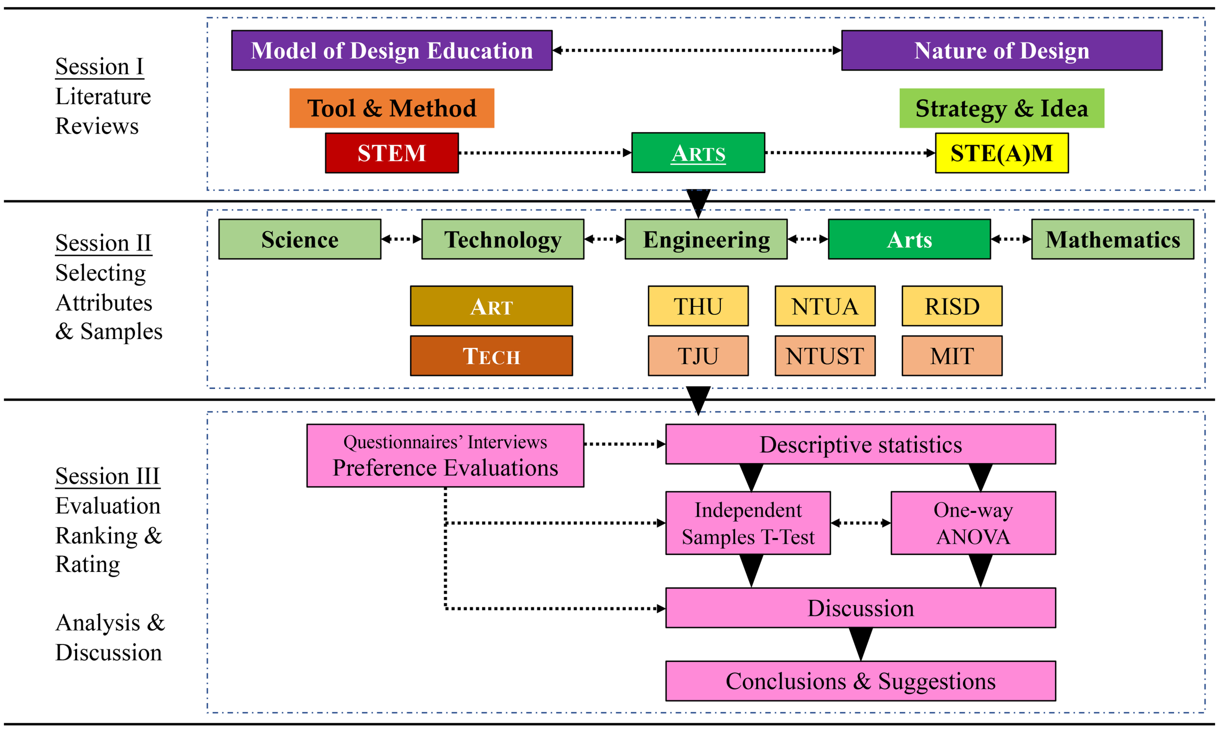

FIGURE 3
The procedures for deriving the effectiveness of the STEAM model which used in design education (Source: this study).

TABLE 1 Samples.

Group	College or laboratory of design in 6 universities
Art	Academic of Art & Design, Tsinghua University (THU)
	College of Design, National Taiwan University of Arts (NTUA)
	Rhode Island School of Design (RISD)
Science	College of Design and Innovation, Tongji University (TJU)
	College of Design, National Taiwan University of Science and Technology (NTUST)
	MIT Media Lab (MIT)

TABLE 2 The second part of the questionnaire (taking NUTA as example).

College of design, NTUA	
Are you familiar with this school?	Very low 1 2 3 4 5 Very high
Science	Very low 1 2 3 4 5 Very high
Technology	Very low 1 2 3 4 5 Very high
Engineering	Very low 1 2 3 4 5 Very high
Arts	Very low 1 2 3 4 5 Very high
Mathematics	Very low 1 2 3 4 5 Very high

general edition, NTUA edition, and NTUST edition. It should be noted that the questionnaires provided to subjects at NTUA and NTUST, we adjusted the options in age and education level, to allow those who have not yet graduated from college to answer the questionnaire.

The questionnaire is divided into two parts: the first part was the basic information of the subjects; in the second part, subjects were asked whether they were focused on STEAM at six universities, and then whether the target schools focused on the five dimensions of STEAM (see Table 2). In this study, a 5-Point Likert Scale was used for subjects with scores from 1 ("Very low") to 5 ("Very high").

The questionnaire was launched on October 26, 2022, and was created and delivered using Google Forms. The time to complete the questionnaire was limited to 2 weeks, and by November 8, 128, 115 and 60 questionnaires were received in the three editions. After analysis, all questionnaires were valid. SPSS 28.0 are used to process and analyze data. After the descriptive statistics are completed, the Independent Samples *t*-test and ANOVA are further used to analyze the data to discover what cognitive differences existed between the subjects.

4. Results and discussion

4.1. Descriptive statistics

This study focuses on whether there are cognitive differences among subjects. The variables were (1) whether the subject is familiar with the sample; (2) whether subjects knew STEAM. For the time being, we will not analyze other elements of the population variant (e.g., gender, age, education level, and experience of studying abroad), however, these data will continue to be used in future studies. The basic data of the subjects are shown in Table 3. The familiarity of subjects with the six universities in the three versions is shown in Table 4. Since the subjects are all from Taiwan, they are more familiar with NTUA and NTUST than the other four schools, which is reasonable.

The three versions of the subjects' assessments of whether these 6 universities whether to focus on STEAM are shown in Table 5:

1. The views of the general subjects and the NTUA subjects are more consistent. They all believe that MIT pays considerable attention to the four attributes of STEM. The most focused on Arts is NTUA. These assessments are based on subjects' intuitive reactions to the characteristics of the school, or they may be objective assessments that they actually know the school well.
2. Subjects from NTUST rated their schools relatively highly, with three attributes scoring first and two attributes ranking second. This may be an intuitive reaction to the subject's feelings about their own school, or it may be an assessment based on objective facts.

4.2. Differences in subjects' perceptions

After the three versions of the questionnaire were merged, we took "whether subjects know STEAM" as an independent variable, and used the Independent Samples *t*-test to grasp the cognitive differences between the subjects.

The results showed that in addition to THU, subjects had differences in cognition of some STEAM attributes for the other 5 universities. Subjects who "know STEAM" have a high average rating (see Table 6). Since the concept of STEAM is relatively professional, if subjects who do not know about it can only rely on intuition to make an assessment, a lower score is expected.

One-way ANOVA was used to determine whether there was any cognitive difference among the subjects of all three versions, and the results are shown in Table 7. It can be seen that in addition to MIT, other attributes with cognitive differences are rated higher by subjects from NTUA and NTUST. The possible reason is that because the subjects from NTUA and NTUST, which have a professional background in design, they will have a more comprehensive understanding and awareness of the relevant properties.

Subsequently, the study analyzed the feedback of subjects from NTUA and NTUST separately to understand the cognitive differences between subjects with professional backgrounds (e.g., art or technology). To facilitate statistical analysis, we divided the subjects' responses to "What do you know about the College" into three groups: subjects who ticked the 5-point were regarded as "expert groups"; Subjects who ticked 1-point are considered "intuitive group"; other subjects were considered "general group." The results of the one-way ANOVA analysis are shown in Tables 8, 9.

There were some differences in perception of some or all the attributes of the six schools between the three groups of subjects from the two schools. Next, we further analyzed the cognitive differences between subjects from NTUA and NTUST, and the results were as follows:

1. Among the three groups of subjects from NTUA, there was only a cognitive difference in the evaluation of NTUA at the level of "art," which may mean that these subjects all had artistic backgrounds and their interpretation of art may be very diverse. Their evaluation of NTUST showed cognitive differences in the

TABLE 3 Basic data of the subject.

Variables		General (*n*=128)	NTUA (*n*=115)	NTUST (*n*=60)
Gender	Female	47/36.7%	79/68.7%	14/23.3%
	Male	81/63.3%	36/31.3%	46/76.7%
Age	18–22	/	29/25.2%	11/18.3%
	23–35	/	18/15.7%	11/18.3%
	26–35	18/14.1%	17/14.8%	4/6.7%
	36–45	31/24.2%	31/27%	12/20%
	46–55	52/40.6%	17/14.8%	15/25%
	56–65	22/17.2%	3/2.6%	7/11.7%
	> 65	5/3.9%	17/14.8%	4/6.7%
Education level	University student	/	33/28.7%	8/13.3%
	Graduated from university	9/7%	8/7%	18/30%
	Master	47/36.7%	42/36.5%	25/41.7%
	Ph.D.	72/56.3%	32/27.8%	9/15%
Do you know STEAM?	Yes	98/78.4%	74/64.3%	37/61.7%
	No	27/21.6%	41/35.7%	23/38.3%
Do you have experience studying abroad (more than 1 year)	Yes	40/31.3%	26/22.6%	8/13.3%
	No (For the next question, please check "None")	88/68.8%	89/77.4%	52/86.7%
The country or region where you are studying abroad	United States, Canada	20/15.6%	14/12.2%	3/5%
	Europe	4/3.1%	6/5.2%	2/3.3%
	Asia	12/9.4%	5/4.3%	2/3.3%
	Australia, New Zealand	3/2.3%	1/0.9%	1/1.7%
	None	88/68.8%	89/77.4%	52/86.7%
	Other	1/0.8%	1/0.9%	1/1.7%

TABLE 4 The mean and standard deviation of subjects' familiarity with six universities.

	THU	TJU	NTUA	NTUST	RISD	MIT
General (*n* = 128)	2.18 (1.111)	2.27 (1.245)	3.95 (1.229)	3.43 (1.215)	2.34 (1.220)	2.91 (1.160)
	NTUA > NTUST > MIT > RISD > TJU > THU					
NTUA (*n* = 115)	2.10 (1.180)	1.77 (1.035)	3.75 (1.220)	2.83 (1.237)	1.93 (1.190)	2.34 (1.263)
	NTUA > NTUST > MIT > THU > RISD > TJU					
NTUST (*n* = 60)	1.65 (1.039)	1.58 (1.062)	2.88 (1.474)	3.42 (1.476)	1.87 (1.255)	2.63 (1.507)
	NTUST > NTUA > MIT > RISD > THU > TJU					

three attributes of "science," "technology" and "engineering" (see Table 8).

2. Among the three groups of subjects from NTUST, there were cognitive differences in the assessment of NTUST in all 5 attributes. The NTUA assessment shows cognitive differences in the three attributes of "science," "technology" and "engineering" (see Table 9).

4.3. Discussion

The characteristics presented by the data are basically in line with the expectations of the study. The first 3 assumptions can therefore be held for the following reasons:

1. All samples are highly specialized design schools, if the subjects do not know enough about them and do not know the connotation of STEAM, then the assessment is very subjective and prone to polarization, which will lower the average score. However, as a preliminary study, we believe that these subjective evaluation results can be used in subsequent studies to cross-compare with expert assessments.
2. In most cases, the STEAM model is developed and operated by professionals, who give high ratings reasonably. Meanwhile, the STEAM mode has a relatively mature operation, so it is reasonable to give it a high rating.
3. There was no significant polarization tendency among subjects who were defined as "general group." These results are more in line with the assessments made by the expert. Indirectly, this also proves the validity of the expert community's assessment.

TABLE 5 The mean and standard deviation of subjects' assessment of the STEAM model.

General (n=128)	THU	TJU	NTUA	NTUST	RISD	MIT
Science	3.23 (1.233)	3.14 (1.085)	2.88 (0.988)	3.88 (0.944)	3.26 (0.941)	4.44 (0.903)
	MIT > NTUST > RISD > THU > TJU > NTUA					
Technology	3.26 (1.186)	3.23 (1.103)	3.16 (1.007)	4.16 (0.903)	3.34 (0.891)	4.50 (0.939)
	MIT > NTUST > RISD > THU > TJU > NTUA					
Engineering	3.16 (1.200)	3.15 (1.065)	2.58 (1.024)	3.97 (0.922)	3.26 (0.982)	4.38 (0.940)
	MIT > NTUST > RISD > THU > TJU > NTUA					
Arts	3.69 (1.266)	3.51 (1.190)	4.57 (0.928)	3.36 (1.070)	3.88 (1.047)	3.62 (1.080)
	NTUA > RISD > THU > MIT > TJU > NTUST					
Mathematics	2.94 (1.228)	2.99 (1.112)	2.35 (0.977)	3.45 (0.971)	2.97 (0.922)	4.21 (0.993)
	MIT > NTUST > TJU > RISD > THU > NTUA					
NTUA (n = 115)	**THU**	**TJU**	**NTUA**	**NTUST**	**RISD**	**MIT**
Science	3.27 (1.15)	3.01 (1.158)	2.79 (1.039)	3.65 (0.937)	3.13 (0.996)	4.21 (1.055)
	MIT > NTUST > THU > RISD > TJU > NTUA					
Technology	3.36 (1.069)	3.27 (1.187)	3.20 (1.061)	4.00 (0.927)	3.37 (1.037)	4.26 (1.027)
	MIT > NTUST > RISD > THU > TJU > NTUA					
Engineering	3.22 (1.138)	3.14 (1.139)	2.80 (1.053)	3.77 (0.974)	3.08 (0.890)	4.19 (1.067)
	MIT > NTUST > THU > TJU > RISD > NTUA					
Arts	4.05 (1.083)	3.67 (1.212)	4.56 (0.797)	3.34 (1.075)	3.77 (1.071)	3.37 (1.151)
	NTUA > THU > RISD > TJU > MIT > NTUST					
Mathematics	3.10 (1.116)	3.01 (1.112)	2.42 (1.043)	3.41 (1.016)	3.06 (1.003)	4.10 (1.068)
	MIT > NTUST > THU > RISD > TJU > NTUA					
NTUST (n = 60)	**THU**	**TJU**	**NTUA**	**NTUST**	**RISD**	**MIT**
Science	3.28 (1.166)	3.20 (1.117)	2.73 (1.071)	4.08 (0.979)	3.17 (0.977)	4.02 (1.066)
	NTUST > MIT > THU > TJU > RISD > NTUA					
Technology	3.53 (1.171)	3.23 (1.079)	3.05 (0.982)	4.20 (1.054)	3.28 (1.043)	4.13 (1.112)
	NTUST > MIT > THU > RISD > TJU > NTUA					
Engineering	3.20 (1.286)	3.23 (1.079)	2.98 (1.157)	4.12 (1.010)	3.35 (1.087)	4.10 (1.130)
	NTUST > MIT > RISD > TJU > THU > NTUA					
Arts	3.60 (1.153)	3.27 (1.133)	4.25 (1.068)	3.98 (1.033)	3.52 (1.112)	3.52 (1.097)
	NTUA > NTUST > THU > MIT > RISD > TJU					
Mathematics	3.13 (1.270)	3.10 (1.040)	2.73 (1.150)	3.73 (1.250)	3.17 (1.080)	3.93 (1.150)
	MIT > NTUST > RISD > THU > TJU > NTUA					

Regarding hypothesis four, the subjects in this study are all from Taiwan, so the focus is on feedback from NTUA and NTUST subjects. Although the subjects of these two schools did give their own schools a higher evaluation since we did not invite subjects from the other four schools to make the same assessment, it is only an assertion that all subjects will make the same judgment. This is mainly because subjects still make more objective assessments based on the actual situation. Additionally, since most of the subjects have no experience studying abroad, their knowledge of universities in other countries or regions may only come from the websites of those schools and have not had real experience, which may be a reason why they can only give higher marks to the schools they have attended.

Since most of the subjects' feedback came from their intuition, in order to further verify whether it was consistent with the actual situation, this study further analyzed the curriculum of NTUA and NTUST. Since the use of the STEAM model in design education needs to be implemented through different courses, it is necessary to analyze and discuss the curriculum. These courses are mainly composed of two parts: the courses prescribed by the department, and the general courses offered by the college. The curriculum of these two universities is shown in Tables 10, 11.

From the curriculum of these two schools, this study makes the following inferences:

1. College of Design, NTUA, which has 4 departments. Courses are mainly focused on the "art and technology" level, while there are relatively few or no courses at the "science, engineering and mathematics" level, which may be related to the positioning of the art university. However, there are exceptions. For example, the Department of Multimedia and Animation Arts, which accounts for more than 60% of the courses at the technical level, may be related to the characteristics of this department, students must use various technical means to effectively complete the creation.

TABLE 6 Cognitive differences between subjects who were familiar or unfamiliar with STEAM.

Sample	Attribute	Self-variation	*N*	Mean	Standard deviation	*t*	Comparison
TJU	Science	Yes	209	3.24	1.115	3.343***	1 > 2
		No	94	2.79	1.066		
	Technology	Yes	209	3.38	1.116	3.124**	1 > 2
		No	94	2.95	1.101		
	Engineering	Yes	209	3.28	1.060	2.779**	1 > 2
		No	94	2.90	1.127		
	Arts	Yes	209	3.62	1.155	2.096*	1 > 2
		No	94	3.31	1.253		
	Mathematics	Yes	209	3.13	1.046	2.619**	1 > 2
		No	94	2.78	1.165		
NTUA	Science	Yes	209	2.92	1.041	2.653**	1 > 2
		No	94	2.59	0.944		
NTUST	Science	Yes	209	3.96	0.916	3.246**	1 > 2
		No	94	3.56	1.001		
	Technology	Yes	209	4.20	0.880	2.417*	1 > 2
		No	94	3.91	1.054		
	Engineering	Yes	209	4.00	0.930	1.979*	1 > 2
		No	94	3.76	1.023		
	Arts	Yes	209	3.60	1.057	2.959**	1 > 2
		No	94	3.20	1.122		
RISD	Science	Yes	209	3.30	0.935	2.989**	1 > 2
		No	94	2.95	0.999		
	Technology	Yes	209	3.45	0.909	2.956**	1 > 2
		No	94	3.10	1.078		
	Engineering	Yes	209	3.33	0.915	3.314**	1 > 2
		No	94	2.94	1.045		
	Arts	Yes	209	3.91	0.952	3.302**	1 > 2
		No	94	3.44	1.249		
	Mathematics	Yes	209	3.17	0.930	3.474***	1 > 2
		No	94	2.76	1.044		
MIT	Science	Yes	209	4.38	0.907	2.634**	1 > 2
		No	94	4.02	1.164		
	Technology	Yes	209	4.47	0.915	3.266**	1 > 2
		No	94	4.03	1.159		
	Engineering	Yes	209	4.37	0.927	2.761**	1 > 2
		No	94	3.99	1.196		
	Arts	Yes	209	3.73	1.008	5.338***	1 > 2
		No	94	3.02	1.182		
	Mathematics	Yes	209	4.24	0.967	3.055**	1 > 2
		No	94	3.82	1.182		

*$p < 0.05$, **$p < 0.01$, ***$p < 0.001$. Do you know STEAM: 1. Yes, 2. No.

2. College of Design, NTUST, which has two departments. In the Department of Design, there are no courses at the "Science and Mathematics" level; The Department of Architecture, on the other hand, does not offer courses at the "Science" level. Relatively speaking, the proportion of courses at the "art" level is relatively high, and the proportion of courses at the "technology and engineering" level is not much different from that at the "Art" level, which may be related to NTUST's philosophy of focusing on science and technology.

TABLE 7 The differences between subjects in the three versions.

Sample	Attribute	Source of variation	SS	df	MS	*F*	*Post hoc* tests
THU	Arts	Between groups	11.311	2	5.655	4.082*	2 > 1; 2 > 3
		Within groups	415.587	300	1.385		
		Total	426.898	302			
NTUA	Engineering	Between groups	7.319	2	3.659	3.242*	3 > 1
		Within groups	338.602	300	1.129		
		Total	345.921	302			
NTUST	Science	Between groups	7.837	2	3.918	4.355*	3 > 2
		Within groups	269.912	300	0.900		
		Total	277.749	302			
	Arts	Between groups	19.338	2	9.669	8.526***	3 > 1;3 > 2
		Within groups	340.226	300	1.134		
		Total	359.564	302			
MIT	Science	Between groups	1.029	2	0.514	0.547*	1 > 3
		Within groups	281.869	300	0.940		
		Total	282.898	302			
	Technology	Between groups	0.268	2	0.134	0.140*	1 > 3
		Within groups	287.719	300	0.959		
		Total	287.987	302			

*$p < 0.05$, ***$p < 0.001$; 3 versions of the questionnaire: 1. General, 2. NTUA, 3. NTUST.

TABLE 8 A comparison of NTUA and NTUST assessments by subjects from NTUA.

Sample	Attribute	Source of variation	SS	df	MS	*F*	*Post hoc* tests
NTUA	Arts	Between groups	15.167	2	7.584	14.845***	2 > 1; 3 > 1
		Within groups	57.215	112	0.511		
		Total	72.383	114			
NTUST	Science	Between groups	7.558	2	3.779	4.574*	2 > 1; 3 > 1
		Within groups	92.529	112	0.826		
		Total	100.087	114			
	Technology	Between groups	13.293	2	6.646	8.788***	2 > 1; 3 > 1
		Within groups	84.707	112	0.756		
		Total	98.000	114			
	Engineering	Between groups	9.858	2	4.929	5.618*	2 > 1; 3 > 1
		Within groups	98.264	112	0.877		
		Total	108.122	114			

*$p < 0.05$, **$p < 0.01$, ***$p < 0.001$; Familiarity with the University: 1. Intuition, 2. Ordinary, 3. Expert.

For students, when choosing a university, they may not have a very detailed understanding of the curriculum of the relevant college or department, but more will use the attributes of the university as an important basis for selection. However, when students enter university, it is essential whether the curriculum is reasonable.

This study believes that the curriculum of design education is very related to the positioning and professional characteristics of the school, and may have different emphases, in addition to giving play to the established characteristics and advantages of the school, how to achieve a certain balance around the STEAM model needs to be further explored: the point is that the curriculum cannot be arbitrarily set up to meet the so-called STEAM model. Simultaneously, it is also necessary to let teachers and students understand the connotation of STEAM during the education process, to help teachers and students understand the intention of certain courses. From an educational perspective, the STEAM model and essence can only be realized through various courses.

5. Conclusion and suggestions

STEAM has been widely used in many fields, and the value and significance of this mindset have been proven many times. Since STEAM is a system and the focus will be different in different fields, it is necessary

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TABLE 9 A comparison of NTUA and NTUST assessments by subjects from NTUST.

Sample	Attribute	Source of variation	SS	df	MS	*F*	*Post hoc* tests
NTUST	Science	Between groups	11.617	2	5.808	7.363**	2 > 1; 3 > 1; 3 > 2
		Within groups	44.967	57	0.789		
		Total	56.583	59			
	Technology	Between groups	12.149	2	6.075	6.478**	2 > 1; 3 > 1
		Within groups	53.451	57	0.938		
		Total	65.600	59			
	Engineering	Between groups	11.350	2	5.675	6.624**	2 > 1; 3 > 1; 3 > 2
		Within groups	48.833	57	0.857		
		Total	60.183	59			
	Arts	Between groups	21.749	2	10.874	15.032***	2 > 1; 3 > 1; 3 > 2
		Within groups	41.235	57	0.723		
		Total	62.983	59			
	Mathematics	Between groups	10.275	2	5.138	3.595*	3 > 1
		Within groups	81.458	57	1.429		
		Total	91.733	59			
NTUA	Science	Between groups	17.107	2	8.554	9.630***	3 > 1; 3 > 2
		Within groups	50.626	57	0.888		
		Total	67.733	59			
	Technology	Between groups	7.582	2	3.791	4.386*	3 > 1; 3 > 2
		Within groups	49.268	57	0.864		
		Total	56.850	59			
	Engineering	Between groups	14.539	2	7.269	6.430**	3 > 1; 3 > 2
		Within groups	64.444	57	1.131		
		Total	78.983	59			

*$p < 0.05$, **$p < 0.01$, ***$p < 0.001$; Familiarity with the University: 1. Intuition, 2. ordinary, 3. expert.

to objectively evaluate the relationship between the five attributes and determine their weight in response to different design areas.

For design education, there are also large differences between different design fields. For example, some need to strengthen the blessing of science and technology, while others pay attention to mathematical logic, and the intervention of “art” provides a new thinking mode, connecting the four attributes in STEM to form a strategy and thought, and enhance the connotation and cultural value of design through the intervention of humanities and art. Technology is the foundation of design thinking, which pays attention to “sensual technology”; human nature is the beginning of design thinking, which focuses on “human-centered design”. Finally, culture is the source of design thinking, which pursues “cultural creativity.” Therefore, designers must integrate the design thinking of “sensual technology” and “human-centered design” to create a humanized organization or living environment with friendly and cultural connotations.

This study believes that the future focus should be on how to better play the characteristics of the five attributes of STEAM, which not only meets the needs of designers in different design fields to cultivate, but also should realize that only by playing the overall thinking of STEAM can we truly achieve the goal of cultivating generalist designers. Only by achieving the above purposes can design better serve society. Additionally, the STEAM model and concept need to be realized through specific courses, and the curriculum of the design department needs to be adjusted and supplemented in time according to the STEAM model under the premise of complying with policies, regulations and the actual situation of the school. Simultaneously, researchers also must grasp the effectiveness of these courses in a timely manner through periodic return visits.

Since the number of subjects is small, and all the subjects are from Taiwan, so it is impossible to determine whether the findings and conclusions apply to other countries or regions. We hope that the above findings will inspire design educators and researchers, and will encourage more people to consider how the STEAM model can be used in design education more effectively.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

RL and YS: conceptualization and writing—review and editing. RL: methodology. YS and C-CN: writing—original draft preparation.

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TABLE 10 The curriculum of the college of design, NTUA.

	Science	Technology	Engineering	Arts	Mathematics	Other	Total
Department of visual communication design							
Curriculum	0	16 (20.50%)	4 (5.12%)	32 (41.02%)	0	26 (33.33%)	78
Credit	0	28 (18.66%)	8 (5.33%)	62 (41.33%)	0	52 (34.66%)	150
Arts > Other > Technology > Engineering > Science = Mathematics							
Department of crafts and design							
Curriculum	1 (1.02%)	6 (6.12%)	6 (6.12%)	53 (54.08%)	1 (1.02%)	31 (31.63%)	98
Credit	2 (0.89%)	12 (5.38%)	15 (6.72%)	131 (58.74%)	3 (1.34%)	60 (26.90%)	223
Arts > Other > Engineering > Technology > Mathematics > Sciences							
Department of multimedia and animation arts							
Curriculum	0	42 (56.75%)	1 (1.35%)	7 (9.45%)	0	24 (32.43%)	74
Credit	0	140 (61.13%)	3 (1.31%)	19 (8.29%)	0	67 (29.25%)	229
Technology > Other > Arts > Engineering > Sciences = Mathematics							
Curriculum in general education							
Curriculum	0	6 (35.29%)	0	6 (35.29%)	0	5 (29.41%)	17
Credit	0	12 (35.29%)	0	12 (35.29%)	0	10 (29.41%)	34
College of design, NTUA							
Curriculum	0	70 (26.31%)	11 (4.13%)	98 (36.84%)	1 (0.37%)	86 (32.33%)	266
Credit	0	192 (30.28%)	26 (4.10%)	224 (35.33%)	3 (0.47%)	189 (29.81%)	634
Arts > Technology > Other > Engineering > Mathematics > Sciences							

Source: The website of NTUA.

TABLE 11 The curriculum of the college of design, NTUST.

	Science	Technology	Engineering	Arts	Mathematics	Other	Total
Department of design							
Curriculum	0	23 (28.78%)	8 (10.00%)	27 (33.75%)	0	22 (27.5%)	80
Credit	0	69 (29.61%)	23 (9.87%)	71 (30.47%)	0	70 (30.04%)	233
Arts > Other > Technology > Engineering > Sciences = Mathematics							
Department of architecture							
Curriculum	0	5 (8.77%)	19 (33.33%)	14 (24.56%)	5 (8.77%)	14 (24.56%)	57
Credit	0	15 (8.47%)	73 (41.24%)	35 (19.77%)	15 (8.47%)	39 (22.03%)	177
Engineering > Other > Arts > Technology = Mathematics > Sciences							
College of design, NTUST							
Curriculum	0	28 (20.43%)	27 (19.70%)	41 (29.92%)	5 (3.64%)	36 (26.27%)	137
Credit	0	84 (20.48%)	96 (23.41%)	106 (25.85%)	15 (3.65%)	109 (26.58%)	410
Other > Arts > Engineering > Technology > Mathematics > Sciences							

Source: The website of NTUST.

All authors have read and agreed to the published version of the manuscript.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Design as the basis for integrated STEM education: A philosophical framework

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STEM—science, technology, engineering, and mathematics—has become important as an educational construct and phenomenon in recent years. However, it is only just recently that STEM education has begun to be examined from a philosophical point of view. There is therefore a need for further investigation of its philosophical basis, particularly in relation to integrated STEM education (iSTEM). Recent conceptual and empirical studies emphasize the crucial role of design in achieving successful STEM integration, and design thinking has also lately gained traction in such integration. The aim of this study is to investigate an integrated philosophy of STEM education, based on the methodological backbone of design. The research methodology consisted of a critical review of the literature regarding the philosophy of STEM (education), science, technology, engineering, mathematics, and STEM education research, related to the current issues of integrating the various STEM subjects. We thus base the philosophical framework on philosophy and studies from/on the STEM subjects in education. It is concluded that from a methodological point of view, design holds promising affordances for unifying the STEM subjects through "pure STEM problems". Design as part of, for instance, particular engineering design projects may consequently require the "design" of applicable scientific experiments as well as mathematics expressions and formulae specifically when engaging in technological modeling.

KEYWORDS

STEM education, iSTEM, design, philosophy of technology, Science, Technology, Engineering, Mathematics (STEM)

Introduction

Integrated STEM education is increasingly viewed as a viable way of preparing students for real-world problem solving in a global society that faces complex social and environmental challenges (Kelley and Knowles, 2016). Integrated approaches to STEM education could promote authenticity and improve learning, prepare students for future STEM careers and higher education paths, as well as develop so-called twenty-first century skills, for example, creativity, innovation, collaboration, and critical thinking capabilities (Hallström and Schönborn, 2019; Banks and Barlex, 2020). Recent conceptual studies emphasize the crucial role of engineering design in achieving successful STEM integration (e.g., Margot and Kettler, 2019; Roehrig et al., 2021). The centrality of design is also largely confirmed by recent empirical studies on integrated STEM education. For example, it is suggested that design connects STEM education to real-world practices and makes students better at applying disciplinary knowledge in the individual STEM subjects (e.g., English and King, 2015; Lin et al., 2021; Hallström et al., 2022; Sung and Kelley, 2022).

However, there is a philosophical vagueness surrounding the concept of integrated STEM education, for example, when it comes to what knowledge components of the individual subjects should be integrated and how (e.g., Erduran, 2020; Ortiz-Revilla et al., 2020, p. 857). The need for a foundational philosophy of integrated STEM education is thus urgent, in order to make educational initiatives rest on a solid philosophical foundation, especially when centered around a particular methodology such as design. It is only just recently that integrated STEM education was first probed from a philosophical point of view, with the aim of investigating what it is and what underpins it theoretically. Most such philosophical work, however good, was done from the point of view of one or two of the individual subjects such as science or mathematics (e.g., Chesky and Wolfmeyer, 2015; Akerson et al., 2018), so there is a need for developing a philosophical framework for integration of more or all of the STEM subjects.

Tang and Williams (2019) tested the concept of integrated STEM literacy empirically, and concluded that:

> Based on the similarities found in several language and thought processes of the disciplines, we conclude that there is presently a research basis for postulating a unitary STEM literacy that reflects the shared general capabilities required in all the STEM disciplines. At the same time, there are also substantial differences that support the retention of the existing literacy constructs (i.e., S.T.E.M. literacies) to reflect the specific linguistic, cognitive and epistemic requirements found in each disciplinary area. This distinction from the singular STEM literacy is necessary to highlight the skills and practices that are unique to each particular discipline, and therefore not applicable in all the other disciplines (p. 675).

If integrated STEM education is to remain philosophically solid and powerful as an educational endeavor it is clear that it should revolve around some kind of integration of two or more of the subjects, at the same time as the core content and methods of each subject have to be respected. Hallström and Schönborn (2019) began developing such a framework based on *design* as a core capability or method common to all STEM subjects, and this study will expand that framework. Design lends itself particularly well to philosophical analysis because it is not only a making activity but also a pattern of planning and thinking, described succinctly by Mitcham (2020): "Engineering design [...] constitutes a distinctive way of turning making into thinking, engendering not only a special kind of making but also a unique way of thinking (p. 78–79)." Design thinking could, however, also be seen as a central pattern of thought even in science and mathematics (Bishop, 1988; Doppelt, 2009; De Vries, 2021), which makes it broader than engineering and technological design and thus potentially more novel for STEM integration than the previous studies mentioned above. The aim of this study is to investigate an integrated philosophy of STEM education, based on the methodological backbone of design. The research question that underpinned the study is: What are the affordances of Mitcham's (1994) 4-fold philosophical framework of technology and engineering for unifying the STEM subjects, with particular consideration of the methodology of design?

The research methodology for this conceptual article consisted of philosophical analysis of a selection of literature in the philosophy of STEM (education), science, technology, engineering, mathematics, and STEM education research, related to the current issues of integrating the various STEM subjects (Hospers, 1997; Dusek, 2006). The selection of literature was carried out by, first of all, searching for journal articles, books and book chapters related to the research question and the just mentioned scholarly fields in pertinent search engines (ERIC, Google Scholar, Unisearch), from roughly 2000 to 2022. Furthermore, we included relevant literature that was found in reference lists in previously known philosophical and STEM educational literature, or the literature found through the searches. This literature could in some cases be older than the year 2000, which is natural in philosophical analysis because philosophy relies at least partly on a cumulative acquisition of knowledge. Our review is not a systematic one but rather a critical review to support a philosophical analysis and, as such, it is the degree of sustainability of the philosophical argumentation that decides and ultimately confirms the thoroughness of the review (see Grant and Booth, 2009, p. 93–97).

As such, a philosophical framework is theoretical and cannot, ultimately, be "proven." However, a philosophical framework, at least in the social sciences and humanities, is used heuristically to advance knowledge of a phenomenon or understand empirical data related to that phenomenon. Thus, to be able to fulfill that function the framework constructed in this study cannot just be made up, but it must be related to the philosophy and science of that phenomenon, in this case integrated STEM education. We consequently base the philosophical framework on (1) Philosophy of STEM and/or science, technology, engineering, and mathematics (education), and (2) Scientific studies from/on the STEM subjects and education. The more sources that can underpin this philosophical framework the better it can be used as a heuristic tool in future studies and in STEM education practice.

A philosophical framework for integrated STEM education

According to the philosopher Mitcham's (1994) 4-fold philosophical framework, technology is manifested as knowledge, volition, activity, and object. Thus, technological knowledge and volition, with their origin within human beings, give rise to technological activities resulting in concrete technological objects. The framework bears many similarities with other frameworks explaining human volition, knowledge and behavioral interaction with an environment, see, for example, Fishbein and Ajzen (2010) and Ankiewicz (2019); the Mitcham framework therefore has a more general and broad application than merely in technology and engineering. These four modes of manifestation of technology have also been linked to the four components of general philosophy, as well as to the analytical tradition within the philosophy of technology, namely, epistemology, axiology, methodology and ontology respectively (Ankiewicz et al., 2006; Ankiewicz, 2016, 2019; De Vries, 2017), as illustrated in Figure 1. There is also a natural affiliation with a general philosophical outlook on the STEM subjects. The subjects/domain-specific knowledge have strong commonalities in terms of knowledge (conceptual knowledge—knowing that), skills/activities (procedural knowledge—knowing how) and axiology, as they form the core of the respective knowledge domain.

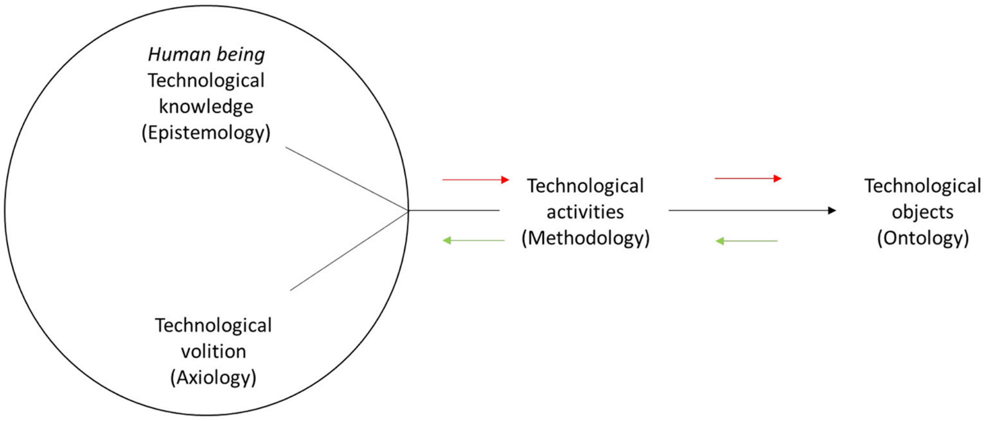

FIGURE 1
Modes in which technology is manifested (Mitcham, 1994, p. 160 and 209, as adapted by Ankiewicz et al., 2006 and Ankiewicz, 2019).

By superimposing the components of general philosophy onto Mitcham's (1994) framework, a "philosophy modulation" of the latter is obtained. This process is metaphorically similar to the concept of frequency modulation in physics, where the characteristics of one system (here, Mitcham's framework) are changed by impressing another system (here, general philosophy) onto it. Consequently, philosophy modulation in the form of superimposing general philosophy onto Mitcham's four modes of a technology-specific philosophical framework shows how the former can be used to analyze/interpret the latter. On the one hand, technological knowledge and volition give rise to technological activities expressed as concrete technological objects (indicated by the red arrows). On the other hand, objects can also influence peoples' activities, knowledge and their will (indicated by the green arrows).

It follows that all of these four components of philosophy, superimposed on Mitcham's framework, could be applied to the "S," "T," "E," and "M" in a STEM education philosophy, although it remains to be seen from the analysis below whether they can be cogently unified philosophically. Evidence from other studies suggests that the STEM subjects may be too dissimilar concerning ontology and epistemology for a successful philosophical integration on these grounds (e.g., Tang and Williams, 2019). Furthermore, ontology and epistemology are also the most researched philosophical aspects (e.g., Mitcham, 1994, p. 209; Ortiz-Revilla et al., 2020). Thus, methodology and axiology are especially pertinent components of a philosophy of STEM education to research. In order to achieve order and focus to our study, we here deal only with methodology as an area to explore philosophically across the STEM subjects, with special regard to design as a methodology equally important across all the subjects. Mitcham's (1994) analysis includes also other forms of activities such as crafting, inventing, and operating, but designing holds the most promising affordances for STEM integration. We thus need to find common ground for a transdisciplinary STEM philosophy built on authentic interaction and cooperation (English, 2016)—"looking sideways" (Banks and Barlex, 2020), whilst respecting the integrity of each subject—in precisely the methodological dimension.

The centrality of design in all STEM subjects can thus be reinforced by looking specifically at inquiry knowledge (Quinn et al., 2020), that is, procedural knowledge, which translates to Mitcham's (1994) activity and methodology in general philosophy, after the philosophy modulation. Design, not as an exclusive feature of engineering (Ortiz-Revilla et al., 2020), is a common activity/methodology in "S," "T," "E," and "M" when integrated STEM is achieved by means of complex, pure STEM problems and inquiry (Pleasants, 2020). We justify philosophically why the STEM subjects can be integrated, and we have through Mitcham (1994) identified design in broad terms as a means to do this: experimental design in "S;" design of mathematical algorithms and models in "M;" technological design in "T;" and engineering design in "E." Thus, design—not engineering design as such, although it plays a major role as a form of problem solving (see Kelley and Knowles, 2016)—integrates the STEM subjects philosophically. According to Pleasants (2020), examining the natures of the individual STEM fields is not a sufficient approach. For Pleasants the more productive approach is to examine "pure STEM problems," which points to the methodological domain, rather than seek overlap among the STEM fields epistemologically (Pleasants, 2020).

It would be possible to view design methodology as a broader societal undertaking (cf. axiology), bringing in even ethical, cultural, political and economic influences as a context in the above model (see Hallström, 2022; cf. "STEM-relevant problems," Pleasants, 2020). However, in this study design is mainly defined in correspondence with what Feng and Feenberg (2009) designate as "proximate design," that is, conceptualized as a technical task at a micro level in workshops, design studios or STEM classrooms. In other words, the focus is on the design process in itself and how it can be conceptualized and modeled as a methodology to promote integrated STEM education with pure STEM problems, in real-world practices as well as in classrooms.

Design methodology as a way of philosophically unifying the STEM subjects

Design processes are studied in the discipline of design methodology (De Vries, 2001). Design by its nature is adapting reality—in fact reality as a whole—by changing situations, objects, systems, and natural environments to optimally serve the needs of people (Mitcham, 2020; De Vries, 2021). Two different paradigms form the basis of the discipline of design methodology, i.e., the rational problem-solving and the reflective-practice paradigm. The rational problem-solving paradigm is a more structured approach generally associated with engineers while the reflective practice paradigm is a less structured approach usually associated with architects (Dorst, 1997; Ankiewicz et al., 2006; Ammon, 2017). A combination of the two approaches into the conceptual, information and embodiment stages of design activity results in a dual model of design methodology proposed by Dorst (1997). In the following paragraph we will argue that Dorst's (1997) dual model of design methodology—the combination of the rational problem-solving and the reflective-practice paradigms—is actually applicable in design processes, which not only consist of rational problem solving but also reflective practices with many intuitive elements that make them relevant across the STEM subjects (cf. Kroes et al., 2009).

Design is the primary methodology of technology which is more intuitive than engineering design (De Vries, 2018; Seery et al., 2022) as it has an element of trial and error to it (Williams, 2011) and is in itself "an independent epistemic praxis" (Ammon, 2017, p. 495); thus, it is largely associated with the reflective practice paradigm. However, this type of design also features in engineering (De Vries, 2018; Sung and Kelley, 2022), and engineering is actually a sub-set of the broad area of technology (Williams, 2011). Based on Dorst's (1997) dual model we suggest a definition of design as the combination of the two approaches to design; rational problem solving which is largely associated with conceptual knowledge production, and reflective practice which is to a great extent connected with procedural knowledge production. Design conceived in this way could provide a clue for the problem of how to exploit the affordances of STEM further regarding science and mathematics (De Vries, 2018). Thus, for example, in engineering design problems the "E" particularly brings together the knowing that (or conceptual knowledge) which also characterizes the "S" and "M," and the knowing how of the "T" (or procedural knowledge; De Vries, 2021).

The roles of design for integrating the STEM subjects

From the literature on STEM education there seems to be mainly two ways of interaction between STEM subjects; the application of existing knowledge from the STEM subjects (e.g., Barlex, 2007) and an approach where there is knowledge development in all STEM subjects at the same time, as well as the application of knowledge from various STEM subjects (De Vries, 2018, 2021). Focusing on design as a methodological characteristic of all STEM subjects as presented above, may be conducive to the application of existing knowledge from the STEM subjects as well as knowledge development in all STEM subjects simultaneously.

In design methodology, therefore, the central methods of the STEM subjects could be integrated. For example, modeling is an integral method of both science, technology, engineering, and mathematics authentic practices and educational endeavors (Hallström and Schönborn, 2019; Tang and Williams, 2019). Models are simplified representations of phenomena. Modeling is therefore used in all STEM subjects, either to represent reality as in science, to represent algorithms as in mathematics, or to represent something that does not exist, for instance, an object or system being innovated, as in engineering and technology (Gilbert et al., 2000; Norström, 2014; Sung and Kelley, 2022). In engineering design, not only engineering and technological modeling are included, but also scientific and mathematical modeling. In many engineering projects, it is common to model scientific phenomena such as when designing structures and materials and making mechanical calculations, in which scientific modeling could be in the form of models of material properties. Mathematical modeling is also frequently applied in engineering contexts and design processes (Brady et al., 2015); in fact, many engineering models are mathematical by nature (Zawojewski et al., 2008; Ryberg et al., 2015).

Barlex (2007) mentions a more incidental type of interaction between the STEM subjects which occurs in design projects when technology students apply knowledge from the other STEM subjects (cf. Williams, 2011). As opposed to incidental interaction between the STEM subjects—and in order to establish a real connection between them—De Vries (2018, 2021) suggests the use of particular technological design challenges around authentic problems in which engineering principles, scientific concepts and mathematical ways of thinking are essential for finding solutions to the challenge. Thus, he advocates an approach where there is knowledge development in all STEM subjects simultaneously, and not merely the application of existing knowledge related to them—similar to how it happens in practice in engineering design projects (Sung and Kelley, 2022). When students' intuitive ideas are challenged in such design projects, they will inquire and perform experiments to understand scientific phenomena that relate to the given problem—scientific design. They will also undertake mathematical calculations to optimize their designs, and do modeling to test this. This activity will result in an integrated STEM activity; a rich technology and engineering design experience, a better understanding of science concepts (that relate to the design) and new experiences and applications of using mathematics (De Vries, 2018, 2021). Such an activity does justice to the nature of design as a process in which both new knowledge is developed (about designing itself, but also science and engineering), and existing knowledge (previously learnt in science, technology, and/or mathematics) is applied (Pleasants, 2020).

De Vries (2018) presents another example from real-world engineering. Scientific knowledge of aerodynamics is developed in the context of designing. Although there are exceptions such as the wholly computer-modeled Boeing 777 (Mitcham, 2020), the design of airplanes is still today also based on tinkering with prototypes and investigating the effects of systematically changing the design of the flying behavior of the airplane by putting models in wind tunnels (cf., Ferguson, 1992). The process of simultaneously developing knowledge about natural phenomena and improving the design can easily be simulated in class by using paper airplane designing and testing. Design in science may also be more experimentally oriented—such as, for example, in synthetic chemistry—whereas design in technology and engineering are not really experiments in the scientific sense but rather epistemic practices of their own that are open ended, iterative and produce their own knowledge (Kroes et al., 2009; Ammon, 2017).

Design in technology and engineering—and even sometimes in mathematics, according to Bishop (1988)—will therefore typically lead to the making of an object, or system (Vermaas et al., 2011). The students will also design mathematical expressions or functions and do calculations to optimize their design by modeling to test their optimisations. The steps of mathematical modeling thus resemble, to a large extent, the stages of engineering design in that they systematically address real-world problems (Wei et al., 2022). These kinds of engineering challenges will fit the nature of design as a process encompassing both rational problem solving and reflective practice, and in the philosophical sense a methodology in which both new knowledge is constructed and existing knowledge is employed (De Vries, 2018; Hallström and Ankiewicz, 2019; Vossen et al., 2020).

Kelley and Knowles (2016) view engineering design as an important component in the integration with science, mathematics, and technology in STEM education, although, for them, it is the community of practice that is the actual integrator (cf. Hacker, 2018; Han et al., 2022; Sung and Kelley, 2022). When considering integrating STEM education components, however, design can become the situated platform and methodology for STEM learning (Hallström et al., 2022). Using design as a catalyst to STEM learning is vital to bring all STEM subjects on an equal platform. The very nature of design thus provides students with a both systematic and reflective approach to solving pure problems that often occur naturally in all the STEM fields. Engineering problem solving could address such problems and build connections among the STEM subjects, which has been identified as key to subject integration (Barnett and Hodson, 2001; Frykholm and Glasson, 2005; Kelley and Knowles, 2016; Daugherty and Carter, 2018; Han et al., 2022; Sung and Kelley, 2022).

Engineers' inquiry is also comparable with scientific inquiry (Sung and Kelley, 2022), something which becomes apparent when designing. Science education can therefore be enhanced by infusing an engineering design approach because it creates opportunity to apply science knowledge and inquiry as well as provide an authentic context for learning mathematical reasoning and modeling for informed decisions during the design process (English, 2022; Wei et al., 2022). The analytical element of the engineering design process allows students to use mathematics and science inquiry to create and conduct experiments that will inform the student about the function and performance of potential design solutions before a final prototype is constructed. This approach to engineering design allows students to build upon their own experiences and provides opportunities to construct new science and mathematics knowledge through engineering design analysis and scientific investigation around a pure STEM problem (Kelley and Knowles, 2016; Han et al., 2022; Sung and Kelley, 2022).

A reinterpretation of Mitcham's framework for STEM education

As we have shown above, Mitcham's (1994) 4-fold philosophical framework holds affordances for cogently unifying the STEM subjects. Bishop (1988) argues that mathematics is basically to be seen as a technology, a human-made "artifact," and specifically expounds on a conception of design similar to in technology and engineering (cf. Kertil and Gurel, 2016), which further underlines the potential fruitfulness of expanding Mitcham's framework for technology to include all of STEM. Consequently, from a methodological point of view the design in technology and engineering holds promising affordances for unifying the STEM subjects, especially when considering that design in mathematics in certain conceptions also aligns with this (Bishop, 1988). Design as part of pure STEM projects therefore may require the "design" of applicable scientific experiments as well as the design of pertinent mathematics expressions and formulae specifically when modeling in engineering and technology. Based on the findings of this article, we thus expand the "philosophy modulation" and reinterpret Mitcham's 4-fold philosophical framework as follows (see Figure 2): On the one hand, transdisciplinary "S," "T," "E," and "M" knowledge and volition give rise to design activities expressed as concrete STEM objects or projects (indicated by the red arrows). On the other hand, specific STEM objects or projects require design activities by students which develop students' "S," "T," "E," and "M" knowledge and influence their will/STEM volition (indicated by the green arrows). Exactly how STEM design activities "re-affect" human learning and volition (left green arrow) is beyond the scope of this study. Suffice it to say here that for pure STEM problems, design as a methodology is crucial for STEM integration.

STEM volition is the will to solve a problem using a transdisciplinary STEM approach. When doing this, knowledge from some or all the STEM subjects is required by "looking sideways" in collaboration without "diluting" the individual subject knowledge/domain-specific knowledge components, as proposed by Banks and Barlex (2020). The specific STEM design activities are embodied in pure STEM problems (Pleasants, 2020), as outlined above representing both a rational problem solving and reflective practice paradigm (Dorst, 1997; Kroes et al., 2009) that would include knowledge from the "S," "T," "E," and/or the "M." The specific STEM objects that are the outcome of the design activities could be technological or engineering objects or systems, mathematical solutions or models, or scientific results, in response to the problem to be solved.

Conclusion

In this article we underpin a new philosophical framework of integrated STEM education through *design*, based on Mitcham's (1994) conception of technology. Such a philosophical framework is much needed because previous frameworks were primarily based on integration of one or two of the subjects (e.g., Chesky and Wolfmeyer, 2015). Furthermore, recent research on the engineering design process, authentic STEM projects and the actual execution of collaborative engineering and/or architectural

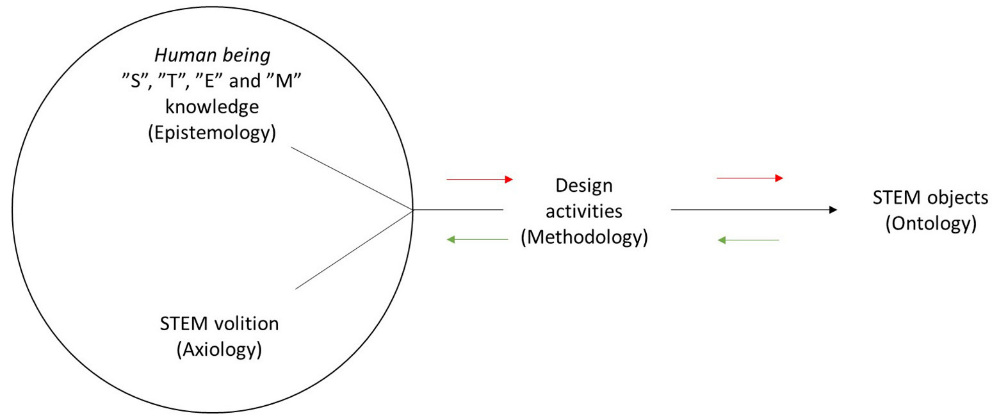

FIGURE 2
A reinterpretation of Mitcham's (1994) philosophical framework for STEM education.

design projects in education support the basic ideas of the framework, in terms of the merger of reflective practice and rational problem solving (e.g., Davidsen et al., 2020). Design in the form of engineering design is also often at the core of integrated STEM projects, either explicitly or implicitly (Hallström et al., 2022), which is also supported by, for example, the American Next Generation Science Standards (2013) and the Standards for Technology and Engineering Literacy (International Technology and Engineering Educators Association, 2020).

Finally, we call for more research about design in STEM classrooms; in particular, studies could test the applicability of the philosophical framework presented in this paper. It is imperative that interventions are carried out which integrate the STEM subjects in, for example, engineering design projects in a similar manner to those described by De Vries (2018, 2021), in which technological and engineering principles, scientific concepts and mathematical ways of thinking are essential for finding solutions to the challenges (cf. pure STEM problems, Pleasants, 2020). Such research should also consider the ways the separate STEM subjects interact around a design challenge, and how students could benefit by engaging in design as a methodology in all STEM subjects. Models and modeling could, for example, be one way of methodologically creating bridges between the STEM subjects in such problems (cf. Hallström and Schönborn, 2019). Furthermore, future studies could consider engineering design in different societal and educational contexts, so as to investigate how both design and integrated STEM education relate to intentionality, contextual and spatial restraints (Feng and Feenberg, 2009; Nazar et al., 2019).

Educational implications

In their recent systematic literature review of classroom iSTEM projects, McLure et al. (2022) argue that "projects that do not allow students to design their own solutions to problems, evaluate those designs and then re-design do not meet criteria for best practice in integrating STEM domains" (p. 10). While this statement certainly validates the philosophical framework put forward in this article, McLure et al. (2022) also express concerns about the lack of relevance to the students' contexts or interests, as well as the lack of actual STEM integration, in the studied projects (p. 10–12). Consequently, we argue that to obtain successful STEM integration and student engagement in classrooms one should import pedagogical approaches to teaching STEM which include problem-, project-, design-, or inquiry-based teaching approaches or strategies (e.g., Wei et al., 2022). We further argue that technology and engineering design projects may be very suitable to promote all the design types which relate to the separate STEM subjects or domain-specific knowledge. Not all science or mathematics projects will necessarily include or promote technology and engineering activities and knowledge. Thus, engineering design could be seen primarily as an authentic instructional problem-solving approach, in which both scientific, technological, and mathematical design will appear. Computational design involving computational modeling or simulations may support such an approach (Tucker-Raymond et al., 2019; Papadakis et al., 2022). Students are thus tasked with an engineering problem, often such a one in which students will need to engage in designing an object or system that will require them to learn and/or use relevant science and mathematics concepts (Ortiz-Revilla et al., 2020, 2022; Pleasants, 2020; English, 2022; Hallström et al., 2022).

Author contributions

Both authors listed have made a substantial, direct, and intellectual contribution to the work and approved it for publication.

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Conflict of interest

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Integrating circular economy into STEM education: A promising pathway toward circular citizenship development

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The young generation is expected to address current development challenges. The main challenge of sustainable development is the problem of waste management and recycling. To promote long-term sustainability, it is crucial to equip youth with contemporary knowledge and skills and to change their daily habits. The Circular Economy (CE) has become a key concept in responding to unsustainable resource use and waste management globally. At the same time, Science, Technology, Engineering, and Math (STEM) education is an innovative teaching approach to promote learners' capacity for self-direction, problem-solving, collaboration, and management. This paper argues the role of STEM education in connecting science with society, the benefits of teaching CE in promoting sustainable consumption and production behaviors, and the potential integration of CE into STEM education through real-world context inquiry and real-world problem-solving. It also presents the case of Vietnam, where integration of STEM education and CE in secondary schools is crucial for a CE toward sustainable development. Questionnaire surveys with 873 secondary school teachers and semi-structured interviews with 54 were conducted during the integrated STEM professional trainings. The aims were to examine teachers' perspectives on the relevance of STEM education and CE to sustainable development and their behaviors toward integrating CE concepts into daily STEM teaching activities. The findings showed a high perception of STEM teachers on the relevance of CE with STEM teaching, the Vietnam context, its interestingness, and the importance of integrating CE into STEM education. Surveyed teachers have also voluntarily integrated development issues and CE principles into STEM teaching. Including CE in STEM education in secondary education offers a promising opportunity to foster more profound societal change toward sustainable development, which contributes to SDG4 — equitable and quality education for sustainable development and sustainable lifestyles and SDG 12.5 — reduce waste generation through prevention, reduction, recycling, and reuse.

KEYWORDS

real-world context, problem-based learning, development issues, CE principles, secondary education teachers, transdisciplinary, Vietnam

1. Introduction

Education for sustainable development (ESD) emerged from numerous international discourses addressing the key sustainability challenge. From Agenda 21 to Target 4.7 "by 2030, ensure all learners acquire the knowledge and skills needed to promote sustainable development, including, among others, through education for sustainable development and sustainable lifestyles, human rights, gender equality, promotion of a culture of peace and non-violence, global citizenship, and appreciation of cultural diversity and of culture's contribution to sustainable development," education is a key mean for achieving sustainable development goals (SDGs) and needs of integrating sustainable development into educational systems (Leicht et al., 2018; Nguyen et al., 2020). The Global Action Programme (GAP), which has existed for a decade, aims to expand and improve ESD initiatives at all educational levels and across all subject areas. Inter-SDG collaboration with ESD is also gaining traction. All the Sustainable Development Goals (SDGs) require education because it equips individuals with the skills, values, and knowledge they need to advance themselves and society. All educational institutions, from preschool to higher education, play a role in preparing tomorrow's citizens to solve problems in the real world by understanding the connections between social, science, and technology (Nguyen et al., 2020). Secondary schools, on the other hand, are crucial in helping young people develop global competence. This multifaceted skill enables them to examine local, global, and intercultural issues, understand and appreciate various world views, interact respectfully with others, and take responsibility for sustainability and well-being (OECD, 2018). Schools are in a unique position to help students better comprehend their place in society and the globe, as well as develop their knowledge and skills for decision-making and actions (Hanvey, 1982). In order to teach sustainable development in schools, it is important to transform the learning environment and teaching approach. Thus, questions emerged in this context: which educational approach is more appropriate and significant in which schools can have an influence on society in two-fold outcomes: equip young people with social and scientific knowledge and skills and change their daily behaviors toward sustainable development? And how must learning and teaching environments and approaches be transformed to implement ESD? The integration of circular economy (CE) concepts into STEM (science, technology, engineering, and mathematics) teaching appears as a promising education approach in the preparation of the young generation with modern socio-scientific knowledge and skills as well as the right social behavior toward addressing the development challenges of our current and future society.

Apparently, STEM education has been extensively brought up within the worldwide landscape of educational development and reform policies in the last decades as it has been considered an innovative and multidisciplinary educational approach (Sanders, 2012; Bissaker, 2014). The approach emphasizes the focus of combining the four disciplines of science, technology, engineering, and mathematics to improve students' proficiency in math and science, but their knowledge also needs to be connected with technology and engineering (Cammaert et al., 2020). STEM instruction employs a "learner-centered" methodology to encourage students' ability for initiative, problem-solving, teamwork, and management (Stehle and Peters-Burton, 2019), and drive learners' innovation through designing and producing solutions to real-world problems (Margot and Kettler, 2019). Another essential feature is that it leverages real-world difficulties as entrance points for combining STEM disciplines (Nguyen et al., 2020). CE concept, on the other hand, has been seen as one among novel approaches to sustainable development drawn from longstanding economic and environmental paradigms which suggest the efficiency of resource use and the balance of benefits and externalities between economy, environment and society (Fitch-Roy et al., 2021). Thus, the CE is essentially a pathway to achieving SDGs. The connection between CE and SGD is shown in SDG 12 and its target 5 "By 2030, substantially reduce waste generation through prevention, reduction, recycling, and reuse." Toward the transition process to a CE and sustainable society, CE-related educational approaches and tools have been outlined by a few scholars to teach the CE in higher education institutions for transition to a CE and sustainable society (Kirchherr and Piscicelli, 2019). The CE principles are built around decreasing the consumption of raw resources and reusing and recycling materials and energy.

However, there has been very little attention on the integration of CE and STEM teaching approaches in secondary schools. Although sustainability, or sustainable development courses, have been taught at the undergraduate and graduate levels in recent years as a growing academic topic (Karatzoglou, 2013; Sedlacek, 2013; Leal Filho et al., 2019). Especially the integration of CE and STEM teaching is designed based on a problem-driven and solution-oriented foundation to address complex anthropogenic challenges. Through literature review, this paper presents a perspective on how STEM education connects science with society, the benefits of teaching CE in promoting sustainable consumption and production behaviors, and the potential integration of CE into STEM education through real-world context inquiry and real-world problem-solving. The paper also presents the case of the Vietnam context, where integration of STEM education and CE in secondary schools is crucial for moving to a circular economy toward sustainable development. It examines the teachers' perspectives on the relevance of STEM education and CE to sustainable development and their perceptions and behaviors toward integrating CE into STEM education in secondary schools toward a CE for sustainable development. The goal is to highlight the necessity of transitioning to a more innovative, interdisciplinary, and real-world context-connected secondary education for a sustainable world.

2. Literature review

2.1. The role of integrated STEM in connecting science with society for sustainability

Today's global citizens are expected to use the scientific and technological knowledge they acquire in school to address real-world problems, including environmental degradation, unpredictable climate change, and resource depletion (Nguyen et al., 2020). STEM education connects challenging academic concepts to real-world applications through an interdisciplinary approach to the teaching and learning (Bybee, 2013). Through the integration of S-T-E-M, a STEM lesson can provide students with quality socio–scientific-technical knowledge, modern digital competencies (Barragán-Sánchez et al., 2020), and their application in addressing real-world problems. It also equips learners with soft skills and competencies crucial for the workforce (Wong et al., 2016). STEM education nurtures young people with innovation abilities – an important skill for adapting to local and global changes and shaping the world.

As a curriculum and instructional approach, integrated STEM education can be helpful in secondary schools at all levels (Margot and Kettler, 2019). The pedagogical principles of STEM education are (i) the combination of knowledge of multiple STEM disciplines, (ii) inquiry through representations, (iii) problem solving and reasoning, (iv) challenge-based learning, (v) design-based, and (iv) digital technologies learning approaches (Nguyen et al., 2020). Because the current local and global concerns cannot be resolved within a single field, the integration of various STEM disciplines aims to improve young people's capacity for learning about or solving problems in the real world. Young people are prepared with interdisciplinary expertise and, with the aid of technology, the ability to assess the complexity of real-world situations as well as to establish integrated solutions by studying comprehensive integrative knowledge of STEM fields.

All science disciplines can be taught and linked with sustainable development concepts thanks to the assistance of engineering, technology, and mathematics in STEM education. This will improve learners' comprehension and roles in the implementation and attainment of the SDGs. As the global job market today demands workers with the multidisciplinary expertise and abilities to address the problems of a complex, connected, and dynamic world, integrating multiple disciplines can prepare multidisciplinary expertise. This could facilitate the young generation's employment pathway.

In addition, real-world, context-based STEM instruction also piques students' interest in solving problems in the world and enables them to see how science is relevant to their everyday lives (George and Lubben, 2002). STEM principles pertinent to these problems can be examined and applied to explain everyday situations that learners are familiar with (Lubben et al., 1996). By tackling real-world problems, students in STEM programs learn about science, math and technology and hone their critical thinking, problem-solving, and cooperation abilities (Asghar et al., 2002). The problem-based learning approach is crucial to engage students in learning about science and developing their skills in solving real-world problems through collaborative learning. In order to make sense of new knowledge, resolve challenging problems, and come up with a solution, the problem-based learning approach encourages students to build on their prior knowledge and work collaboratively (Wyness and Dalton, 2018).

Science, technology, engineering, and math education also teaches students how to tackle problems in the actual world through design learning tasks. The design-based learning approach, which uses technology, mathematical reasoning, creative design, construction engineering, and scientific investigation to solve problems in the real world, is crucial in STEM education (Zheng et al., 2020). Students are encouraged to use the inquiry and reasoning processes to produce creative products or objects and solutions when learning using design-based methods (Gómez Puente et al., 2013). The fundamental qualities of a contemporary global citizen, including systems thinking, interpersonal competence, interdisciplinary knowledge, strategic action, and management skills, are provided to students through the design-based learning (Wiek et al., 2011). Design-based learning can aid in achieving the SDGs since it starts with describing an issue from a real-world setting and creating the best solutions for social challenges (Huang et al., 2020). The entire society must, however, work together to implement the SDGs. The aim of STEM education is to provide students with a wide range of skills and interdisciplinary knowledge; as a result, cooperative learning in STEM education is crucial to the growth, dissemination, and maintenance of education's place in society. Students can greatly contribute to the implementation of SDGs such as conservation, sustainable consumption and production, and social responsibility for the development, peace, and equity through their positive behavior in the collective responsibility (Pawlowski, 1996) for the sustainable development of their community and country.

2.2. Integration of circular economy principles in integrated STEM education and the promotion of sustainable consumption and production

The issue of waste management and recycling is currently the primary challenge facing sustainable development. Domestic residences and industrial settings both produce waste. In addition to consuming a significant quantity of raw materials and resources, industrial facilities, restaurants, hotels, stores, markets, and homes all generate significant amounts of solid and liquid waste. Consumption depletes natural resources and leads to waste generation, which increases environmental pollution. In response to unsustainable resource consumption and waste management worldwide, the CE has quickly emerged as a key idea. The closed-loop economy debates of the 1970s are where the CE notions originated, and they impacted waste management and resource use regulations (Fitch-Roy et al., 2021). The original CE concepts center upon integrated waste management (IWM) and Reducing, Reusing, and Recycling (Dockery et al., 1993). The CE is extendedly defined as "an economic system that is based on business models which replace the 'end-of-life' concept with reducing, alternatively re-using, recycling and recovering materials in production/distribution and consumption processes, thus operating at the micro-level (products, companies, consumers), meso-level (eco-industrial parks) and macro-level (city, region, national and beyond), with the aim to accomplish sustainable development, which implies creating environmental quality, economic prosperity and social equity, to the benefit of current and future generations" (Kirchherr et al., 2017).

The CE, according to some scholars (e.g., Kirchherr and Piscicelli, 2019), is the novel pathway to sustainable development; thus, it must be part of school curricula and hence educational programs/policies for sustainable development. CE education is grounded on curriculum development and outcome-based learning approaches, which are mainly developed on constructivist teaching methods. For example, in EC education, some authors (e.g., Sanchez-Romaguera et al., 2016) suggested "the use of contextual, active, multidisciplinary, collaborative and cumulative approaches to learning," while others (e.g., Whalen et al., 2018) recommended experiential learning through the use of a game that supports holistic and transdisciplinary thinking for a CE. On the other hand, constructivist teaching methods such as problem-based learning approach, real-world context inquiry, design-based, and collaborative-based learning are crucial pedagogical approaches in STEM education. These instructional methods are used to integrate the four disciplines of S-T-E-M, connect science lessons to the real-world context, and apply engineering and technology to problem-solving and the production of solutions.

For this reason, STEM education offers an essential ground for integrating CE principles in designing school curricula and courses. By learning the CE through STEM education, students can make connections to real-life problems that make them more interested in learning and acting to solve problems in their daily lives. This will change students' behavior toward their environment. Through the integration of the CE principles into STEM education, students' internal representations of the real world and attitudes toward sustainable consumption can both be changed and ultimately triggers their innovation for sustainable development (Nguyen et al., 2020).

3. Vietnam case study

3.1. Vietnam context and ESD

Vietnam is a middle-income country with a population of approximately 98.168 million people in 2021. The population bomb and rapid economic growth have heavily pressured resource consumption and waste generation in Vietnam. In recent decades, the amount of raw materials produced from natural resources has increased, roughly proportionate to the nation's economic growth during the 1990s. Over the past three decades, Vietnam's per-capita material consumption has steadily increased, from less than 2 tons *per capita* in 1990 to more than 9 tons *per capita* in 2010 of domestic material consumption (Schandl et al., 2015). Consequently, waste generation in Vietnam has been increasing substantially. The annual average municipal solid waste generation in 2003 was 6,400,000 tons, but it increased almost three times in 2015, estimated to be around 30,368,000 tons annually in 2025 (MONRE).

The Vietnamese government has made many efforts to implement policies in sustainable environmental management and resource consumption. The development strategies of the Vietnamese government have highly focused on the "knowledge economy" and "green economy." Economic development, cultural and social development, environmental protection, and a proactive reaction to climate change are the main focuses of the most recent five-year socioeconomic development plan. The success of the nation's development plans, which include goals like raising workforce quality through increased science and technology capability and promoting economic restructuring with a new growth model, as well as raising productivity, efficiency, and competitiveness of the economy, has also credited been in part to STEM education and CE. The integration of STEM and CE has been made within a number of policies, such as "Sustainable Development Strategy for 2011–2020," promoting "sustainable and effective growth" that entails "social progress and equality" and "national resources and environment protection." The draft for the subsequent period 2020–2030 of the National Action Plan on Sustainable Production and Consumption up to 2020 has been made with a vision for 2030. These strategies' fundamental premise recognizes the crucial contribution of science and technology to creating the conditions and driving forces behind sustainable development. The use of cutting-edge, squeaky-clean, and environmentally friendly technologies in production is the goal of these initiatives.

Although the term 'CE' is not commonly used and addressed in legislation, the 3R CE principles have been adopted in resource efficiency and waste management practices in Vietnam, for example, the VAC model (Garden–Fishery–Husbandry) in sustainable farming, domestic waste composting, cement and concrete production from reusing fly ash and slag from thermal power plants, waste segregation, and treatment, etc. State and non-state actors have both worked to promote CE. Some CE programs have been supported by the private sector, such as "Zero Waste to Nature" by the Vietnam Chamber of Commerce and Industry in partnership with Unilever Vietnam, Coca-Cola Vietnam, and Dow Chemicals to increase student, community, local government, and private trash collector awareness of waste segregation, and a circular system of plastic waste management established by the public-private partnership between MONRE and these same private companies.

The promotion of the CE understanding and practices relies very much on education and awareness-raising as well as technology and innovation; thus, the role of education is crucial to the transition to a circular economy toward sustainable development in Vietnam. The Vietnamese government established the educational development policy for 2011–2020, concentrating on improving the teaching of law, foreign languages, life skills, and information technology, as well as intellectual and moral values. The national panorama of educational policies and changes has included STEM education heavily as well. The goal is to give students the knowledge, technical expertise in STEM subjects, and 21st-century abilities, including collaboration, critical thinking, and creativity. In the last 3 years, a STEM program has been implemented as part of the Second Secondary Education Sector Development Program II (SESDPII), which was started by the Ministry of Education and Training and funded by the Asian Development Bank. Its goal is to prepare the labor force and economy for Industry 4.0. Other STEM programs are developed through collaborations between governmental and non-governmental organizations, such as the STEM Alliance, a team of researchers, university professors, and private businesses dedicated to STEM education. The primary target audience for STEM Alliance's robotics and coding education programs is private secondary schools.

3.2. Vietnamese secondary education teachers' perceptions and behaviors toward the relevance of CE in STEM education

This study has examined STEM teachers' perceptions and behaviors toward integrating CE concepts into STEM teaching at secondary schools. Vietnam is an instrumental case representing a country that generates rapid economic growth from inefficient resource use and consequently encounters serious negative environmental impacts and waste management problems. The participants in the study were the trainees of integrated STEM training organized by the Vietnam Ministry of Education and Training under the Second Secondary Education Sector Development Program (SESDP II) in 2019, funded by the Asian Development Bank (ADB).

The study was conducted through three stages. Firstly, 635 teachers who participated in the four integrated STEM training sessions in the Highlands, Central, and Northern regions of Vietnam were requested to list down the main development challenges in

Vietnam that they wanted to address through their STEM teaching projects/topics. Open-ended questions were used to give respondents a chance to express freely their interests in teaching topics that could contribute to sustainable development. Secondly, 238 teachers who participated in the other three integrated STEM training sessions in the North, Center, and South of Vietnam were surveyed to gauge their understanding of the CE and attitudes toward it through a questionnaire. The first question focuses on CE knowledge regarding CE principles such as natural resource conservation, waste value enhancement, correct producer and consumer behavior, eco-product design, sustainable waste management, product life cycle enhancement, fossil fuel, and renewable energy use, the hierarchy of 3R (Reduce, Reuse, and Recycle). Correct answers received a score of "1," wrong answers a score of "−1," and "unsure" answers a score of "0" in terms of knowing the CE concepts. The second survey question was whether the respondents agreed on the relevance of CE to STEM teaching, to the local context, and the importance and interestingness of CE. Teachers' responses were graded on a Likert scale ranging from 1 to 5.

In addition, the questionnaire in the second stage was followed by 54 semi-structured interviews to examine teachers' perspectives on the CE further, and their relevant teaching experiences were gleaned *via* open-ended questions. Eighteen teachers, from each training location which made a total of 54, were approached randomly and asked for their voluntary participation in a short interview of 15 min during the break time. Lastly, 77 STEM teaching project proposals of teachers across the country submitted to the SESDP II were also examined. The analysis of these projects focused on the main teaching STEM topics, and pedagogical methods were proposed.

3.2.1. Top development issues indicated by secondary education teachers for teaching integrated STEM

Most of the development issues indicated by the 635 teachers in the first survey are relevant to CE (Figure 1). 82.8% of the 635 teachers who participated in the first survey said that to improve their students' environmental literacy, appreciation for environmental protection, and comprehension of the tools and procedures needed to monitor and analyze the environment; they preferred to incorporate the topic of environmental pollution into their STEM projects and classes. The creation of sustainable daily goods and objects, material recycling, and the promotion of renewable energy and water sources are other significant development concerns (69.7, 73.5, and 53.4%, respectively). These teachers found STEM education vital as it enhances the responsibilities and the significance of secondary schools in solving the nation's current development concerns, which helped achieve the SDGs.

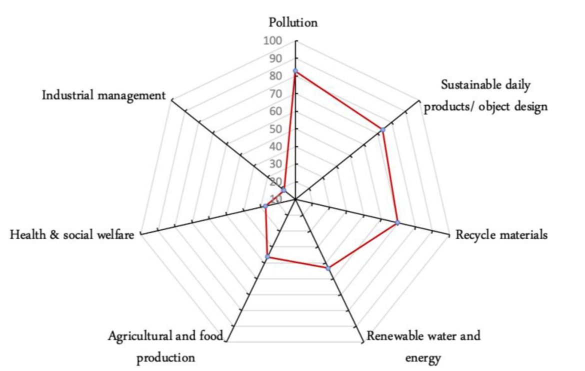

FIGURE 1
Top development issues to be used in the STEM lectures of the surveyed teachers. % Responses were counted based on the topics listed by the surveyed teachers. (N = 633).

3.2.2. The CE knowledge of the secondary education teacher

Many teachers who responded to the 2nd survey agreed that it is crucial to incorporate the idea of sustainable production and consumption into the curriculum to ensure that natural resources are used wisely; that less harm is done to the environment. Their understanding of the CE was evaluated by a series of questions on the CE's principles, to which they responded with "right" or "wrong" responses or "unsure" if they were unsure of the proper response. The average knowledge score was then determined by adding all the responses with incorrect answers given a value of −1, correct answers with a value of 1, and uncertain responses with a value of 0. The teachers' CE principles relevant knowledge of "natural resource conservation," "waste value enhancement," and "correct producer and consumer behavior" is exceptionally high, with ratings of 0.92, 0.9, and 0.9, respectively. "Eco-product design,' sustainable waste management," "product life cycle enhancement," and "fossil fuel and renewable energy use" were also highly known as relevant to the CE, which ranged from 0.82, 0.78, 0.76, and 0.74. However, the surveyed teachers did not know the hierarchy of 3R waste management actions (Reduce, Reuse, and Recycle). It was acknowledged in the literature that of the "3Rs," Reduce was the most important, followed by Reuse and Recycle, in the hierarchical structure for waste management; however, the study's teachers showed little knowledge of the subject (Figure 2). In further interviews, a few teachers also said they had never heard of "CE" or "sustainable production and consumption" terms.

3.2.3. Experiences of integration of CE concepts in STEM teaching of secondary education teachers

The analysis of 77 STEM teaching projects submitted by teachers who participated in integrated STEM training provided by SESDPII showed that many secondary education teachers have voluntarily integrated the CE concept into their STEM projects and lessons using several constructivist pedagogical methods to connect science with the real context problem (Figures 3, 4). 31.17% of projects focused on sustainable consumption and production, in which sustainable daily products and artifacts design (21%), waste management, and material recycling (10%). Sustainable water, food, and energy were also the 2nd theme that 29.87% of projects focused on. Pure scientific theory, inquiry, environment, climate, and health and education were less focused on the projects. Several constructivist pedagogical methods were used, including inquiry and experimental-based learning (24.68%), problem and collaborative-based learning (18.18%), and problem, inquiry-based learning (11.69%) and design-based learning (10.38%). For example, inquiry, experimental- and design-based learning approaches were applied to illustrate water pollution, and

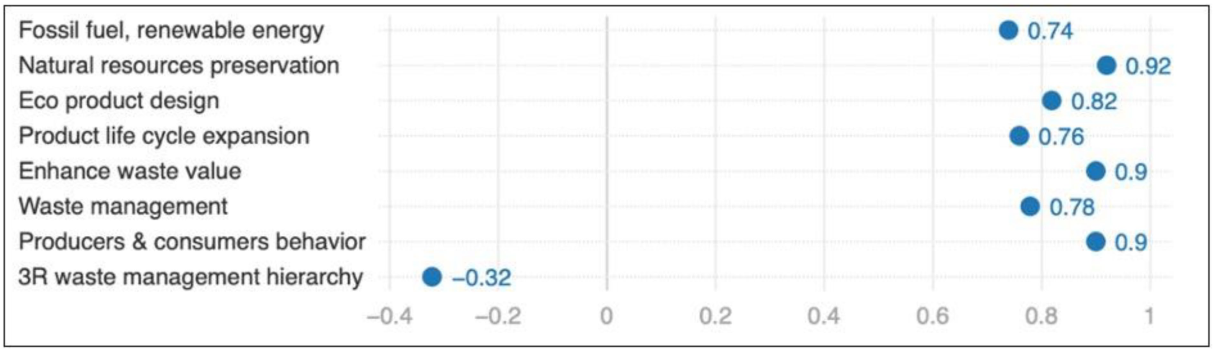

FIGURE 2
Teachers' CE knowledge. The average knowledge score ranges from −1 (low) to 1 (high) calculated by adding up all responses with wrong answers=−1, right answer=1, unsure=0. The value of 1 is considered a full understanding of the CE concepts. *N*=238.

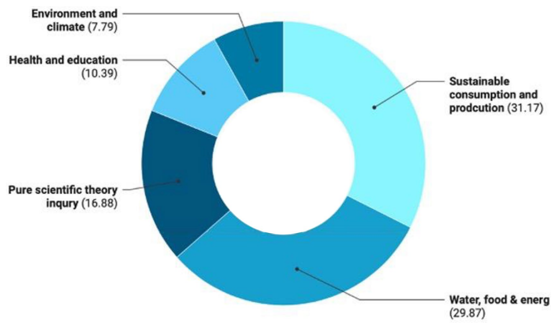

FIGURE 3
Themes of STEM teaching projects were developed by the surveyed teachers. The percentage is calculated using a total of 77 projects.

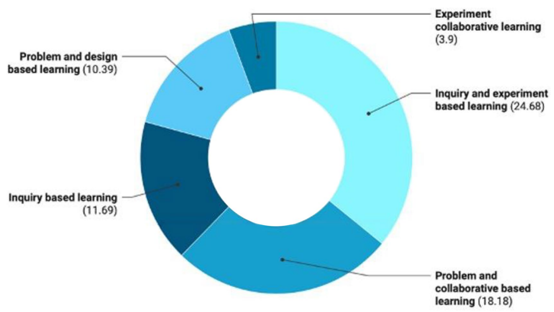

FIGURE 4
Constructivist pedagogical methods deployed in teaching STEM lessons. The percentage is calculated using a total of 77 projects.

design water filter or design-based learning was used to teach the designing a sprayer from recycled materials, or inquiry, experimental- and design-based learning for teaching and designing electricity circuit using bioenergy from fruits and vegetables. This real-world context-based inquiry would help students see the relevance of science to their daily lives, and the design-based learning approach is used to solve real-world problems. The collaborative-based learning approach would develop students' positive behavior in collective responsibility for the sustainable development of their society.

In addition, through the interviews, many teachers expressed their experiences in integrating the CE concepts, including collaborative skills through STEM education; students develop their positive behavior in collective responsibility for the sustainable development of their country in their science classes, as some Chemistry teachers shared *"Each unit of the Chemistry curriculum has a section labeled Application. There is information about CO2 gases and SO2 gases in the chapter on oxygen and sulfur. I made sure to include information about environmental concerns in these courses… I assigned the students the task of putting together a presentation on an environmental issue. They presented and engaged in a discussion."* Or *"I teach Chemistry so in my subject there are sections related to the environment, … for example, the polymer […] I showed students a video in which a flock of birds died when migrating because of plastic waste […] I let students explore the environment around them and feel and think about our impacts on the environment. If we use one nylon bag daily, what will happen 10, 15, and 45 years later?"*

Some other teachers revealed that they had included CE ideas in their STEM teachings, including manufacturing, pollution, waste segregation, material selection, recycling, and energy. For example, some biology teachers stated, *"I had a lesson in which I taught students to make products from different materials. Product ideas come from students, and they must explain why they chose those ideas. Concerning waste, I asked students to segregate."* Or *"I taught students to dispose of trash appropriately such as organic fruit skin, recyclable and non-recyclable trash," or "I taught students to] make new products from the trash. Students can make cards from the trash."* CE was taught in various ways, including lectures, presentations, debates, and field trips; as technology expressed, *"students had excursions to observe the waste station and the landfilling process."*

3.2.4. Teachers' attitudes toward integrating CE in integrated STEM teaching

Surveyed teachers had positive attitudes toward integrating CE into STEM education. They tended to agree that CE concepts are highly relevant to integrated STEM, to the Vietnamese context, and it was important and interesting in integration into STEM education. Kruskal–Wallis test shows that there is no difference in teachers' attitudes among the three groups of subject teachers. However, although more science teachers found the CE concepts relevant to

TABLE 1 Surveyed teachers' attitudes toward integrating CE in STEM teaching.

	Mean±SD				*H*-statistic	Value of *p*
	Overall	Math	Science	Technology		
Attitudes	4.11 ± 0.52	4.02 ± 0.59	4.29 ± 0.60	4.18 ± 0.55	3.15	0.207
Relevance to STEM	4.21 ± 0.59	4.25 ± 0.56	4.24 ± 0.56	4.16 ± 0.64	0.74	0.691
Relevance to context	4.00 ± 0.68	3.86 ± 0.73	4.06 ± 0.70	3.97 ± 0.61	2.403	0.301
Importance	4.18 ± 0.61	4.09 ± 0.63	4.25 ± 0.62	4.11 ± 0.58	4.212	0.122
Interestingness	4.06 ± 0.60	3.90 ± 0.58	4.13 ± 0.57	4.02 ± 0.65	4.391	0.111

Mean calculated from 5 Likert scale responses 1 = strongly disagree, 2 = disagree, 3 = neutral, 4 = agree, 5 = strongly agree ($N = 238$).

STEM teaching, to the Vietnamese context, and important and interesting to teach in science classes, math, and technology, teachers also showed positive attitudes toward teaching the CE in integrated STEM (Table 1).

However, during the interviews, some barriers were expressed by the teachers that might constrain their voluntary of combining CE and STEM teaching. The knowledge of the CE principles and practices is the first barrier; as some teachers explained, "*these concepts of CE are very difficult*." Or "*The barrier is the interdisciplinary knowledge. We must learn knowledge of many subjects, and it takes time*." Or "*How can I connect these subjects? I still do not know how*." The lack of collaboration among teachers, the rigid school curriculum and textbook-based exam models, and the lack of managers' support in incorporating CE in STEM education are other barriers stated by the surveyed teachers. Low interest and capacity of students is also a problem in encouraging teachers to be innovative and creative in their daily teaching. This is because of past and current discipline or subject-centered conventional teaching approaches and lack of demonstration with real-world experiences. Inadequate facilities in disadvantaged regions also hammer the teachers' interest in teaching STEM by integrating CE concepts.

4. Discussion

The study showed integrated STEM method, which combines design-based learning and context-based real-world inquiry, helps change the old didactic triangle—teacher, student, content (Lubben et al., 1996) —that many secondary schools in Vietnam utilized to indoctrinate passive students and open opportunities for teachers to integrate the development issues and CE principles and practices in their everyday teaching in secondary education. Teachers in this study have already voluntarily integrated the CE principles into STEM teaching, which has created a great opportunity to promote the integration of CE into STEM education in secondary schools. Although there was a lack of familiarity with the CE principles and their link to taking a whole picture of a CE, certain CE concepts and principles were taught by surveyed teachers in isolation within the context of environmental education and STEM projects and lessons. Thanks to integrated STEM thinking and systems thinking, teachers created STEM modules and lessons geared at development concerns and CE principles with a sense of excitement, understanding the challenges through the eyes of someone who was confronting them. Students were given the opportunity to participate in science and technology, play agentive roles in reshaping their individual and communal futures, and contribute to long-term sustainability.

Teaching CE in integrated STEM using constructivist pedagogical methods encourages the "learning by doing" of students through real-life lessons (Kong, 2021). As they learn about "touch" and experiment with real-world problems as part of the learning process, it boosts students' motivation to address real-world challenges, the cornerstones of social change. This approach would have changed the way that many public and private schools in Vietnam taught, as they had previously depended on a teacher-centered, textbook-based method that precluded students from gaining from contextualized learning (Nguyen and Nguyen, 2008). The study showed that the secondary surveyed teachers were aware of the developmental challenges they face; thus, among the most common themes that teachers incorporated in their STEM modules or intended to teach in their STEM lectures were sustainable consumption and production and water–food-energy sustainability.

However, barriers to collaboration among disciplines since secondary education are characterized by discipline division and specializations, and inadequate general CE and subject-based knowledge of teachers could be the challenges of integrating the CE into STEM teaching. The disconnection between the school and the community, as well as other private and public sectors, could pose another obstacle to the integration of CE into STEM education. This could constrain the bridging of community-based knowledge and school-based knowledge (Bouillion and Gomez, 2001) and the provision of intellectual and meaningful science learning through practical experience of CE-related STEM teaching.

5. Conclusion

The study finding shows the high-level perception of secondary school teachers in Vietnam on the relevance of CE with STEM teaching, the Vietnam context, its interestingness, and the importance of integrating CE into STEM education. It also reports teachers' unconscious application of CE principles in their daily STEM teaching activities and their willingness to teach CE demonstrated through their STEM projects. As the key agents in advancing CE-related STEM education, teachers must get professional development that gives equal weight to improving their scientific and CE knowledge as well as training them on how to incorporate CE into STEM lectures, curriculum development, and pedagogical procedures. This study suggests that including CE in STEM education is part of a "breadth and depth" educational strategy. A "breadth and depth" educational strategy encourages teachers to cross disciplinary lines while sticking to their specialty. Although it prepares students for work in frontier disciplines, it is still essential for them to develop a thorough understanding of their primary field. This research illuminated that integrating CE in STEM education would aid students in developing their abilities and knowledge while also altering their behavior on contemporary real-world issues. The strategy promotes using a transdisciplinary approach and contextual scaffolding to link science with community and connects community knowledge with school-based knowledge. Therefore, Including CE in STEM education in secondary education offers a promising opportunity to foster more profound societal change toward sustainable development, which contributes to SDG4 — equitable and quality education for sustainable development and sustainable lifestyles and SDG 12.5 — reduce waste generation through prevention, reduction, recycling, and reuse.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

TN conceptualized, designed the research, analyzed the data, drafted and edited the manuscript. The author contributed to the article and approved the submitted version.

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Conflict of interest

The author declares that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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The teaching of physics at upper secondary school level: A comparative study between Indonesia and Ireland

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This study aims to investigate the teaching approaches taken by physics teachers in Indonesia and Ireland when teaching a module on Medical Physics in the classroom. Additionally, students' attitudes to the module on Medical Physics were also explored. In particular, the views of these teachers toward inquiry based science education (IBSE) and direct instruction (DI) when implementing this module with students in the 14–16 age group were examined. Data were collected to investigate how teachers in the two countries used combinations of the IBSE and DI teaching approaches when teaching the module to their students. Arising out of the implementation of the module, it was hoped that the module would serve as a "hook" to interest students in physics by teaching topics in physics *via* real-life applications of physics. Thus, the attitudes of the students toward science on completion of the module were assessed. A total of 15 schools in Indonesia (402 students) and 15 schools in Ireland (263 students) participated in the project. Data were collected from the teachers and students using questionnaires. Among the findings were that while teachers in Ireland were unanimous in their agreement with the inclusion of IBSE activities in the lesson plans supplied, only 67% of the teachers in Indonesia agreed with the inclusion of these activities in the module. There was a strong relationship between the type of school and the students' attitude toward the module. Students in the more academic type schools in both Ireland and Indonesia were less positive about the module. Among the problems highlighted by teachers in Indonesia was the lack of laboratory facilities. Also, students in both countries commented on the problems with terminology and literacy in general when studying physics. While the module brought out a positive response from students convincing them to continue with their study of physics at the upper secondary school level.

KEYWORDS
attitude toward science, direct instruction, inquiry based science education, medical physics, comparative study

1. Introduction

In the 2012 program for international student assessment (PISA) test results, it was found that of the 65 countries that participated in the test, Indonesia ranked 60th in literacy skills, and 64th in mathematics and science (OECD, 2014). A similar pattern was observed for Indonesia in the PISA 2009 results. On the contrary, Ireland has seen considerable improvement in recent years where it is now ranked ninth out of 65 OECD countries for science, fourth out of 65 countries for reading, and 13th of the 65 OECD countries for mathematics (OECD, 2014). Arising these results, it was felt appropriate to carry out a comparative study between the two countries in order to investigate the issues involved in teaching science in very different environments.

In comparing the teaching approaches adopted by teachers in the two countries, it was decided to investigate the different approaches to teaching physics using either an inquiry based inquiry based science education (IBSE) approach or a direct instruction (DI) approach. When discussing these contrasting teaching approaches, the inquiry-based approach is often described in terms of being student-centered [Sweitzer and Anderson, 1983; American Association for the Advancement of Science (AAAS), 1990; National Research Council (NRC), 1996, 2000; Alberts, 2008; Juntunen and Aksela, 2013; Jiang and McComas, 2015]. On the contrary, the direct instruction approach is often described in terms of a teacher-centered approach (McKeen, 1972; Peterson, 1979; Becher, 1980; Rosenshine, 1995; Cobern et al., 2010). However, as will be discussed in this paper, these two categories of IBSE and DI are part of a continuum or spectrum of teaching approaches. Some authors represent DI in terms of a traditional classroom setting where students are perceived as sitting in straight rows of desks and learning through rote memorization (Brown et al., 1982; Borko and Wildman, 1986; Brooks and Brooks, 1999). In this scenario, students are described as attentively listening to the teacher standing in front of the class to impart information and compliantly taking notes without necessarily interacting with the topic being taught. Direct instruction should not be confused with didactic teaching. Hattie (2009) discusses in detail the main characteristics of direct instruction and outlines them in terms of seven major steps as outlined in Table 1 (Hattie, 2009, pp.205–206).

It is the above description of direct instruction that was adopted in this study, and which may be summarized as follows:

> "In a nutshell: The teacher decides the learning intentions and success criteria, makes them transparent to the students, demonstrates them by modeling, evaluates if they understand what they have been told by checking for understanding, and re-telling them what they have been told by tying it all together with closure" (Hattie, 2009, p. 206).

The inquiry based science education approach is described as "*the art of developing challenging situations in which students are asked to observe and question phenomena; pose explanations of what they observe; devise and conduct experiments in which data are collected to support or contradict their theories; analyze data; draw conclusions from experimental data; design and build models; or any combination of these*" (Hattie, 2009).

In the IBSE approach, students are described as being actively involved in their own learning with the teacher using student investigations and discussions to challenge the students to think about the work being undertaken.

Many teachers will recognize the above descriptions as being at the extreme ends of the spectrum of teaching approaches and may see themselves as using various aspects of the two approaches in their everyday teaching to achieve the learning outcomes of the lesson. In this paper, we will investigate and discuss how teachers in Indonesia and Ireland used combinations of the IBSE and DI teaching approaches when teaching a module on Medical Physics to their students. Arising the implementation of the Medical Physics module, it is hoped that more students will be encouraged to undertake the study of physics at the senior high school level.

TABLE 1 The seven major steps involved in direct instruction (DI; Hattie, 2009).

Direct instruction involves seven major steps:
1. Before the lesson is prepared, the teacher should have a clear idea of what the *learning intentions* are. What, specifically, should the student be able to do, understand, care about as a result of the teaching?
2. The teacher needs to know what *success criteria* of performance are to be expected and when and what students will be held accountable for from the lesson/activity. The students need to be informed about the standard of performance.
3. There is need to *build commitment and engagement* in the learning task. In the terminology of direct instruction, this is sometimes called a "hook" to grab a student's attention. The aim is to put students into a receptive frame of mind; to focus student attention on the lesson; to share the learning intentions.
4. There are guides to *how the teacher should present the lesson*—including notions such as input, modeling, and checking for understanding. Input refers to providing information needed for students to gain the knowledge or skill through lecture, film, tape, video, pictures, and so on. Modeling is where the teacher shows students examples of what is expected as an end product of their work. The critical aspects are explained through labeling, categorizing, and comparing to exemplars of what is desired. Checking for understanding involves monitoring whether students have "got it" before proceeding, it is essential that students practice *doing it right,* so the teacher must know that students understand before they start to practice. If there is any doubt that the class has not understood, the concept or skill should be re-taught before the practice begins.
5. There is the notion of *guided practice*. This involves an opportunity for each student to demonstrate his or her grasp of new learning by working through an activity to exercise under the teacher's direct supervision. The teacher moves around the room to determine the level of mastery and to provide feedback and individual remediation as needed.
6. There is the *closure* part of the lesson. Closure involves those actions or statements by a teacher that are designed to bring a lesson presentation to an appropriate conclusion; the part wherein students are helped to bring things together in their own minds, to make sense out of what has just been taught. "Any questions? No. OK let us move on" is not closure. Closure is used to cue students to the fact that they have arrived at an important point in the lesson or the end of a lesson, to help organize student learning, to help form a coherent picture, to consolidate, eliminate confusion and frustration, and so on, and to reinforce the major points to be learned. Thus, closure involves reviewing and clarifying the key points of a lesson, tying them together into a coherent whole, ensuring they will be applied by the student by ensuring they have become part of the student's conceptual network.
7. There is *independent practice*. Once students have mastered the content or skill, it is time to provide for reinforcement practice. It is provided on a repeating schedule so that the learning is not forgotten. It may be homework or group or individual work in class. It is important to note that this practice can provide for decontextualisation: enough different contexts so that the skill or concept in which it was originally learned. For example, if the lesson is about inference from reading a passage about dinosaurs, the practice should be about inference from reading about another topic such as whales. The advocates of direct instruction argue that the failure to do this seventh step is responsible for most student failure to be able to apply something learned.

Thus, we first consider some aspects of students' attitude toward physics as a subject and then investigate the effect that the intervention package had on the attitude toward physics of the participating students.

1.1. Students' attitude toward physics in school science

The study of students' attitudes toward science is not a new topic in science education. For almost 50 years, hundreds of journal papers as well as reviews (Gardner, 1975; Schibeci, 1984; Simpson and Oliver, 1990; Crawley and Koballa, 1994; Osborne et al., 2003; Koballa and Glynn, 2007; Hofstein and Mamlok-Naaman, 2011; Bennett et al., 2013; Ültay et al., 2017, 2021; Ültay and Alev, 2017a,b) and dissertations have been published at international level in the area of students' attitudes toward science.

The concept of an attitude toward science is somewhat nebulous, often poorly articulated and not well understood (Osborne and Dillon, 2008). Considerable clarity was brought to the topic in the PISA 2012 project since when discussing the results of this project (PISA 2013) the area of students' attitudes toward science was discussed under four main headings:

a. Support for scientific inquiry, i.e., do students value scientific ways of gathering evidence, thinking logically, and communicating conclusions?
b. Self-belief as science students, i.e., what are students' appraisals of their own abilities in science?
c. Interest in science, i.e., are students interested in science-related social issues, are they willing to acquire scientific knowledge and skills, and do they consider science-related careers?
d. Responsibility toward resources and environments. Are students concerned about environmental issues?

It is in part (c) above that the focus of this research took place, i.e., looking at the challenges involved in trying to improve students' attitudes toward science and increasing their interest in science. At the international level, the falling numbers choosing to pursue the study of physics at senior high school level (OECD, 2014) are mirrored in Indonesia and Ireland (Kompas, 2013; Hyland, 2014).

Enhancing a positive attitude toward science lessons is essential for two reasons: (a) students' attitudes and their academic performance are closely related and (b) attitudes may be used to forecast students' behavior in encouraging them to choose to continue with their study of physics (Glasman and Albarracín, 2006; Cheung, 2009). The subject of Physics presents particular difficulties for students as they encounter problems related to the use of mathematical equations and the manipulation of mathematical data (Angell et al., 2004; Ornek et al., 2007; Collins, 2011). This results in many concepts and principles of physics being difficult to understand. Hence, the interest of students in studying physics is adversely affected.

Of the several factors that can affect students' interest in science, especially in the area of Physics, the approach to teaching that is adopted by the teacher is one of fundamental importance (Wellington and Ireson, 2008). We now focus this approach in terms of the two main sub-divisions, i.e., inquiry-based science education and direct instruction.

1.2. The balance of inquiry-based science education and direct instruction

As previously mentioned, some authors have put forward the idea that direct instruction represents an undesirable form of teaching and interpret the term "direct instruction" as didactic teaching. Direct instruction has been described as "authoritarian" (McKeen, 1972), "regimented" (Borko and Wildman, 1986), "fact accumulation at the expense of thinking skill development" (Edwards, 1981), and "focusing upon tests" (Nicholls, 1989). Direct instruction has also been portrayed as a "passive" mode of teaching (Becher, 1980). Direct instruction has been described as the "pouring of information from one container, the teacher's head, to another container, the student's head" (Brown and Campione, 1990). All of these critics of direct instruction are proposing that teachers use forms of "student-centered" or activity-based instruction in place of direct instruction.

Many educators feel that inquiry instruction rather than direct instruction is mostly in keeping with the widely accepted constructivist theory of how people learn, i.e., that meaningful knowledge cannot simply be transmitted and absorbed but learners have to construct their own understanding (Anderson 2002; Cobern et al., 2010). Some studies have found a positive effect of IBSE [e.g., Bredderman, 1985; National Research Council (NRC), 1996, 2000, 2005; Donnelly et al., 2014; Ireland et al., 2014]. Other researchers have found a negative effect of IBSE, e.g., Buntern et al. (2014) argued that IBSE leads to high cognitive load and is thus not effective in the classroom. On another side, Arnold et al. (2014) argue that direct instruction cannot embrace the complex nature of scientific reasoning in an authentic fashion (Chinn and Malhotra, 2002) nor is it consistent with the constructivist views of learning (Hmelo-Silver et al., 2007). One of the big challenges facing teachers is in deciding when to use IBSE, when to give support and when to hold back information in order to maintain authentic inquiry settings, especially in upper secondary school (Crawford, 2000; Furtak, 2007). Wiggin and McTighe call it the dilemma of "direct instruction versus constructivist approach" (Wiggins and McTighe, 2005).

Educators have been indoctrinated with the mantra "constructivism good, direct instruction bad" (Hattie, 2009). Colburn (2000) stated perhaps that one source of confusion about inquiry based science education is that it is only for "advanced" students. This is a misconception as all students can achieve success if teachers guide them toward understanding by implementing different activities in the classrooms. However, there are many times when inquiry-based science education may be less advantageous than other methods. It depends on our experiences as teachers to find the right balance between inquiry and non-inquiry methods that engages our students in their study of science (Gagne, 1963). In addition, Kennedy (2013) argues that "one of the clear outcomes from the research literature is that IBSE approaches to science teaching do result in an increase in the interest levels of students in sciences. Based on the research evidence outlined in this paper, it does not seem wise to "put all our eggs in one basket" and promote IBSE as the only approach to effective science teaching. We need to get the right balance between the direct instruction and approach and the IBSE approach" (Kennedy, 2013).

In most cases, it may be best for teachers to use a combination of approaches to ensure that the needs of all students in terms of knowledge, understanding, skills, attitudes, values, scientific literacy, and overall interest in science and science-related topics are met. The

TABLE 2 Advantages and disadvantages of inquiry based science education (IBSE).

Advantages of IBSE	Disadvantages of IBSE
Students learn best when they take an active role and practice what they have learned (Smart and Csapo, 2007). It is very important that in order to facilitate inquiry-based learning, the teacher make simple changes and organize the classroom in a way so he/she could manage transition and gain attention as the children use hands-on investigative activities, use of science journals, use of group-based activities, and guided studies students to reflect on their learning process.	Many teachers experience interactional difficulty with their students. Teachers also face lots of difficulties in channeling and maintaining the interest of students as they engage themselves in inquiry activities and try to derive appropriate conclusions about nature (Bencze, 2009)
Theorists such as John Dewey believed that inquiry-based scientific approach could improve education. Children can also use their natural activity and curiosity when learning about a new concept (Vandervoort, 1983; Dewey, 2008).	Many science teachers are unprepared for the social demands of this of type of strategy (Oliveria, 2009).
Inquiry method of teaching requires taking into consideration the psychological needs of the child rather than introducing science as a logical coherent subject (Eshach, 1997; Henderson and David, 2007).	Careful planning and preparation is also required for adequate content information to be imparted to students, which makes it difficult for some science topic to be taught using the inquiry method (Robertson, 2007).
Piaget, believes that as the child grows and his/her brain experiences intellectual development and he/she starts to construct mental structures through his interaction with the environment (Lawson and Renner, 1975).	Science being a vast accumulation of discoveries must be transmitted through books, charts, tables etc. Therefore, a great deal of science content must be taught and education cannot possibly fulfill its obligation by simply arranging for rediscovery (Skinner, 1987).
	Inquiry teaching methods does not provide for much adult support. The child always needs the support of an adult (Beliavsky, 2006).

advantages and disadvantages of IBSE as outlined in the literature are summarized in Table 2.

The advantages and disadvantages of direct instruction as outlined in the literature are summarized in Table 3.

1.3. Overview of the medical physics intervention package

The Medical Physics module used in this research was designed to encourage an interest in physics among young students through a relevant hands-on interactive learning experience using many real life examples. The module offers an introduction to medical physics through investigative and cooperative learning experiences.

TABLE 3 Advantages and disadvantages of direct instruction (DI).

Advantages of DI	Disadvantages of DI
Many teachers prefer to use direct instruction methodology because it is structured and can be assessed with validity. Many researchers advocate direct instructions so children can have planned experience in science rather than incidental experiences as with inquiry method (Mason, 1963).	It is possible for students to forget facts if rote memorization is a method of imparting information. Dewey was disturbed to see rote memorization and mechanical routine practices in science classroom (Vandervoort, 1983).
Teachers prefer to use direct instructions because this is the most organized way of teaching (Qablan et al., 2009).	The danger with this practice is that there is no foundation of knowledge built which the students can draw from in the event that he/she forgets the memorized knowledge. Their process skills and abilities to make judgment would not have been significantly developed (Vandervoort, 1983; Wang and Staver, 1995).
Teachers find it hard to keep students motivating as they are left by themselves to acquire knowledge through inquiry-based learning (Bencze, 2009).	With direct instruction, the teacher poses the problem and may then solves it without giving the students an opportunity to discover. Therefore the child is not given an opportunity to use the necessary process skills (Ray, 1961).
Children receive more guidance as teachers make sure that students have understood the step before moving on to the next (Skinner, 1987).	Teachers who do not possess a major understanding of scientific principles can find it difficult to teach using the direct method of instruction. It is therefore advisable that the use of the inquiry method instead of the direct instruction method in the elementary school should be emphasized (Chiapetta and Collette, 1973). However, in using IBSE teachers need to have a good foundation in subject content in order to answer the many questions that arises.
It is also considered the best teaching method for learning content and new skills. Robertson made a very important point in his article that not every science topic can be taught using the inquiry method (Robertson, 2007).	
This method is accepted and promoted in many cultures and languages (Lee, 2002).	

The module is divided into five units (X-Rays, Ultrasound, Endoscopy, MRI & CT Scans, and Radioactivity) with the objectives of each units clearly stated at the beginning of each unit. Each unit focuses on basic physics concepts presented in a logical sequence with learning outcomes stated at the end of each unit. The Medical Physics module is designed to challenge and motivate students. Whereas each lesson can be taught in a single class

(40 min), it is recommended that, if possible a double lesson (80–90 min) be devoted to each lesson in order to allow time for discussion and other activities.

The module encourages a teaching approach involving a balance between inquiry based science education and direct instruction approaches. These approaches are encouraged by the inclusion of a detailed Teacher's Guide and a wide variety of student activities to encourage IBSE. Practical work activities are included throughout the module. These practical activities are used to model scientific principles as applied to medical physics. Expert Group Tasks are included in the module and are designed to encourage IBSE. The students work collaboratively and prepare presentations for the rest of the class. In addition this module is designed for teaching using an integrated IBSE-DI approach in each lesson.

2. Methods

This study involved a case study comparative research approach using qualitative method. Also, some aspects of action research were involved as feedback from the schools involved in the implementation of the module was used to incorporate modifications in the module for implementation with schools that will participate in future trials. Due the fact that the main language of the target sample is both native English speakers and native Indonesian speakers, the teaching package was translated from English into Indonesian by the researcher. A total of 34 teachers received in-service training on the module. Of these, 15 schools in Indonesia and 15 schools in Ireland were selected to participate in the project using random sampling. In Indonesia, the researcher took samples from three different school types, i.e., Madrasah secondary schools which are equivalent to the voluntary schools in Ireland, general secondary schools in Indonesia which are equivalent to community/comprehensive schools in Ireland, and vocational secondary schools in Indonesia which are equivalent to Education and Training Board (ETB) schools in Ireland. Circulars were distributed to schools and teachers were invited to attend training workshops to familiarize them with the teaching package. Trialing was carried out by seven schools in each country, and this helped to "fine-tune" the teaching package. No major modifications were necessary.

In general, there were over 5.1 million secondary school pupils enrolled in Indonesia. 26,000 secondary schools exist. The Ministry of Education and Culture oversees 84% of these schools, and the Ministry of Religious Affairs oversees the remaining 16%. In Indonesia, high school lasts 3 years to complete. Indonesians have access to pre-professional and vocational high schools in addition to traditional high schools. In Indonesia, attending elementary through high school is required (Pambudi and Harjanto, 2020; Setiawan, 2020). In comparison, there are roughly 395,611 secondary school students in 3,968 secondary schools in Ireland. Dublin is the largest province, accounting for 18% of the market (706 Secondary schools). With 428 secondary schools (11%), Cork comes in second. Galway also has 233 secondary schools, which is a lot. Together, these three provinces account for 34% of the market for Irish secondary schools (Coolahan, 1995).

For this study purposes, a total of 402 students in the 14–16 age group from Indonesia and 263 students from Ireland participated randomly. The smaller number of students in Ireland was due to the fact that many transition year students (age 15–16) were involved in work experiences programs and therefore were unable to participate in the project. Teachers were supplied with the module as a teaching package and were given complete freedom in how they wished to implement it in the classroom. Questionnaires were issued for completion by teachers and students. In this study, all questionnaires were distributed to the teachers in in-service training courses and returned to the researcher *via* the postal system. The response rate was 100%. The data were analyzed using quantitatively and qualitatively. Triangulation was carried out by comparing data obtained from the students about each lesson with descriptions from teachers on how they taught the lesson.

3. Result and discussion

3.1. Response of teachers to the medical physics intervention package

The questionnaire issued to teachers ranged over a number of areas, e.g., type of school, size of the school, subject specialism in degree, teaching experience, gender, time spent implementing the intervention package, the assistance obtained from level of detail in objectives, learning outcomes and lesson plans, and the Teacher's Guide. Teachers were asked about their use of IBSE and DI when implementing the intervention package in the classroom. In this paper, we concentrate on the teachers' responses to the questions relating to IBSE and DI.

When the Irish science teachers were asked their opinion about the inclusion of inquiry based science education activities in each of the lesson plans provided, all of the teachers (100%) agreed that it was a good idea to include these activities. Typical responses were:

- *Yes, IBSE results in greater student engagement.*
- *Allowed students the opportunity to think/reflect on their own knowledge.*
- *Inquiry based science education is an advanced approach. Students questioning, researching, thus enhancing their communication skills; solving problems or creating solutions. Also encourages student "thinking" visible to the center of the learning. So, it is a good idea to included IBSE activities.*

This result compares with Indonesian teachers' responses where only 67% of the science teachers had a positive response to the inclusion of IBSE activities in the lesson plans provided. Interestingly, 33% of science teachers argued that it wasn't a good idea to put IBSE activities in the learning process.

> *This approach is designed for students of high ability; most science teachers have difficulties implementing this method of teaching. This approach takes too much time.*
>
> *This method of teaching is difficult to implement and difficult to design assessment for it. There is a lack of laboratory equipment, administrative support and school facilities to help me to use this approach.*

Clearly, the majority of the sample of teachers in both countries expressed a positive attitude toward IBSE. However, it is clear that in the case of a significant number of science teachers in Indonesia, the perception that IBSE was only for higher ability students and the lack of laboratory facilities were clearly seen as an impediment to the teachers in implementing an IBSE approach due the fact that some of the practical activities could not be carried out.

Some interesting points of agreement were observed between the science teachers in Ireland and in Indonesia when asked about the balance between IBSE and DI in their teaching for the lessons in the intervention package. The results are summarized in Figure 1.

Clearly, the comparative analysis above showed that approximately 40% of teachers in both countries reported that the balance of IBSE and DI was in the ratio of 50:50 DI. It is also worth noting that a significant number of teachers in Ireland (41%) and in Indonesia (29%) felt that that that a balance between IBSE and DI was in the ratio of 1:3. Some typical comments obtained were:

> "In my classroom, I tried to teach with more emphasizes on inquiry based learning, but it needs more time allocated. Comparing IBSE with DI is a good idea."
>
> "I think there are many reasons why the balance should be 50% IBSE-50% DI": (1). The number of students in the classroom, (2). Laboratory equipment, (3). Students' abilities, (4). Allocation of learning time."

When teachers were asked to comment on the benefits that they saw of IBSE and DI approaches to teaching, a wide variety of comments were received. These comments are summarized in Tables 2, 4.

As seen from the above summary of the data obtained, the science teachers do not believe that there is any one perfect teaching approach to implementing the intervention package. There appears to be a continuum of a shifting balance (dynamic equilibrium) between student-centered learning (inquiry based science education) and teacher-centered learning (direct instruction) to ensure that these two approaches complement each other.

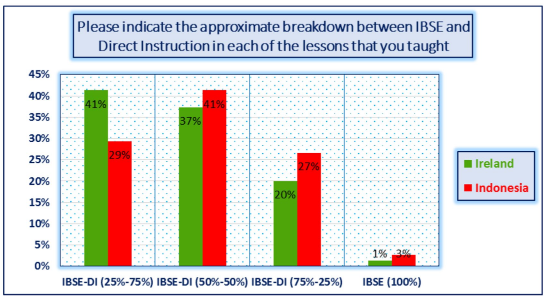

FIGURE 1
Comparative analysis regarding the reported balance between inquiry based science education (IBSE) and direct instruction (DI) during the teaching process.

3.2. Response of students to the medical physics module

The questionnaire issued to students asked their views on a number of areas, e.g., (1) gender, (2) age, (3) type of school, (4) level of interest in science, (5) performance in past science examinations, (6) level of difficulty in understanding topics, (7) participation in group activities, (8) level of interest in topics covered in module, and (9) willingness to continue with their study of physics. Due to restrictions on space, in this paper, we concentrate on the students' responses about their level of enjoyment of the module and their interest in the study of physics. A detailed analysis of all the data is given elsewhere (Sudirman, 2016).

Students were asked to indicate their level of enjoyment on a five-point Likert scale ranging from "extremely unenjoyable" to "extremely enjoyable." The results are summarized in Figure 2.

It is clear that the majority of the students in both countries reported that they found the module enjoyable. Typical comments received from those who found the module enjoyable were:

- *It was really enjoyable to learn about different topics in physics.*
- *It was interesting and helped further my studies.*
- *I really enjoyed it because it shows how medical analysis works.*
- *Not my favorite topic but it was a good lesson to know in general.*
- *I thought the lessons were enjoyable. I participated in the expert group task and my role was as a speaker when my group presented our research project.*

It is clear from Figure 2 that while Irish students showed a higher level of enjoyment of the module than Indonesian students, overall, the majority of students reported that they enjoyed the module. A statistical analysis of the data was carried out and some interesting points emerged:

- In Ireland male students were more interested in the module than female students but in Indonesia female students were more interested in it than male students.
- In both Ireland and Indonesia, students in vocational type schools expressed the most positive attitude toward the module. Students in the more academic type schools were less positive about the module.

When the Irish students were asked if the study of this module would encourage them to continue with their study of physics at senior level (Leaving Certificate), 45% indicated "yes" while more than half (55%) said "no." Interestingly, a significant number of Indonesian students (78%) said "yes" while only 22% said "no." Some typical comments from students were:

> *Science = awesome, Science makes me happy to further…it increased my curiosity and interest in physics.*
>
> *I actually like physics, but for the next year I will choose the Social Sciences Program which does not include physics (compulsory). Maybe if I were allowed to choose physics, I would also choose it.*

TABLE 4 Summary of the benefits of inquiry based science education (IBSE) and direct instruction (DI) in teaching physics as outlined by teachers who participated in the study.

IBSE	DI
Engages students and provides a greater cognitive challenge, i.e., scientific attitude and scientific process.	Teachers are able to guide students in face-to-face teaching and maximize students' understanding.
Students work independently.	Can be adapted for the complete range of students' abilities.
Can serve the needs of students who have above average ability. That is, students who have good ability and good study skills.	Can determine what the students need in facing difficulties in understanding.
IBSE is a teaching strategy that emphasizes the development of a balance between the cognitive, affective, and psychomotor domains.	Creates an interactive learning environment, particularly for students with lower abilities.
Allows students to understand the scientific process.	Listening activities play a key role for success in implementing the DI approach.
The teacher identifies the depth of students' knowledge and understanding of the concepts being discussed.	Can be used to determine the important points or difficulties that may be faced by students.
Pace and content can be adapted to suit individual learning needs of students and also helps develop critical thinking skills.	The most effective way to teach concepts and skills to students who are underachieving.
Allows students to think more critically about the topic being explored.	Teachers can demonstrate how a problem can be approached, how the information is analyzed, and how the knowledge is generated.
Provides a space for students to learn according to their learning styles.	It makes learning science interesting and relevant to students' everyday life by establishing a direct link between theories and its application.
	Focuses the students' attention on relevant content.

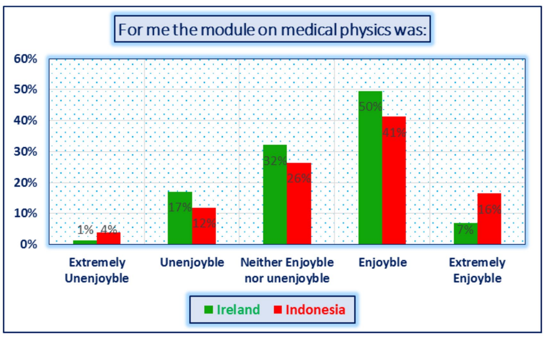

FIGURE 2
Responses of students indicating their level of enjoyment of the module.

The latter quotation above points to the fact that in Indonesia it is not possible to choose to study science subjects if one is specializing in subjects that are part of the Social Sciences program. This problem does not arise in Ireland where students study a total of seven subjects which include both social science subjects and science subjects.

Analysis of the comments from the students in both countries revealed that some terms used in this module affected their interest due to a lack of literacy skills. The study shows that students had difficulty not only with the technical words, but more commonly with everyday words used in the module. It would appear from the analysis of the student questionnaires that some of the teachers did not explain the meaning of many of the common terms encountered in the module as they may have assumed that they were understood by the student. This is in keeping with the findings of Cassells and Johnstone (1985) and Wellington and Osborne (2001). The use of the DI approach during the teaching process has clear significance for helping students to overcome literacy problems. Without an emphasis on supporting literacy, students may become frustrated with the problems being encountered and this may contribute to develop a negative attitude due to the difficulty of understanding the subject matter.

4. Conclusion and recommendation

Analysis of the data obtained from teachers and students clearly shows that the Medical Physics module has been successful in generating positive responses from both teachers and students. There is a statistically significant difference of responses regarding some variables in the module between Indonesian and Irish science teachers as well as in the responses from students. Analysis of the data from teachers and students shows that the teaching package was teacher-friendly, clear and concise, well laid out, and easy to follow. Teachers reported that the various methodologies and strategies used in the package were popular and could be easily adapted and modified for use in secondary school science lessons.

Based on the findings of the study that arise from the data analysis and bearing in mind its implications the following recommendations are confirmed. (1) There are some clear implications arising from this study for policymakers. Policymakers refer to those involved in curriculum design, members of the inspectorate, and other government agencies whose responsibility involves guiding the future of science education. Policymakers must ensure that continuing professional development programs for science teachers are provided to help them to develop a balance in their teaching between inquiry based science education and direct instruction. Also, teachers were clearly happy with the clearly defined learning outcomes for each lesson in the module. Hence, it is important to provide training to science teachers in the writing of learning outcomes and the methodology involved in teaching within a learning outcomes framework. While the concept of learning outcomes is well known in Ireland, the concept of a learning outcomes framework is quite new to teachers in Indonesia. (2) The availability of suitable laboratory facilities is very important in supporting an effective science teaching and learning environment. Policymakers at national and local level could better address the needs of science teachers in schools in terms of providing better quality laboratory facilities—this problem was particularly acute in Indonesia in promoting IBSE. (3) The Medical Physics module has received strong positive response from both teachers and students. Similar modules could be devised such as in astronomy, biotechnology, electronics, and other areas. Learning physics in the context of applications of science and technology allied with good pedagogy can create a good learning atmosphere.

While the students enjoyed studying the module, it had limited success in convincing them to continue with their study of physics at a higher level. The response of the teachers showed that there was a good balance between IBSE and DI in the teaching approach used by teachers when implementing this module. It is hoped that the study presented here will contribute to the development of new and innovative ways of teaching physics at the secondary school level.

Data availability statement

The data that support the findings of this study are available from the corresponding author.

Ethics statement

Ethical approval was not required for the study involving human participants in accordance with the local legislation and institutional requirements. Written informed consent to participate in this study was not required from the participants in accordance with the national legislation and the institutional requirements.

Author contributions

SuS conceived of the presented idea, developed the theory, verified the analytical methods, and performed the writing–original draft and conceptualization. DK supervised the findings of this work. SoS performed writing–review and editing. All authors contributed to the article and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Practical work in science education: a systematic literature review

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Practical work has taken a leading role in science teaching, particularly since the 1960s. Its goals are mainly oriented toward the development of sensitivity and taste for the study of physical and natural phenomena, bringing students closer to the daily reality experienced by researchers working in these areas of knowledge, while promoting educational success. However, these purposes have not always been achieved so, over time, limitations to the way that practical work has been developed have also been identified. In order to recognize the current state of the art on the development of the practical work in the teaching of sciences, a systematic literature review was designed, especially focused on the definition of the concept of practical work, its advantages, evaluation methodologies, and the criticism/limitations attributed to its implementation. To this end, four databases and one aggregator were used, to identify 53 international scientific publications. Analysis of this *corpus* allowed the identification of 8 categories associated to the concept of practical work, 5 categories associated to its advantages, 6 categories with the types/methodologies of evaluation and 5 categories associated with the limitations of this methodology. (From this analysis) it is concluded that most authors considers that the main idea integrative idea of the concept of practical work should be the manipulation of materials in practical activities (hands-on style), and the main advantage of this methodology comes from the fusion between the development of practical skills and the conceptual understanding (minds-on). In the evaluation methods, the context, procedures and specific instruments are favored and the main limitation pointed to this methodology is that the way practical work is implemented, is often not in agreement with the methods and techniques used by scientists and researchers.

KEYWORDS
science education, practical work concept, practical work advantages, practical work assessment, practical work disadvantages, systematic review

1. Introduction

The role of practical work in science teaching has long been a theme of intense debate and reflection, a function of scientific experimentation being understood as a landmark of modern science, particularly, from the days of Bacon (Rheinberger, 2001). The reflection on the teaching of science, more specifically, over the development of the practical work, took on special importance, in the early 1960s, in the United States of America, during the Cold War, from the moment the Union of Soviet Socialist Republic launched the first satellite to orbit the Earth. Mayer (1964) wrote that "the impact of this grape-fruit sized object on the American ego was several orders of magnitude greater than any event of this century" (p. 226). The missing step was taken and triggered a profound revolution, both in the curricula as well as in the methodologies applied in the teaching of sciences, with echoes that quickly made themselves felt a bit all over the globe. Programs such as the *Biological Sciences Curriculum Study (BSCS)* and the *Earth Science Curriculum Project (ESCP)* establish that in addition to their content, the Biological Sciences and Geosciences programs, respectively, should reflect, from that moment on, the science enterprise in its broadest scope, adopting a more investigative spirit, contrary to its teaching as mere observational sciences.

To reach this goal, practical, investigative, laboratory and field activities in the programs of these areas of knowledge would have to be included. Simultaneously, the need to create new materials that allow the proper development of new strategies and approaches of teaching should also be included, giving a big emphasis to the use of multimedia resources. Within the scope of the BSCS it was produced, for example, a sequence of forty movies allusive to specific research topics, developed in a way to promote the student's engagement, as well as debate in a classroom environment. These movies served as a source of research data regarding biologic problems, allowing the observation, formulation of hypothesis, gathering and analysis of data as well as the establishment of temporary conclusions reached by the students.

Both programs and materials were planned, written, and produced by multidisciplinary teams, where the ESCP, for example, counted with the contribution of scientists specialized in the most diverse fields of science, such as Astronomy, Physical Geography, Geophysics, Geology, Geochemistry and Oceanography. These scientists developed a very important collaborative work, integrating secondary school science teachers, as well as science educators, in their work teams (Heller, 1964).

At the end of the 20th century, practical work continued to enjoy a privileged status in the science teaching, however, Hodson (1996) argues that, paradoxically, practical work is simultaneously overused and underused. Overused, in the sense that the teachers develop it with the expectation of reaching all the science learning objectives. And underused, where its real potential is rarely fully explored. In a way to get out of this confusing and educationally unproductive situation, the author proposes a reconceptualization of practical work in terms of three associated purposes which would contribute to helping students: (a) learn science; (b) learn about science, developing an understanding about the nature and scientific methods, as well as the awareness regarding the complex interactions between science, technology, society and the environment; and (c) make them capable of doing science – including them and developing their experience in scientific research and problem solving Hodson (1996).

Reflecting on the arguments that justify carrying out practical work, Wellington (1998) suggests that it can be grouped into three main domains: the cognitive, the affective, and the skills and processes. In the arguments regarding the cognitive domain, the author suggests that practical work allows to illustrate, verify and affirm theoretical content. Thus, it helps the students to improve their understanding of science, allowing them to "visualize" scientific laws and theories, which promotes their conceptual development. Regarding the affective arguments, the author demonstrates that because practical work is motivating and exciting, it will contribute to an increased interest in science, consequently helping the students to better remember lessons, developing their memorization abilities. Lastly, about the domain of skills and processes, Wellington (1998) indicates that practical work has the potential to develop transferable skills of great relevance, not only for future scientists, but it is also of great use to students with other callings. Some examples of these skills are the observation, the measurement, the prediction, and inference.

However, the author shows in their study that for each set of arguments used in favor of practical work, there are also counterarguments. For example, concerning the cognitive domain, Wellington (1998) concludes that in certain situations practical work might confuse just as easily as it may help with the conceptual understanding. As for the affective domain, they conclude that some students may even "turn off" their concentration, especially when the practical work goes wrong, or when they fail to understand its purpose. Lastly, regarding the skills and processes domain, the author recognizes there is little proof that the skills learned in science are in fact general and transferable, or that they still present vocational value. Nevertheless, even though practical work is seen as a fundamental part of the science teaching, its relevance has never stopped being criticized. Wellington (1998) warned that beyond its ability to excite, improve the illustration and understanding of phenomena, practical work can also be criticized due to economic matters, the ability to cause conceptual confusion, issues of bias of gender and, also, and the possibility of arousing less ethical behaviors from teachers and students in the classroom.

Science research refers to how scientists study, disclose ideas, explain and justify propositions regarding the natural world, based on the evidence that resulted from scientific work (Hofstein and Lunetta, 2003; Millar and Abrahams, 2009; Osborne, 2014; Koliander, 2019) and, equally, in more authentic ways through which students can investigate the natural world, propose ideas, explain and justify evidence based claims, acquiring and developing the scientific approach (Itzek-Greulich and Vollmer, 2017; Shana and Abulibdeh, 2020; Aydin et al., 2022).

To reflect on the efficiency of a teaching and learning activity of any nature, it is useful to consider the different steps in the development of such activity, and the monitoring of what happens when it is promoted. For that reason, in the assessment process of the efficiency of a certain practical work, four structural dimensions should be integrated: (a) the developers' objectives (what is expected for students to learn); (b) the tasks guidelines (what is expected for students to do); (c) what happens in the classroom (what students actually do); and (d) learning outcomes (what students actually learn).

Wei and Li (2017) studied the teachers' perceptions of scientific experimentation and the implications for the restructuring of practical work in science teaching, developed by scientists and students in schools. The results from their research suggest that participants' views on experimentation are generally framed in eight dimensions (conceptual, epistemological, procedural, material, social, safety, temporal and pedagogical) although they show uneven distributions among them. Thus, for example, regarding the experiments carried out by students, the three main dimensions are the pedagogical, the experimental and the epistemological; for the scientific experiments are the procedural, epistemological and the material.

This and other important reasons, such as the fact that the conceptual and social dimensions, widely discussed in literature and rarely mentioned by the study participants, have made different authors of studies present in the *corpus* of this systematic review defend a greater approximation of practical work developed in science teacher education programs for practical work effectively developed by scientists while conducting experiments (Toplis, 2012; Abrahams et al., 2013; Donnelly et al., 2013; Anza et al., 2016; Musasia et al., 2016; Wei and Li, 2017; Oguoma et al., 2019; Adamu and Achufusi-Aka, 2020; Babalola et al., 2020; Wei et al., 2020; Pols et al., 2021). Because of this, they suggest that courses, modules, and teacher training programs should focus on how real scientific experiments are developed, what scientists actually do when conducting these experiments, and how the scientific experiments are performed in different social contexts. It is, therefore, essential that science teachers can be provided with opportunities to learn how to transform traditional practical work in scientifically grounded experiments at a conceptual, epistemological, and procedural level. In summary, it is possible to contest that the quality of the practical work developed in the scope of science teaching depends, not only on the frequency that it is used, but also, and mainly, on the quality with which it is accomplished.

Based on this framework, this article presents the results of a systematic review of the literature on the state of the art in the development of practical work in science teaching. This type of literature review becomes advantageous in the way that it suggests the adoption of explicit and systematic procedures in its performance, making the emergence of biases introduced by their authors, less likely.

With this, it is possible to understand that if the process of including studies in the literature review is not explicit, it is not possible to determine the suitability of that selection, nor whether the process was performed in a rigorous, consistent, and reasoned way. Thus, it would become more difficult to correctly interpret the meanings of the outcomes of the literature review (Bryman, 2012; Gough et al., 2012; Page et al., 2021).

This systematic review starts from the following research question: what is the current state of the art on practical work in science teaching at the pre-university education level? In order to arrive at a more conclusive answer, this guiding question is divided into the following sub-questions: (a) what aspects are integrated in the concept of practical work; (b) what are the defined advantages attributed to the development of the practical work in science teaching?; (c) what assessment types/strategies are performed for the development of practical work?; (d) what are the defined disadvantages attributed to the development of the practical work in science teaching? It is intended that this review essentially reflects the students, teachers, and researchers on this matter.

2. Methods

2.1. Data sources, search engines and key words

The data collection process for this systematic literature review, was performed in four international data bases (ERIC; Google Scholar; Scopus and Web of Science) and in Portuguese database aggregator (B-on). The research in these data sources respected the assumptions established in a research protocol, which included inclusion and exclusion criteria, with the aim to identify the documents that are more relevant for the development of this review. It is also included in the protocol the goals associated to this systematic literature review, the main research question, as well as essential keywords to be applied during research.

The first step was to formulate the big guiding question for the entire investigation, using the research strategy tool SPIDER (Sample, Phenomenon of Interest; Design, Evaluation, Research type), for this purpose, as it is considered the better adapted for investigations of qualitative natures rather than the PICO strategy (Population, Intervention, Comparison, Outcome) (Cooke et al., 2012).

The considered sample were pre-university education institutions. The *Phenomen of Interest* identified was the employment of practical work in the teaching of science. The Design included a qualitative approach embodied in the performance of a systematic review of the literature. The Evaluation consisted of determining the status of the art over the implementation of practical work in science teaching and, lastly, it was determined that the Research Type would include studies carried out with the quantitative, qualitative methodology and the mixed methodology.

Going off the research question, for the research in the different databases and selected aggregator, the following keywords were defined: practical work, science education, secondary schools. The research protocol was registered in the International Platform of Registered Systematic Review and Meta-analysis Protocols – INPLASY, and its structure is outlined in Table 1 (Oliveira and Bonito, 2023).

2.2. Study selection: inclusion and exclusion criteria

The study selection in the *corpus* under analysis involved the definition of inclusion criteria and exclusion criteria. The establishment of these criteria worked as a filter that allowed refining the research, in order to identify the most relevant publications and

TABLE 1 Structure of the investigation protocol.

Goals of systematic literature review	Create an overview of how practical work is currently conceived and applied for teaching sciences on the secondary education level, according to students, teachers and researchers.
Research question	What is the state of the art of practical work in science teaching in a pre-university education level?
Keywords	Practical work; Science education; Secondary schools
Inclusion criteria	Complete Open Access documents; Peer reviewed studies; Studies developed on/how sciences are taught on pre-university education institutions; Documents written in English.
Exclusion criteria	Systematic Literature Reviews; Bachelor thesis dissertations/Final papers; Master's thesis dissertations; Documents published prior to 2011

TABLE 2 Findings from initial identification of studies to be included in investigation corpus.

Databases	Query options	Query criteria	Document count
B-on	*Limitators* - Latest 10 years - Peer reviewed - Available from library - Full text available *Expanders* - *Search whole article body* - *Search for equivalent topics*	"Practical work in science education" AND "secondary schools"	30
ERIC	- Latest 10 years - Peer reviewed	"Practical work" AND "science education" AND "secondary schools"	58
Google scholar	- Latest 10 years	Allintitle: "practical work" "science education" OR "secondary schools"	43
Scopus	- Latest 10 years	"Practical work" AND "science education" AND "secondary schools"	19
Web of science	- Latest 10 years	"Practical work" AND "science education" AND "secondary schools"	13
Total			163

better framed with the main research question. This way, the inclusion criteria to build the *corpus*, considering complete documents available in open access, peer-reviewed studies, studies developed in/about science teaching in pre-university teaching establishments and publications written in the English language. Also, with of refining the research, the exclusion criteria were defined with the goal to remove from the data collection publications resulting from systematic literature reviews, final degree work, masters dissertation and publications prior to 2011 (Table 1).

The fact that we chose to exclude studies published before 2011 does not mean that we disregard the structuring and extremely important research work carried out by many leading authors until then. On the contrary, it was a strategic choice, given the need to set a time frame for this systematic literature review, considering that one of its objectives is to help understand, in the most possible current way, the state-of-the-art on practical work in science teaching. Therefore, for this contemporary portrait of its conceptual dimension, the assessment methodologies used, and the advantages and disadvantages perceived by researchers and educators, we decided to focus this systematic literature review on research on practical work in science education, which took place after 2011. Also, the authors of this systematic literature review consider that doctoral theses correspond to the characterization of in-depth research projects, developed over a period of time, which allow obtaining solid results with a high degree of reliability and validity. Therefore, these manuscripts were considered in the process of selection and constitution of the *corpus* under study.

Another important inclusion criteria of this systematic literature review is the inclusion of research on pre-university education, particularly at the secondary education level. According to the International Standard Classification of Education (ISCED), this level is divided between lower secondary education (level 2) and upper secondary education (level 3), in a pathway that in different countries starts between 10–13 years and ends between 17–18 years of age (UNESCO, 2012).

Although research studies were not excluded on the basis of their country or language of origin, this systematic literature review established, as one of its inclusion criteria, the inclusion of studies published in English. This strategic option is not intended to take away the merit of important research studies developed and published in other languages, namely those from the Ibero-American space. It was a decision taken with the aim of considering manuscripts that are more likely to be interpreted by a wider audience of readers, increasing, consequently, the probability of having a greater impact on the conceptions and practices of a larger number of educational communities.

2.3. Synthesis of results and quality assessment

The research done in the four databases and the in the selected database cluster was performed on July 20, 2021. After applying the defined keywords, using adequate descriptors, employing specific Boolean operators, and fulfilling the criteria established in the planned research protocol, the initial result of data collection found 163 publications of potential interest (Table 2).

In the next stage, duplicate publications were removed ($n = 14$) before moving onto the screening phase, resulting in 149 publications. In the initial phase of the screening process, some publications were excluded through an analysis over the title's adequacy ($n = 20$), leaving the remaining ones identified for recovery ($n = 129$). From these last records, a small number was not retrieved, after an analysis over the adequacy of the abstract ($n = 10$). Thus, 119 publications were evaluated for eligibility, some of which are inaccessible ($n = 13$), others were final degree papers or masters dissertation ($n = 3$) and others corresponded to publications outside the scope of investigation ($n = 50$), that is, they did not address, in a clear and unequivocal way, one or more of the following dimensions related to practical work: concept, advantages, methodologies/typologies of assessment; limitations. At the end of the screening process, 53 studies were selected to constitute the *corpus* of this systematic literature review. The process to identify the studies considered is found on a flow diagram (Page et al., 2021) (Figure 1).

After obtaining the definitive number of studies to be considered, the *corpus* was constituted (Table 3). The analysis, characterization and organization of the studies was performed with the support of the Mendeley bibliographic management software (. Pdf visualization and analysis functionality), and research was carried out on the following dimensions of practical works: concept, advantages; methodologies / typologies of assessment; limitations. The results were recorded in a .docx file for later analysis.

Lastly, the data were synthesized, and the quality of the evidence was evaluated, by triangulating the information obtained through each individual study, integrating it into a holistic view of the state of the art on practical work in the last 10 years, with the goal to disperse the results obtained through its publication.

3. Results and discussion

The analysis of the distribution of articles that constitute the *corpus* reveals that most studies show a qualitative research approach ($n = 31$; 58.5%), followed by studies of a quantitative nature ($n = 18$; 34.0%) and those that adopted a mixed research approach, merging both data collection and qualitative data analysis methods, with quantitative methods ($n = 4$; 7.5%) (Table 4). The studies included in the classification categories defined for each

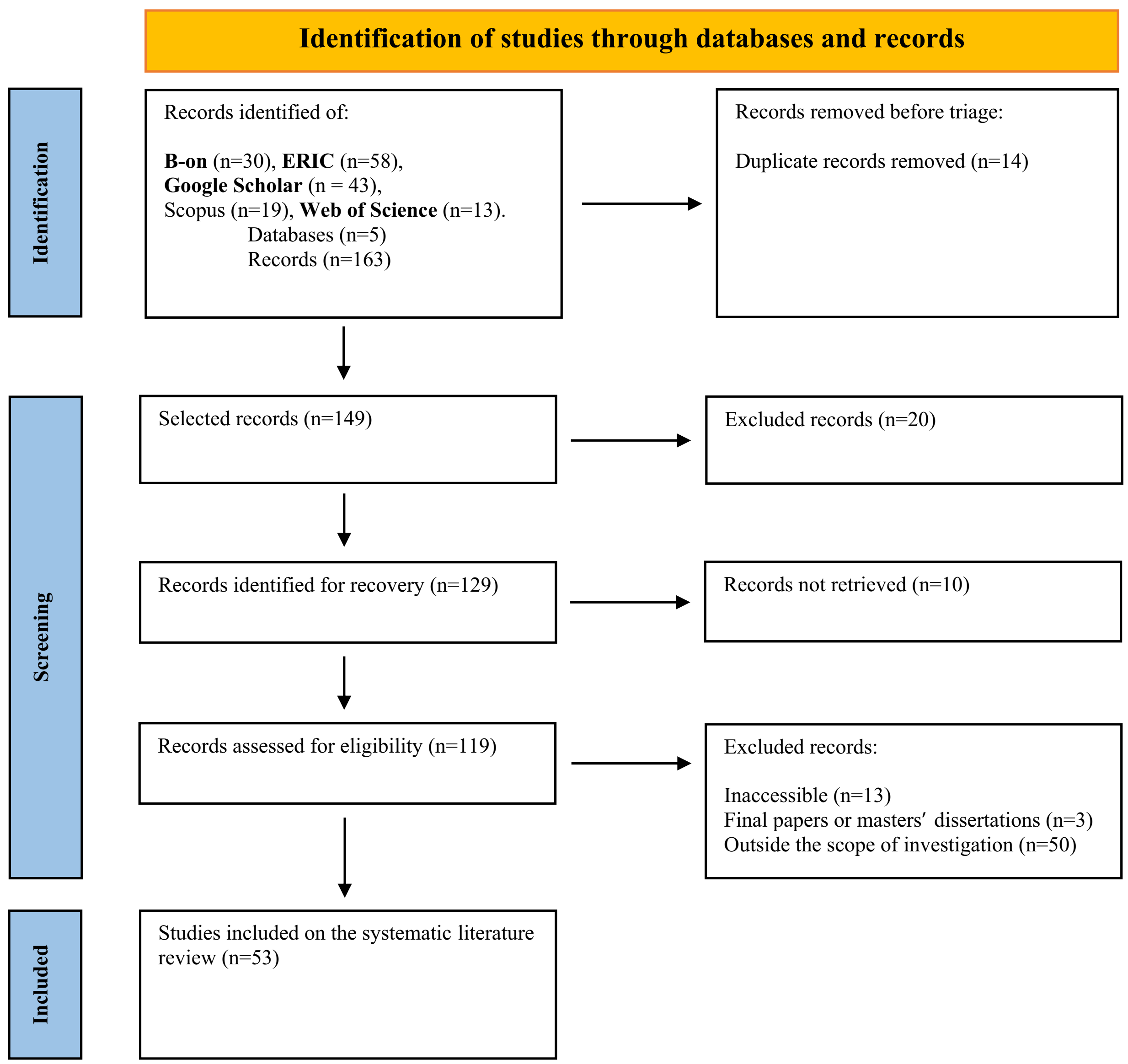

FIGURE 1
Screening results for the constitution of the corpus.

TABLE 3 Studies included in the constitution of the corpus.

Characteristics	S1	S2	S3	S4	S5	S6		
Authors	Babalola et al. (2020)	Donnelly et al. (2013)	Ferreira and Morais (2014)	Oguoma et al. (2019)	Rukavina et al. (2012)	Shana and Abulibdeh (2020)		
Country	Ghana; South Africa; Nigeria; Tanzania	Ireland	Portugal	South Africa	Croatia	United Arab Emirates		
Type of study	Mixed methods research	Multiple case study	Mixed methods research	Quantitative research approach (survey)	Quantitative research (survey)	*Quasi*-experimental research		
Objectives	Examination of the current views on the aims of practical physics teaching in sub-Saharan Africa.	Determination of how a virtual chemistry laboratory may support greater teacher enactment of inquiry-based approaches to practical work.	Analysis of the level of complexity of practical work in science curricula, focused on the discipline of Biology and Geology at high school.	Investigation of the teacher's concerns with the implementation of practical work in Physical Sciences by the Curriculum and Assessment Policy Statement (CAPS)	Determination of the interest and motivation among children aged 10 to 14 years, who participated in science or mathematics workshops.	Evaluation of the overall effect of practical work on students' academic attainment in science, specifically Chemistry and Biology.		
Instruments	Semi-structured interview protocols; Surveys; Audio recordings; NVivo Pro 11 Software.	Inquiry Science Implementation Scale (ISIS); video record; Reformed Teaching Observation Protocol (RTOP); Final interview	Instrument to characterize: the complexity of scientific knowledge; the cognitive skills; the relation between theory and practice, the explicitness of practical work and the analysis made of each unit of analysis.	Questionnaires; Statistics Analysis Software.	Survey; Statistical Software Package STATISTICA	Pre-test and pos-test to assess the effect of practical work on high school students' understanding of science.		
Subjects	Students (*N* = 80) Teachers (*N* = 55) Other educational staff (N = 30)	Teachers (*N* = 4; three males and one female)	Students (*N* = 96) Teachers (*N* = 4)	Teachers (*N* = 81)	Students (*N* = 1,240; Age 10–14)	Students (*N* = 98)		
Characteristics	**S7**	**S8**	**S9**	**S10**	**S11**	**S12**	**S13**	**S14**
Authors	Sund (2016)	Toplis (2012)	Abrahams et al. (2014)	Abrahams et al. (2013)	Akuma and Callaghan (2019)	Musasia et al. (2016)	Andersson and Enghag (2017)	Bohloko et al. (2019)
Country	Sweden	England	England	England	South Africa	Kenya	Sweden	Lesotho
Type of study	Empirical case study research	Grounded theory research	Multi-site case study	Documentary analysis	Multimethod case study approach	Quasi-experimental research	Case study research	Quasi-experimental research

(Continued)

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TABLE 3 (Continued)

Characteristics	S1	S2	S3	S4	S5	S6		
Objectives	Investigation of the obstacles that prevent teachers to make individual assessment of student's practical abilities in science.	Investigation of students' views about the role that practical work plays in their school science lessons.	To evaluate the impact of the Getting Practical: Improving Practical Work in Science CPD program on teachers' ideas and practice in science practical work in primary and secondary schools in England.	Review how practical work, including practical skills, is currently summatively assessed in school science in a number of countries and compare with how other subjects, such as music and modern foreign languages, summatively assess skills.	To determine in what extent is inquiry-based practical work being implemented in selected resource-constrained South African physical sciences classrooms.	The study sought to find out the difference in academic achievement in physics between students taught using intensive practical activities and those taught using conventional teaching methods, mostly theoretically.	To investigate the relation between the interaction and content of students' communication and outcomes of their actions, with the purpose of finding new knowledge for informing teachers in their choice of instruction during practical work.	To investigate the effectiveness of introducing open-source YouTube videos in the teaching and learning of the Chemistry topic 'Group Properties' at a high school in Lesotho.
Instruments	Mounted video cameras; Spy camera glasses.	Notes of the observed lessons; Semi-structured interview protocols.	Interview scripts; Observational field notes; pre- and post-CPD training observations in practical lessons.	Documentary analysis.	Semi-structured interview protocols, Classroom observation protocol; Learner worksheets.	End of Term One Form Two examination (EOTOFTE); Performance Tests on the Chosen Topics (PTCT).	Video recordings; Transcripts;	JC Science Score; Pre-test; Post-test
Subjects	Teachers ($N=2$) Students ($N=38$; ages: 15–16)	Students ($N=29$)	Teachers ($N=30$)	Examination of the science curriculum for 5–16 and 16–18 years-old	Teachers ($N=6$) Demonstrator ($N=1$)	Students ($N=450$)	Students ($N=20$) Teacher ($N=1$)	Students ($N=109$)
Characteristics	**S15**	**S16**	**S17**	**S18**	**S19**	**S20**	**S21**	**S22**
Authors	Erduran et al. (2020)	Fadzil and Saat (2019)	Haigh et al. (2012)	Hamza and Wickman (2013)	Harrison (2016)	Itzek-Greulich and Vollmer (2017)	Köksal (2018)	Kácovský and Snětinová (2021)
Country	Norway	Malaysia	New Zeland	Sweden	England	Germany	Turkey	Czech Republic
Type of study	Documentary analysis	Qualitative research	Qualitative research	Practical epistemology analysis	Qualitative research	Quantitative research	Survey	Quantitative research

(Continued)

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TABLE 3 (Continued)

Characteristics	S1	S2	S3	S4	S5	S6		
Objectives	To investigate how practical work is represented in the assessment frameworks of several countries that demonstrate above average performance in the latest PISA science assessments.	To discuss the development of a resource guide in assessing secondary school students" manipulative skills during practical work.	To determine how does engagement in illustrative practical work enhance students' understandings of the redox reaction occurring when steel wool is added to copper sulfate solution.	To compare how pairs of high-school students engage with the educational artefacts and scientific ideas on offer in the classroom in two different school science activities traditionally considered to lie far apart on the theory–practice scale.	To determine if the use of targeted discussion improves learning through practical work.	To research on activity emotions (state) and motivational outcomes (situational interest and situational competence) in science education.	To construct a self-efficacy scale for pre-service science teachers on using fieldtrips. The study also aimed to determine whether these beliefs vary by gender, class, secondary school type, whether fieldtrip was used in high school and university courses.	To identify factors predetermining students' positive acceptance of physics demonstrations.
Instruments	Science summative assessments; PISA 2015 scores.	Diagnostic tests; Assessment rubrics for activity A and B; Description of the competency level of manipulative skills.	Pre- and post-practical tests; Surveys; Interview.	Audio-recordings; Video-recordings;	Questionnaires; booklets; Audio-recording.	Learning-related emotion scale; Situational interest scale; science grades from the last school certificate; multiple-choice test; intrinsic motivation scale; Consciousness scale; Cognitive ability scale.	Self-Efficacy Beliefs on Fieldtrip Scale;	The modified Intrinsic Motivation Inventory questionnaire.
Subjects	Students' PISA science assessments from Singapure, USA, Canada, New Zeland and England.	Teachers ($N = 40$)	Students ($N = 17$)	Students ($N = 10$; ages: 16–17)	Students ($N = 700$; ages: 11–18)	Students ($N = 1{,}228$; age on average: 15,3)	Pre-service science teachers ($N = 249$)	Students ($N = 4{,}962$; ages: 15–20)
Characteristics	**S23**	**S24**	**S25**	**S26**	**S27**	**S28**	**S29**	**S30**
Authors	Karpin et al. (2014)	Kennedy (2013)	Abrahams and Reiss (2012)	Oyoo (2012)	Phaeton and Stears (2017)	Pols et al. (2021)	Ramnarain and de Beer (2013)	Sharpe and Abrahams (2020)
Country	Finland	Ireland	England	Kenya	South Africa	Netherlands	South Africa	England
Type of study	Quasi-experimental	Documentary analysis	Multi-site case study	Qualitative research	Case study	Qualitative participatory research design	Case study	Mixed methods research

(Continued)

TABLE 3 (Continued)

Characteristics	S1	S2	S3	S4	S5	S6		
Objectives	To analyze to what extent in designed lessons students learned to apply structural models in explaining the properties and behaviors of various materials.	To describe recent developments in Ireland to promote a greater interest in science among students in the 12–15 age group by means of practical work involving Inquiry Based Science Education (IBSE).	To report the first of two evaluations of a national project designed to improve the effectiveness of practical work in both primary and secondary schools.	To report and discuss findings in an investigation of physics teachers' approaches to use of and their beliefs about classroom instructional language.	To analyze the alignment between the intended and implemented A-Level Biology curriculum through the lens of teachers' interpretation of the Zimbabwean curriculum.	To investigate whether students who have just finished the compulsory part of science education in the Netherlands have the ability to analyse and interpret exper- imental data by constructing adequate data representations and drawing qualified, appropriate, defensible conclusions from these data.	To report the experiences of three 9th-grade South African students in doing open science investigation projects for a science expo.	To examine students' attitudes to practical work in biology chemistry and physics in secondary schools in England.
Instruments	Pre- and post-tests.	Documentary analysis	Audio recordings; Interviews; Observational field notes.	Direct classrooms observations; Interview scripts; Audio-recordings; Written test; outline of a student focus group interview schedule; a student in- depth interview schedule; classroom observation framework/ schedule; an outline of teacher interview schedule.	Padilla's (1990) categories of Science Process Skills; Questionnaire; Interview scripts.	Interview scripts.	Interview scripts; Qualitative data software.	Questionnaires; Audio-recordings; Field notes.
Subjects	Students ($N=45$; age: 16)	Examination of the subject Science which is studied as part of the Junior Certificate examination for 15-year-old students	Students ($N=857$)	Teachers ($N=9$)	Teachers ($N=5$)	Students ($N=51$; age on average: 15)	Students ($N=3$; ages: 13–14)	Students ($N=607$; ages: 11–15)
Characteristics	**S31**	**S32**	**S33**	**S34**	**S35**	**S36**	**S37**	**S38**
Authors	Wei et al. (2020)	Wei et al. (2019)	Wei and Li (2017)	Wei and Liu (2018)	Xu and Clarke (2012)	Adamu and Achufusi-Aka (2020)	Preethlall (2015)	Anza et al. (2016)
Country	China	China	China	China	Australia	Nigeria	South Africa	Ethiopia

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TABLE 3 (Continued)

Characteristics	S1	S2	S3	S4	S5	S6		
Type of study	Multiple case study	Survey	Grounded theory research	Case study	Qualitative research	Descriptive survey design.	Multiple case study	Descriptive survey design
Objectives	To investigate how three beginning science teachers deal with practical work during their first 2 years of teaching careers in high school.	To investigate the contributions of different sources in developing science teachers' practical knowledge of teaching with practical work.	To explore science teachers' perceptions of experimentation for the purpose of restructuring school practical work in view of science practice.	To examine an experienced chemistry teacher's pedagogical content knowledge (PCK) of teaching with practical work in China.	To report a detailed analysis of two lessons on density in a 7th Grade Australian science classroom, employing the theory of Distributed Cognition	To investigate the extent of integration of practical work in the teaching of chemistry by secondary school teachers in Taraba State, Nigeria.	To establish the relationship of teachers' knowledge and beliefs about science education and the teaching and learning of investigative practical work (IPW) in the Life Sciences.	To explore factors that influence practical work in chemistry for secondary schools in Wolaita Zone, Ethiopia.
Instruments	Interview protocol; Field notes; Lesson plans.	Questionnaire;	Interview scripts.	Interviews; Classroom observation notes; Textbooks; Lesson plans.	Video recordings; Interview scripts; Copies of lesson materials; Student written work; The results of the International Benchmark Test for Science; Student class tests; Teacher questionnaires.	Questionnaires.	Questionnaire; Interview scripts; Lesson observation notes; Documents with tasks completed by the participating teachers; Teacher and learner artefacts; South African Biology and Life Sciences curricula.	Questionnaires; Interview scripts.
Subjects	Teachers ($N = 3$)	Teachers ($N = 280$)	Teachers ($N = 87$)	Teacher ($N = 1$)	Students ($N = 27$) Teacher ($N = 1$)	Students ($N = 45$)	Teacher ($N = 4$)	Students ($N = 75$) Teachers ($N = 56$) Principals ($N = 5$)
Characteristics	**S39**	**S40**	**S41**	**S42**	**S43**	**S44**	**S45**	**S46**
Authors	Childs and Baird (2020)	Danmole (2012)	di Fuccia et al. (2012)	Malathi and Rohini (2017)	Wilson (2018)	Musasia et al. (2012)	Ruparanganda et al. (2013)	Sani (2014)
Country	England and Wales	Nigeria	Germany	India	England	Kenya	Zimbabwe	Malaysia
Type of study	Narrative critical evaluation	Descriptive survey design	Documentary analysis	Descriptive survey design	Design-based research approach	Quasi-experimental research	Qualitative research	Case study

(Continued)

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TABLE 3 (Continued)

Characteristics	S1	S2	S3	S4	S5	S6		
Objectives	To analyze the policy trajectory for the assessment of science practical work, through the GCSE, in the English National Curriculum from 1988 to the present.	To investigate biology teacher views on practical work on the Nigerian senior secondary schools.	To give account of the development of practical science work in German schools and to discuss the most prominent trends in practical science efforts in German secondary science education which have taken place in recent years.	To identify the problems that are experienced by physical science teachers in doing practical work.	To conceive, develop, and pilot Labdog: a novel web-based technology for the teaching laboratory.	To investigate the effect of practical work on girls' performance in physics; To determine whether there is an attitude change toward physics for girls as a result of participating in practical work; To investigate whether practical work enables the girls to acquire science process and practical skills; To determine the effect of practical work on girls enrollment in the physics class in form three.	To explore possibilities of implementing the Project Approach as an alternative to Regular Laboratory Practical Work in Ordinary Level Biology Teaching in Rural Secondary schools where science equipment is limited or where there are no laboratories.	To gain an understanding of teachers' views and practices in conducting practical work in lower secondary schools in Malaysia.
Instruments	Published research work; Policy documents.	Questionnaire.	Published research work.	Questionnaire.	Meaningful learning in the laboratory instrument (MLLI); Corpus of responses to in-lab Labdog questions; Open-answers given by laboratory members	Pre-tests (end of form one term three physics examinations); Post-tests (Student's Achievement Tests; Form Two Students Attitude Questionnaire); Observation Checklist for Skills Acquired.	Questionnaire; Lesson observation notes; Focus group discussion notes.	Interview scripts; Classroom observation field notes; Documental analysis notes.
Subjects	Examination of the GCSE coursework (student ages between 11 and 16 years old).	Teachers ($N = 96$)	Examination of the trends in Practical Work in German Science Education.	Teachers ($N = 30$)	Students ($N = 46$; ages: 18–40)	Students ($N = 271$)	Teachers ($N = 12$) Lecturers ($N = 3$)	Teachers ($N = 3$) Students ($N = 35$)

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TABLE 3 (Continued)

Characteristics	S1	S2	S3	S4	S5	S6	
Characteristics	**S47**	**S48**	**S49**	**S50**	**S51**	**S52**	**S53**
Authors	Tesfamariam et al. (2014)	Viswarajan (2017)	Lowe et al. (2013)	Mamlok-Naaman and Barnea (2012)	Mkimbili and Ødegaard (2019)	Šorgo and Špernjak (2012)	Ye et al. (2021)
Country	Ethiopia	England	Australia	Israel	Tanzania	Slovenia	China
Type of study	Quasi-experimental research	Documentary analysis	Survey	Documentary analysis	Group-interview study	Documentary analysis	Fuzzi delphi technique and Analytic hierarchy process
Objectives	to explore the possibility of using the SSC approach as a means of performing chemistry hands-on practical activities in Ethiopian secondary schools, and thereby reducing the need for costly equipment and expensive laboratories	To explore the range of literature available on the effectiveness of science practical work in English secondary schools and consider the possible effects of the removal of internal assessment of practical work from the GCSE curriculum.	To describe trials of the use of remote laboratories within secondary school science education, reporting on the student and teacher reactions to their interactions with the laboratories.	To describe the chemistry laboratory curriculum in Israel, its development, implementation and assessment strategies.	To invite a selection of Tanzanian students to reflect on what motivates them in learning science and their suggestion with regards to improving students' motivation.	To analyse and compare syllabi of Biology, Chemistry and Physics to find out if they are enhancers or blockers for the introduction of active, student-centered teaching methods, particularly hands-on laboratory work, in everyday teaching practice at lower and general upper secondary schools in Slovenia.	Research on the core competences of middle school science teachers.
Instruments	Chemistry concept test; Student questionnaire; Individual teacher interview; Classroom observation notes.	Published research work.	Student's survey; Teacher's survey.	Published research work.	Interview guide; Audio recordings.	Syllabi booklets.	Fuzzy Delphi questionnaire; Analytic Hierarchy Process questionnaire.
Subjects	Students ($N = 383$; ages: average 17) Teachers ($N = 6$)	–	Students ($N = 112$; ages: 9–11) Teachers ($N = 13$)	–	Students ($N = 46$; ages: 15–19)	–	Science teachers ($N = 10$) Science education administrators ($N = 8$) University professors ($N = 12$)

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TABLE 4 Corpus organization by research methodology.

Research approach	*f* (%)	Research design	*f* (%)	Studies
Qualitative research	31 (58.5)	(Multiple) Case study research	17 (32.1)	S2, S7, S9, S11, S13, S17, S19, S25-S27, S29, S31, S34, S35, S37, S45, S46
		Documentary analysis	7 (13.2)	S10, S15, S24, S41, S48, S50, S52
		Grounded theory approach	3 (3.8)	S8, S33
		Group-interview study	1 (1.9)	S51
		Design Research	1 (1.9)	S16
		Practical epistemology analysis	1 (1.9)	S18
		Qualitative participatory research design	1 (1.9)	S28
		Narrative critical evaluation	1 (1.9)	S39
Quantitative research	18 (34.0)	Survey	10 (18.9)	S4, S5, S21, S22, S32, S36, S38, S40, S42, S49
		Quasi-experimental research	6 (11.3)	S6, S12, S14, S23, S44, S47
		Cluster Randomized Trial	1 (1.9)	S20
		Fuzzi delphi technique and Analytic hierarchy process	1 (1.9)	S53
Mixed methods research	4 (7.5)	Exploratory sequential mixed methods	1 (1.9)	S1
		Convergent mixed methods	1 (1.9)	S3
		Explanatory sequential mixed methods	1 (1.9)	S30
		Design-based research approach	1 (1.9)	S43

dimension under analysis (conceptual dimension, advantages dimension, evaluation dimension and disadvantages dimension) are not exclusive. This means that each study of the *corpus* under analysis, may include indicators from more than one category and be framed in different dimensions. Thus, there will be situations in which we may have identified the same study in different dimensions and in different categories. The global overview of the considered dimensions and their associated categories is presented in an organizational chart (Figure 2).

3.1. The concept of practical work

There is not a very broad consensus on the definition of practical work. It is possible to find references to several authors who, in turn, present different conceptions regarding the characterization of the concept of practical work. On the other hand, some similarities are also seen, in this conceptual issue, between the international studies considered here. The content analysis of the different investigations for the *corpus,* allowed the establishment of a distribution of studies by eight structuring categories, as indicated in Table 5.

Some studies integrate the concept of "hands-on skills" into that of practical work (S3, S4, S7-S11, S15, S16, S18, S20, S21, S23-S25, S27-S30, S32-S34, S36-S38, S40- S50, S52). Thus, in 69.8% ($f = 37$) of the studies, a conception of practical work that represents a direct interaction with equipment or materials, individually or in small groups, contemplating observation and/or manipulation, particularly associated with practical activities, is presumed. Others, however, associate practical work to the mobilization of practical skills in handling materials applied to scientific investigative processes (S8-S11, S15, S16, S18, S20, S21, S23-S25, S27- S30, S32-S34, S36-S38, S40-S45, S48-S50, S52). In this category are found 60.4% ($f = 32$) of the studies under review.

The factor that assumes prominent relevance in the definition of the concept, for another study group (37.8%, $f = 20$), is the fact that practical work presumes the mobilization of scientific knowledge, in order to allow the understanding of the processes of certain phenomena, in line with a "minds-on" approach, promoter of critical thinking (S3, S15, S16, S19, S20, S23, S26, S28, S29, S35-S37, S41-S45, S48, S50, S52). Another relevant idea is that practical work should also assume a strong involvement in the process of developing investigative queries and designing experimental procedures, in a logic of promoting of Inquiry-Based Learning (S4, S11, S21, S24, S27, S29, S34, S37, S38, S43, S51, S52), with this aspect highlighted in 22.6% ($f = 12$) of the studies.

Learning through everyday phenomena that promote student motivation and engagement as a result of more relevant learning episodes, drawn from experiences and selected contexts, allows building a fifth category (7.5%, $f = 4$) with this integrating element (S12, S29, S33, S35).

In a sixth category (5.7%, $f = 3$), the studies considered are the ones that show the integration of aspects associated with "scientific communication," in the conceptual definition of practical work (S4, S24, S27). One study (1.9%, $f = 1$) integrates the possibility that this methodology can be an accessible and low-cost alternative for science learning, in the conceptual framework of practical work (S19), and

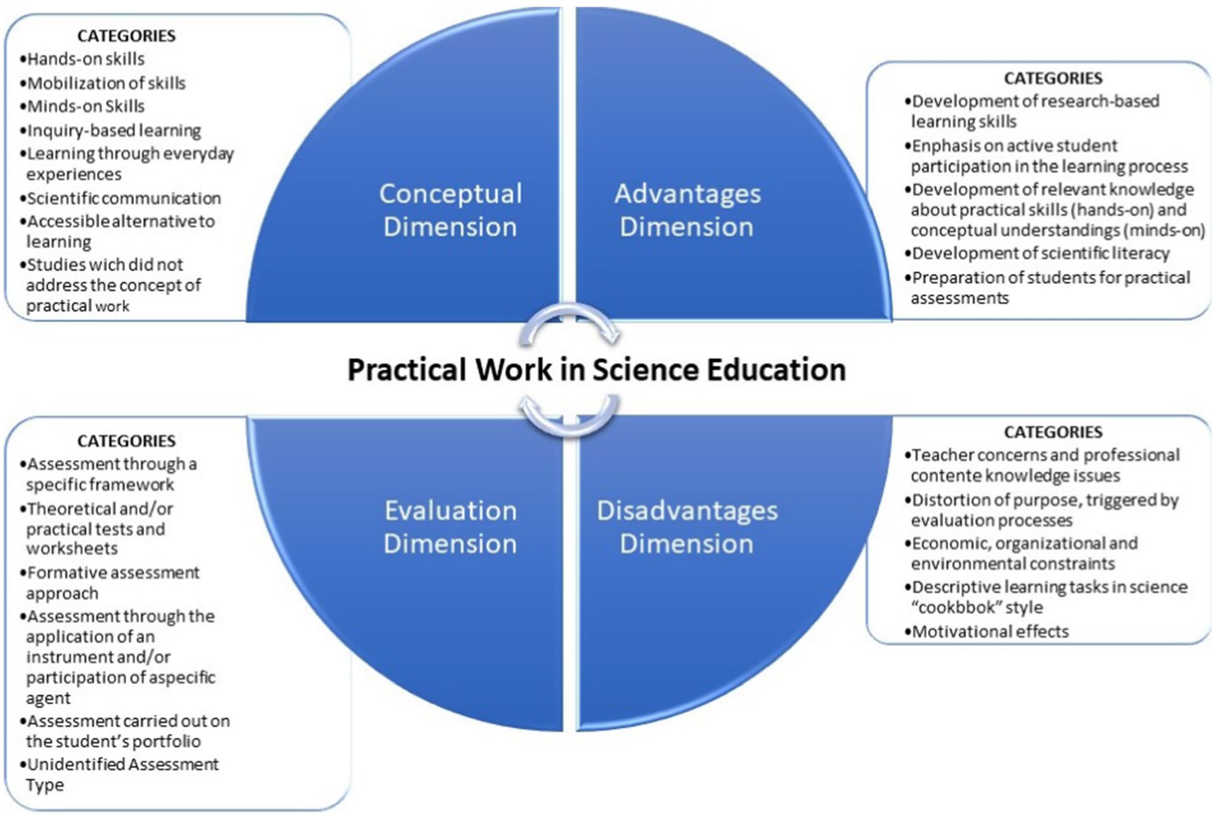

FIGURE 2
Categories of the practical work dimensions under analysis.

TABLE 5 Elements integrated within the concept of practical work.

Categories	*f* (%)	Studies
Hands-on skills	37 (69.8)	S3, S4, S7-S11, S15, S16, S18, S20, S21, S23-S25, S27-S30, S32-S34, S36-S38, S40-S50, S52
Mobilization of skills	32 (60.4)	S8 - S11, S15, S16, S18, S20, S21, S23, S24, S25, S27-S30, S32-S34, S36-S38, S40-S45, S48-S50, S52
Minds-on skills	20 (37.8)	S3, S15, S16, S19, S20, S23, S26, S28, S29, S35-S37, S41-S45, S48, S50, S52
Inquiry-based learning (IBL)	12 (22.6)	S4, S11, S21, S24, S27, S29, S34, S37, S38, S43, S51, S52
Learning through everyday experiences	4 (7.5)	S12, S29, S33, S35
Scientific communication	3 (5.7)	S4, S24, S27
Accessible alternative to learning	1 (1.9)	S19
Studies which did not address the concept of practical work	8 (15.1)	S3, S14, S17, S18, S22, S31, S39, S53

lastly, there are those that do not address the concept of practical work in a clear and unequivocal way (S3, S14, S17, S18, S22, S31, S39, S53), this category corresponding to 15.1% of investigations ($f = 8$).

Overall, the systematic literature review reveals that the concept of practical work is prominently assumed as a process that goes beyond allowing the development and improvement of practical skills associated with handling of laboratory material. It is above all, a method that allows the students to understand the nature of science by involving them in activities that mimic the action of scientific research processes. This understanding results from the construction and mobilization of scientific knowledge, through critical thinking capable of raising hypotheses and formulating ways to test them, simultaneously enabling the theoretical and conceptual reflection of the phenomena in question, in a minds-on approach.

3.2. Advantages of practical work

Regarding the advantages associated with the promotion of practical work, the content analysis of the different investigations of the *corpus* allowed a distribution of studies by five global categories, as specified in Table 6.

TABLE 6 Identified advantages in practical work.

Categories	*f* (%)	Studies
Development of research-based learning skills	37 (69.8)	S1, S4-S7, S11-S21, S24, S27-S30, S32, S34-S36, S38, S40-S45, S47, S50-S53
Emphasis on active student participation in the learning process	36 (67.9)	S1, S3-S5, S6-S10, S12, S16, S17, S19-S21, S23, S26-S31, S34, S36, S37, S41-S47, S49-S51, S53
Development of relevant knowledge about practical skills (hands on) and conceptual understanding (minds on)	30 (56.6)	S1, S2, S4, S6, S9-S12, S16, S19, S20, S24, S25, S27, S28, S30, S33-S36, S38, S40, S43-S48, S51, S52
Development of scientific literacy	21 (39.6)	S3, S7-S9, S12-S14, S22, S23, S27-S29, S34, S38, S40, S42, S44-S46, S48, S50
Preparation of students for practical assessments	4 (7.5)	S1, S14, S44, S46

In the first category and in 69.8% ($f = 37$) of the investigations, practical work is considered to allow the development of learning skills based on research processes (S1, S4-S7, S11-S21, S24, S27-S30, S32, S34-S36, S38, S40-S45, S47, S50-S53). This methodology presents the ability to make the contents more relevant to students, increasing their motivation and the emotion of discovery (S7), promoting positive attitudes toward science (S6), being, at the same time, able to increase their intrinsic motivation (S51). Likewise, the adoption of this methodology allows, through the dynamics developed in learning environments outside the classroom, the realization of on-site investigations on objects, tools, cases, and events that cannot be brought directly to school (S21).

Thus, practical work is considered the key to capturing and maintaining students' interest in science, encouraging them to continue their studies in this area (S1, S6, S12, S14, S16, S20, S24, S28, S29, S34, S38, S43, S44, S51, S52). As seen by many teachers, practical work is still an essential aspect of daily practice in science teaching, being essential for effective learning (S1). It allows the development of prediction, observation, and interpretation skills, which are transferable to new contexts (S47). It also provides immediate feedback (S14). Moreover, the fact that practical work stimulates an active and in-depth approach to learning, resulting from work sensitive to real problems related to everyday life (S5, S36, S45), is also seen as an important advantage, along with its ability to improve the dynamics of collaborative work (S7, S11).

Another study group (67.9%, $f = 36$) identifies the advantage of practical work to allow the active participation of the student in the learning process (S1, S3-S10, S12, S16, S17, S19-S21, S23; S26-S31, S34, S36, S37, S41-S47, S49-S51, S53). The conversations about learning activities during the practical work are of great importance, contributing to the improvement of communication skills (S26). It is also identified as an advantage that practical work allows the development of essential practical skills, which allow students to feel motivated to pursue scientific careers, giving them more confidence to study these areas at higher and more complex levels (S10). The development of practical work may also help students develop the capacity to construct mental models, about scientific phenomena that cannot be observed directly (S17) and may also manifest a significant impact on the emerging professional identities of students, as well as on their value charts, of eventual future science teachers (S31). Another notable advantage associated with practical work is that it can lead to better learning, as students are more likely to understand and remember actions they have taken, rather than actions they have been told to perform (S44).

The fact that practical work involves students in scientific themes, developing their relevant knowledge on these topics, hands on skills and conceptual understanding (minds on), involving students simultaneously in the process of building their own knowledge, in a constructivist perspective (S9, S19, S25) is pointed out by several publications (S1, S2, S4, S6, S9-S12, S16, S19, S20, S24, S25, S27, S28, S30; S33-S36, S38, S40, S43-S48, S51, S52), corresponding to a percentage of 56.6% ($f = 30$) of the studies analyzed. Practical work, particularly through laboratory work, also helps to understand the difference between observation and data presentation (S6). This methodology supports students' learning, motivating their involvement, while specific curricular requirements are met (S51). Here, it is also relevant that practical work allows improvement of teachers' knowledge and professional practice (S33).

For another group of authors (39.6%, $f = 21$), practical work emerges as a central strategy for the development of scientific literacy (S3, S7-S9, S12-S14, S22, S23, S27-S29, S34, S38, S40, S42; S44-S46, S48, S50). In this category, the studies emphasize understanding processes and concepts, helping to diagnose and correct students' misconceptions, as well as alternative conceptions, stimulating their curiosity (S3, S28). It is also highlighted the important contribute brought by practical work to the students' social development (S29). The development of critical and creative thinking is also highlighted as an important advantage. Practical work also contributes to the learning of the nature of science (S8, S9).

Finally, we group the studies (7.5%, $f = 4$) where the advantage of practical work is evidenced to assume a core role in the process of preparing students for the moments destined to practical evaluations (S1, S14, S44, S46).

3.3. Practical work evaluation

About the evaluation, there is a great dispersion of selected methodologies, which would initially be expectable due to the differentiated nature and scope of practical work, analyzed in each investigation that is integral to this systematic review. However, it is also possible to group the types/methodologies of practical work evaluation into a set of six unique categories, as illustrated in Table 7. In a first category and corresponding to 24.5% ($f = 13$) of the studies, there are investigations in which the evaluation of practical work takes place through a specific framework, that is, through an evaluation system whose structure includes a set of strategies and instruments, specially designed to allow the evaluation of a specific type of practical

TABLE 7 Practical work evaluation types/methodologies.

Categories	*f* (%)	Studies
Assessment through a specific framework	13 (24.5)	S7, S9-S11, S16, S20, S25, S28, S37, S41, S44, S46, S48
Theoretical and/or practical tests and worksheets	11 (20.8)	S8, S12, S14, S15, S17, S23, S27, S29, S39, S42, S47
Formative assessment approach	4 (7.5)	S13, S18, S19, S43
Assessment through the application of an instrument and/or participation of a specific agent	3 (5.7)	S16, S24, S49
Assessment carried out on the students' portfolio	1 (1.9)	S50
Unidentified assessment type	22 (41.5)	S1-S6, S21, S22, S26, S30-S36, S38, S40, S45, S51-S53

TABLE 8 Identified disadvantages in practical work.

Categories	*f* (%)	Studies
Teacher concerns and professional content knowledge issues	26 (49.1)	S1, S2, S4, S8, S10, S12, S17, S18, S23, S24, S26-S28, S31, S32, S34, S36, S38, S40, S41, S44, S46, S47, S50-S52
Distortion of purpose, triggered by evaluation processes	21 (39.6)	S2, S3, S6, S7-S10, S13, S16, S22, S25, S27, S34, S36, S39, S42, S45, S47, S48, S52, S53
Economic, organizational and environmental constraints	20 (37.7)	S1, S4, S14, S21, S29, S34, S36, S38, S40-S45, S47-S51, S53
Descriptive learning tasks in science "cookbook" style	18 (34.0)	S2, S4, S6-S8, S11, S15, S17-S19, S25, S26, S30, S33, S37, S39, S46, S52
Motivational effects	3 (5.7)	S1, S20, S43

work. The evaluation includes elements such as general settings, physical context, the relationship between skills and knowledge, and how realistic and interesting the task is for students (S7, S9-S11, S16, S20, S25, S28, S37, S41, S44, S46, S48).

Other authors (S8, S12, S14, S15, S17, S23, S27, S29, S39, S42, S47) perform the assessment through national tests/exams. The dominance of this type of evaluation is a factor that restricts the authentic nature of investigative science, which often follows strict and stereotyped routines, and having, also often, a test model influenced by national policies. This paradigm, leads students, at various times, to view practical work only as a way to obtain good marks, to the point that in certain situations they falsify the practical results obtained in an exam situation, in order to reach the expected results. Within the analyzed studies 20.8% ($f = 11$) are found within this category.

Another set of studies (7.5%, $f = 4$) favors formative evaluation (S13, S18, S19, S43). After the practical work activity there is room for discussion and explanation of a set of questions. The discussion focuses on various aspects of the practice such as forecasting, creating methods, problem solving, conclusions or phenomena explanations. Practical activities can benefit from a formative assessment approach when they foresee asking questions to students, which will be used to inform better learning and understanding of phenomena. The intention is to give students a reason to recapture the material and help them understand the limits of their own knowledge, starting from the basis of a summative assessment that educators can store, presenting evidence that students have properly performed a series of practical activities.

The evaluation of practical work is also done through the application of an instrument and/or participation of a specific agent (S16, S24, S49). In this category, which includes 5.7% ($f = 3$) of the studies, the evaluation may even include the involvement of an external examiner, whose function is to interview the students and examine their ability to perform laboratory tasks in the school context. Here is also the possibility of the evaluation going through the application of a specific instrument, aimed at evaluating the effect of laboratory experiences on the attitudes of students. Finally, it is also considered the possibility of developing a resource guide, in order to evaluate the scientific manipulative competencies of students in secondary schools.

The second to last category is filled solely with the S50 study (1.9%, $f = 1$), with the practical work evaluation being predicted through the student's portfolio of laboratory reports, conducted by the teacher and an external reviewer, or by a special case-based assignment in the national matriculation examination. The classification of this oral or written exam contributes to 25% of the students' final grade, while the other 75% is based on the information (i.e., reports, reflections, teacher evaluation) collected continuously in a personal portfolio.

Finally, the types/methodologies of evaluation that were not clearly identified and/or unequivocally presented were included (S1-S6, S21, S22, S26, S30-S36, S38, S40, S45; S51-S53), corresponding to a percentage of 41.5% ($f = 22$) of the studies.

3.4. Disadvantages of practical work

Regarding the disadvantages associated with the promotion of practical work, the content analysis of the different investigations of the *corpus* allowed a distribution of studies by five categories, as demonstrated in Table 8. In the first, corresponding to 49.1% ($f = 26$) of the studies, the disadvantages associated with teachers' concerns about the development of practical work are framed, as well as questions of knowledge of professional content (S1, S2, S4, S8, S10, S12, S17; S18, S23, S24, S26-S28, S31, S32, S34, S36, S38, S40, S41, S44, S46, S47, S50-S52). Thus, teachers have to consider various concerns related to fostering practical work, from management concerns, maximization of practical work with students, working with other teachers using effective laboratory methods, and also concerns related to the refinement of tasks, always having the development of students' skills in mind (S4).

On the other hand, there is also concern associated with the possibility of teachers being influenced by a powerful rhetoric that understands practical work as a universal panacea, that is, the educational solution for all learning problems in science (S8). This is particularly worrying, as teachers often reveal a lack of skills to effectively guide students in the conduct of practical work (S32). Despite the previously flagged gaps, teacher education and disciplinary curricula have been emphasizing the relevance of practical work, but not proceeding in the same way regarding the nuclear importance of clarification, on the meanings of words/ concepts, during its performance.

It is possible to argue that the use of language for effective communication in the classroom (as a pedagogical competence) is not sufficiently emphasized in the initial training of science teachers, as well as in their professional development programs, reflecting this aspect in the frequency and quality of the dynamic of practical work (S26). In addition, there are also cultural questions about how adequately prepared students and teachers are, within their zone of proximal development, so that progress toward research learning practices (S2) is allowed.

Although a considerable part of practical work, associated with the encounter and interpretation of relationships, also involves the performance of an adequate data analysis, increasing competence in data analysis is rarely the central objective of practical work, and the lack of competence in this procedure, contributes to a limitation of learning outcomes (S28). Finally, in this category, another of the concerns pointed to the fostering practical work in science, results from a serious misalignment between the intended curriculum, and the one effectively implemented. This situation may be caused by the teachers' misinterpretation of a poorly elaborated global curriculum, making it necessary to make efforts to develop more effective curriculum designs. However noble the ideals of curriculum developers, if the formal curriculum is not clearly articulated, erroneous interpretations will occur, leading to the misalignment mentioned above (S27, S32, S34, S36, S47). In addition, instead of a teacher-centered curriculum, the design of a student-centered curriculum should be promoted according to a constructivist approach (S52).

Other studies (39.6%, $f = 21$) refer to the disadvantages of practical work for the distortion of its purpose, triggered by evaluation processes (S2, S3, S6, S7-S10, S13, S16, S22, S25, S27, S34, S36, S39, S42, S45, S47, S48, S52, S53). In this category, and from the point of view of the students, it is observed that their fundamental concern is the completion of the tasks associated with practical work, mainly due to evaluative questions. This concern can lead to a drastic reduction of any serious possibilities of effective learning (S13). Also due to a congested curriculum, and now from the point of view of teachers, the approaches associated with practical work can also be seen as implausible in the light of the evaluation (S2, S27, S34, S36, S47, S48).

Moreover, a major problem regarding the evaluation of laboratory performance is that such assessment rarely falls on the actual practical performance and is mainly based on the application of written tests (S10). It is also verified in this category that the occurrence of evaluation moments with greater weighting – such as national exams – distort the ways in which practical work has been used to facilitate teaching and learning in science classes (S39). For the evaluation to be effective, it is necessary to consider conceptual understanding, procedural understanding, procedural competences, or practical competences.

Procedural competencies are generalizable, transferable from one context to the other and readily applicable at any juncture. However, the term "practical skills" or "practical competencies," although often referred to in the literature on practical work, is rarely explicitly defined from the perspective of science teaching (S10). It is also considered that the fact that there are alternatives to practical tests in science, means that students can take exams without being exposed to practical work dynamics. This means that in this case, students will be less able to put the knowledge learned into practice, in order to solve real problems of their daily lives (S45).

In a third category and corresponding to a percentage of 37.7% ($f = 20$), there are studies which point to limitations based on economic, organizational and environmental restrictions (S1, S4, S14, S21, S29, S34, S36, S38, S40-S45, S47-S51, S53). It is verified that research learning is not as common in countries with few economic resources, because the implementation of practical work requires facilities with new and updated equipment, with an adequate space for effective participation in practical investigations – the laboratory. For this reason, funding limitations are pointed out - for cases where schools are unable to afford laboratory equipment and technical assistants - as a factor that can prevent teachers from performing practical work.

This situation, in turn, has the potential to contribute to a continuous disengagement with scientific courses, and their subsequent professional careers (S4, S36, S38, S45, S47). In line with these restrictions, the reason why practical work, such as field outings, is not often used in schools, may derive from the general idea that knowledge is acquired in the classroom, classically organized by teachers and students. Out-of-school experiences are often considered unimportant, and field trips have several limitations, such as: planning takes time; available transportation and accommodation budgets are often structured for only half day or at most one day; large classes; disturbance of compliance with the subject's "program"; the climatic instability associated with the exploitation of open spaces, in short, without a preliminary preparation the learning experiences can be quite limited (S21).

Regarding inquiry-based learning, it is found that the fact that it does not occur often in schools relates to the school learning environment that is often rigidly structured, not allowing students to engage in open investigations. These investigations are usually framed in a climate of uncertainty and unpredictability, and the classroom is often not adapted to its proper development. In addition to the situations previously mentioned, the school system also requires teachers to perform a large amount of work for evaluation purposes, and this discourages them from involving students in open and sometimes time-consuming investigations (S29).

Although practical work is often considered essential, it is also associated with concerns related to the risk of chemical hazard and environmental pollution, particularly in the teaching of Chemistry (S38). The problems also arise when the teacher has to deal with large classes, in classes of an investigative nature (S21, S53). Finally, there is also a permanent pressure to justify the continued inclusion of practical work at a time when greater resource management efficiency is required. This pressure becomes more significant in countries facing greater economic challenges (S1).

A set of studies (34%, $f = 18$) identifies limitations associated with the type of learning tasks, mostly descriptive, and with a "cookbook" style (S2, S4, S6-S8, S11, S15, S17-S19, S25, S26, S30, S33, S37, S39, S46, S52). The analysis of these studies allows us to determine that students can become frustrated in learning environments by research, not obtaining a greater conceptual understanding, when compared to direct instruction (S2). This is because, generally, the focus of teachers in practical classes is predominantly to develop scientific knowledge instead of developing scientific research skills, making practical work more effective in getting students to do what is intended, through the manipulation of physical objects, instead of making them mobilize scientific ideas and reflect on the data (S8).

Another limitation pointed to the development of practical work is that sometimes it can be applied so that students only follow the instructions given by the teacher, not needing to use creativity or critical thinking to process the information. In this case, practical work will constitute a waste of time, being confusing and counterproductive (S6). In addition, it can be criticized for not being consistent with the way scientists work, nor to demonstrate how to use scientific ideas to guide their actions, such as reflection on the data that are collected, summarizing only the description of what was done and what was observed (S19). It is increasingly recognized that scientific processes cannot be separated from scientific ideas, and this dialectical relationship between process and content has been accepted by most researchers (S33).

Finally, and corresponding to a percentage of 5.7% ($f = 3$), studies are grouped where limitations are essentially associated with the motivational effects that practical work triggers on students (S1, S20, S43). In this category, it can be seen that the real contributions of practical work are sometimes minimal, with regard to the acquisition of professional and personal skills, not contributing sufficiently to the motivation of students (S1) Students often only prefer practical work and group work when placed in comparison with other more theoretical teaching strategies (S20). Finally, if practical work is not properly performed, it may constitute a cause of stress or anxiety, which in turn can neutralize or prevent the potential educational benefits to be achieved by students (S43).

4. Conclusion

The systematic review of the literature allows us to perceive, with evidence, that the concept of practical work includes, more often, three great ideas: it should be integrator of the manipulation of materials in practical activities according to a *hands-on* approach; include the mobilization of competencies associated with scientific processes, addressing a better understanding of the nature of science; and mobilize scientific knowledge, in line with a *minds-on* approach. The main advantage of the use of practical work is the fact that it allows the development of practical skills in scientific processes and, at the same time, a central conceptual understanding, resulting from the fusion between the *hands-on* approach with the *minds-on* approach in the development of activities. This merger contributes to increasing the motivation for learning sciences, increasing the likelihood that more students will want to pursue a scientific career, which can have a very positive impact on the lack of human resources, which in certain contexts is felt in STEM areas. The second advantage associated with practical work is that researchers consider this methodology to be essential for the development of students' scientific literacy, with a significant impact on a better understanding of the concepts associated with the scientific phenomena under study. In this line, practical work contributes to the important mission of mitigating arguments, beliefs, and/or alternative conceptions, without scientific background, contributing to the formation of better-informed individuals, and able to apply critical thinking. The third major advantage is to enable the development of research skills, allowing students to be immersed in processes in everything similar to the research carried out by scientists, thus bringing them closer to a deeper understanding of their mission and their work in everyday life. This type of practical work will also depend on adequate teacher training.

The most significant practical work evaluation methodology consists of a type of evaluation carried out through a specific framework, using procedures specially designed for practical work to be developed in a specific context, and which focuses on a given phenomenon. In these cases, specially designed assessment tools are used and/or adapted to the specific situation concerned. Practical work is also evaluated through theoretical and/or practical tests and work forms. Training approaches that provide, for example, for discussion and explanation of a number of issues, as well as aspects associated with forecasting, the creation of methods, problem solving, discussion of conclusions or explanations of scientific phenomena, do coexist.

The great disadvantage of practical work is a consequence of the type of strategies adopted. If practical work is not properly conducted, it can easily become a methodology that is not in agreement with the way scientists develop their research, even transforming it into a practice that consists essentially of a mere description of what has been seen, and what has been accomplished, promoting overly descriptive and formatted activities in a "cookbook" style. A second criticism points out that it is difficult to perform the proper realization of practical work in the teaching of sciences in countries and in contexts with low economic resources. These financial difficulties have a direct impact on adequate training of human resources, preventing the development of the full potential of this methodology, also having an impact on the creation of appropriate spaces and infrastructures, such as laboratories and non-formal science education centers, and also impact on the ability to acquire materials and reagents for a proper equipping of these spaces.

The development of practical work with open investigations requires adequate areas and classes not very large, which is not the reality lived in many schools. On the other hand, the consumption of time and the amount of work associated with the evaluation process of activities of this nature discourages students and teachers. Fourthly and lastly, it is also verifiable that students are often more concerned with completing practical work, according to what they think is expected by the script/protocol or the teacher himself, thus blocking a good part of the learning opportunities and, consequently, deviating from and misrepresenting the main purpose of the role of practical work.

In conclusion, and particularly recovering the identification of the advantages and limitations associated with the development of practical work in science education, it should be noted that the effect of the advantages appears to be more significant, having the ability to overcome the limitations identified in the different studies of the corpus. In this sense, it is therefore important to mention that the investigations which recognized these disadvantages or limitations do not call into question the performance of practical work, given its enormous relevance in learning, doing, and understanding the nature of science. What the research, several times, put into question, are the form and conditions in which the practical work is carried out.

So, in simple terms, the great reflection that can be made, with a view of the future of practical science teaching is: How can we turn these limitations into opportunities? Although this is a complex challenge, evidence suggests that the answer lies, among other aspects, in the appropriate initial and in-service training of science teachers in this particular field. This is because if teachers are more confident in their professional content knowledge, also in the area of practical work, they will increase the range of appropriate strategies to adopt in their teaching practice, increasing the probability of this being positively reflected in students' academic performance.

In order to carefully investigate whether practical work is relevant and successful in science education, it is undoubtedly of interest to investigate the everyday reality of teachers and students, in order to apprehend their perception of the practical work relevance, whether the textbooks they use favor this methodology, if the curriculum is designed taking into account an adequate operationality of practical work, if there are opportunities for non-formal science education where practical work is carried out, if the assessment methodologies are adapted to the purposes of practical work, and if the human and material resources available in schools are also compatible with its appropriate implementation.

Lastly, practical work is considered to remain a methodology with high formative value, provided that there are resources to develop it and the orientation given to the various strategies is in accordance with its potential and limitations.

Author contributions

HO: conceptualization and writing – original sketch. JB: formal analysis and writing – review and edition. All authors contributed to the article and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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