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Mobile Technology-supported Inquiry-based Learning in Secondary School Science Education: A Systematic Review

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Abstract

Recent years have seen a growing call for inquiry-based learning (IBL) in science education and mobile technologies are perceived as increasingly valuable tools to support this approach. However, there is a lack of understanding of mobile technology-supported IBL (mIBL) in secondary science education. More evidence based, nuanced insights are needed about how using mobile technologies might facilitate students' engagement with various levels of inquiry and enhance their science learning. We therefore conducted a systematic review of the research articles on mIBL in secondary science education that have been published from 2000 to 2019. We reviewed and analysed 31 empirical studies (34 articles) to explore the types of mIBL, and the benefits and constraints of mIBL in secondary science education. The findings of this SLR suggest new research areas for further exploration and provide implications for secondary science teachers selection, use and design of mIBL approaches in their teaching.

Keywords: M-learning, Inquiry-based learning, Secondary school education, Science education, Systematic literature review

1. Introduction

Inquiry-based learning (IBL) is a pedagogical approach in which students begin with a question followed by investigating the solutions, reflecting and communicating findings, and creating new knowledge based on the collected evidence (National Research Council, 2000; Savery, 2015). It can be also viewed as a process of "*discovering new causal relations*" (Pedaste et al., 2015), as learners propose and test hypotheses by carrying out experiments and/or observing phenomena (Pedaste, Mäeots, Leijen, & Sarapuu, 2012). Recent years have seen a growing call for IBL in science education because this approach has the potential to facilitate more positive student attitudes toward science and a deeper student understanding of science concepts (HarlEn, 2013; Suárez, Specht, Prinsen, Kalz, & Ternier, 2018). Banchi and Bell (2008) discussed four levels of IBL: confirmation (students are provided with the question, procedures and solutions in advance), structured (students are provided with the question and procedures, and they come up with solutions based on the collected evidence), guided (students are provided with the question, and they design the procedures and generate the solutions), and open (students develop their own questions, design and perform investigations like scientists, and create their results). It is in guided and open inquiry where students develop a deeper scientific thinking and reasoning.

Mobile learning (m-learning) is the process of learning mediated by handheld technologies such as smartphones and tablet devices (Authors, 2018b). The flexibility and increasingly diverse capabilities of these mobile devices have created considerable interest in education. For instance, claims of enhanced collaboration and social interactivity; in-situ data collection and sharing; communication between peers, teachers and experts; and customisation of students' learning have been reported (Authors, 2015; Mifsud, 2014). In science education, researchers have begun to investigate the application for m-learning across a variety of contexts (Authors, 2016), particularly supporting inquiry-based teaching approaches (Song, 2014; Zhang et al. 2010).

Use of mobile technologies for science learning provides potential opportunities to: (1) support various levels of inquiry and generate new types of inquiry (Edelson, Gordin, & Pea, 1999); (2) facilitate learners' curiosity and motivation (Chiang, Yang, & Hwang, 2014); (3) facilitate seamless learning across a range of learning spaces (Kong & Song, 2014; Song & Wen, 2018); and (4) bridge formal school-based science curriculum and informal science learning in daily life (Specht et al., 2012). There have been numerous projects aiming to design and create mobile applications/software systems for inquiry-based science learning (e.g. LETS GO project [S16] and Zydeco project [S21, S22]). However, much attention from the research has been paid to more techno-centric foci (Authors, 2018a), rather than more extensive investigations of how the use of mobile technologies might support inquiry-based science learning. Prior studies only partially reviewed the role of mobile technology-supported IBL (mIBL) in science education (Authors, 2018a; Zydney & Warner, 2016) or focused on mobile activities in the context of mIBL in any discipline (Suárez et al., 2018). Limited attention has been directed toward more nuanced understandings of inquiry-based mobile learning (m-learning) in secondary science education, a context with well-known student engagement problems (Palmer, Burke, & Aubusson, 2017).

The objectives of the present study are to identify the types of mIBL being adopted, and ascertain advantages and disadvantages of mIBL in secondary school science education by reviewing the extent literature. The study aims to develop fresh insights into mIBL in secondary science education such as identifying inquiry settings and contexts that have been addressed in the literature. The findings of this review delineate the trends of mIBL in secondary school science education and uncover potential areas for further investigation. Furthermore, the findings serve as a starting point to help teachers select and use types of mIBL for achieving desired outcomes and organise relevant activities. Our review benefits developers and policymakers in their decision-making on further developments of mobile technologies/applications (or ‘apps’) to support IBL in secondary school science education. To achieve these aims, the study is guided by two research questions (RQs) in relation to m-learning in secondary school science education:

RQ1*: What types of mIBL have been adopted?*

RQ2*: What are the benefits and constraints of mIBL?*

To address these questions, following the guidelines of the PRISMA statement (Liberati et al., 2009) and Evidenced Based paradigm (Kitchenham, Budgen, & Brereton, 2016), we conducted a systematic literature review (SLR) of the empirical studies that have investigated mIBL in secondary science education during 2000-2019. A SLR follows a rigorous procedure for search and selection of the sample studies in the review. It is a methodical process of collecting and collating the published empirical studies with systematic criteria for selection and quality assessment to reduce bias and provide transparency to the process. The SLR method is well suited to providing a summative overview of existing empirical research undertaken within the field.

2. Related Studies

A considerable number of review studies have been published on mobile technology used in education. These reviews include capturing specific research facets of this area (Authors, 2018a; Cheung & Hew, 2009; Crompton & Burke, 2015; Crompton et al., 2016; Hwang & Tsai, 2011; Hung & Zhang, 2012; Hwang & Wu, 2014; Liu et al., 2014; Wingkvist & Ericsson, 2013; Wu et al., 2012), such as publication trends, research methods, data collection methods, research topics/purposes, sample groups selected, categories of disciplines represented in the m-learning studies. Some researchers also addressed the types of mobile devices used in learning (Cheung & Hew, 2009; Crompton & Burke, 2015; Liu et al., 2014; Wu et al., 2012), types of mobile applications/operating systems used to support learning together with their main features (Authors, 2018a; Hsu & Ching, 2013; Naismith et al., 2004; Pereira & Rodrigues, 2013; Sung, Chang & Liu, 2016; Zydney & Warner, 2016) and theoretical foundations underlying the design of these applications (Park, 2011; Zydney & Warner, 2016). A few studies reviewed and analysed pedagogical affordances of m-learning (Authors, 2018a; Park, 2011; Zydney & Warner, 2016) and impacts of using mobile technology for learning (Authors, 2018a; Crompton & Burke, 2015; Crompton et al., 2016; Hsu & Ching, 2013; Hwang & Wu, 2014; Liu et al., 2014; Sung, Chang & Liu, 2016; Wu et al., 2012; Zydney & Warner, 2016). For example, learning performance, engagement, participation and interaction have been the foci of these studies. Frohberg, Göth, and Schwabe (2009) analysed m-learning activities based on context, tools, control, communication, subject and objectives. Among the aforementioned reviews, although several researchers emphasised their study scope on m-learning and mathematics/science (Authors, 2018a; Crompton & Burke, 2015; Crompton et al., 2016; Zydney & Warner, 2016), only two of them included a mIBL focus in their studies. Zydney and Warner (2016) examined mobile apps used to support IBL and the theoretical foundations for design of these mobile apps. While Authors (2018a) identified IBL as one of the most popular pedagogical approach utilised in secondary mathematics and science education and cross analysed IBL approaches with the outcomes based on different types of mobile apps/technologies. However, investigating types as well as benefits and constraints of mIBL were not a feature of these SLRs.

Suárez et al. (2018) focused on mIBL and analysed the types of mobile activities based on a range of dimensions including goals, action, strategy, reflection, content, and monitoring. In our SLR, we converge on the context of secondary science education, scrutinising the fundamental research facets of mIBL and looking at the settings and contexts of mIBL (e.g. level of inquiry, mobile applications/software systems, mobile devices, activity settings applied). We also analyse and synthesise types of mIBL as well as benefits and constraints of mIBL in secondary science education. This helps us to understand trends of mIBL and reveal potential areas for further exploration. Our study also assists teachers in (1) selecting certain types of mIBL based on their affordances and limitations for achieving expected outcomes and (2) organising activities for implementing these types of mIBL.

Our SLR differs from existing review studies in the following ways (see Figure 1):

- *Scope of educational level, discipline, and pedagogical approach*: In this review, we focus on studies where mobile technology was used to support IBL in secondary science education. Figure 1 shows that related SLRs on m-learning either investigated IBL at all educational levels and multiple disciplines (Suárez et al., 2018) or focused on multiple pedagogical approaches (Authors, 2018a).
- *Timeframe of review*: The 20 year timeframe of our review ranges from 2000 to 2019 to capture all developments during this period.
- *Focus of review:* This study gives various frequency analyses and cross analyses of the results from the reviewed studies, such as research designs, types of mIBL, and benefits and constraints of mIBL.
- *Included studies:* We only included the studies that followed empirical research designs (e.g. case study, survey, experiment, and quasi experiment as advised by

(Kitchenham, Budgen, & Brereton, 2016)) for investigating mIBL in secondary science education.

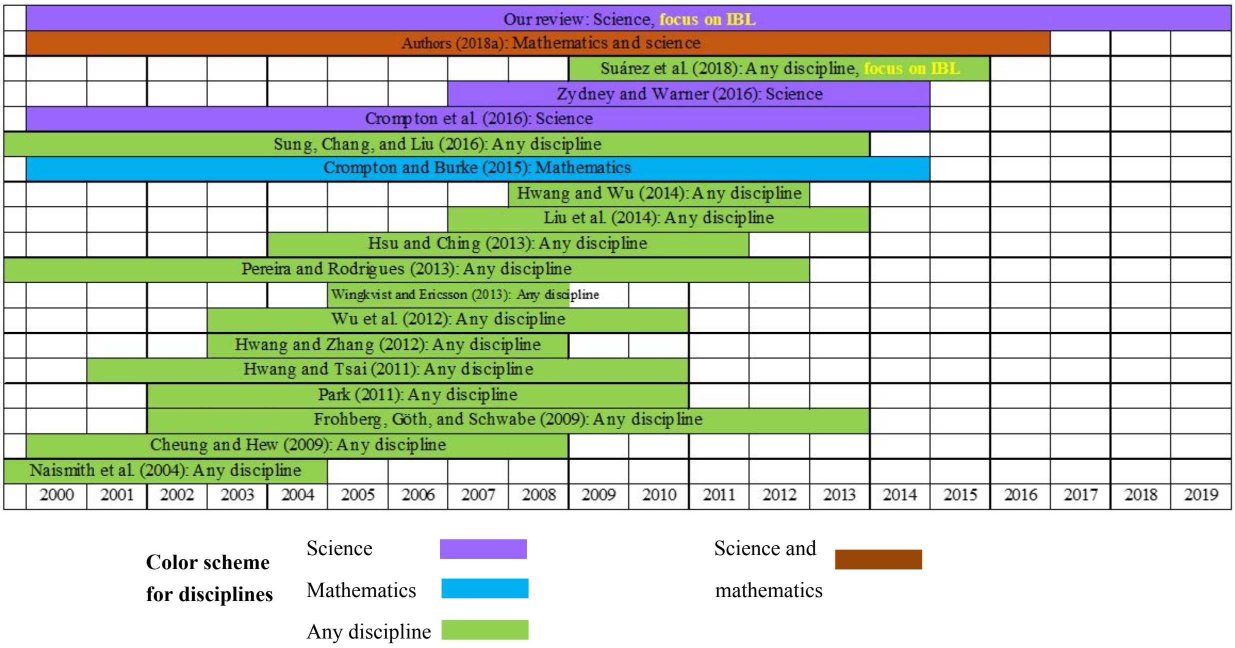

Figure 1. Comparison of review studies in m-learning with our SLR, based on discipline and timeframe on the reviewed studies

3. Research Methods

To conduct this systematic review, we followed the guidelines of PRISMA statement (Liberati et al., 2009) and Evidenced Based paradigm (Kitchenham et al., 2016), including the following three main activities: (1) development of search strategy; (2) selection of relevant studies; (3) extraction, synthesis, and analysis of data from the included studies.

3.1 Development of search strategy

Our search process began by defining a search strategy that assisted in searching for all possible relevant studies (Authors, 2018a). Three steps were involved in this process: identification of major search terms, formulation of search terms, and selection of databases and outlets (Kitchenham et al., 2016; Liberati et al., 2009).

3.1.1 Identification of major search terms

Informed by our objectives and research questions, we identified the following major search terms: inquiry-based, mobile learning, science, and secondary education.

3.1.2 Formulation of search terms

Before generating the synonyms and alternative terms from the major search terms, we performed a preliminary survey on the existing literature reviews of mIBL and m-learning in science education. From these literature reviews (Authors, 2018a; Crompton & Burke, 2015; Crompton, Burke, Gregory, & Gräbe, 2016; Hwang & Tsai, 2011; Suárez et al., 2018), we come up with a list of alternative words for the major search terms (see Table 1). These selected keywords that were most frequently used in the literature, enabled us to identify an exhaustive set of publications related to mIBL in secondary science education. Accordingly, our search began with those keywords by using the Boolean operators as the following search strings: ((“m-learning” OR “m-Learning” OR “mLearning” OR “ubiquitous learning” OR “wireless learning” OR “seamless learning” OR “situated learning” OR “digital learning” OR “mobile technology enhanced learning”) AND (Science OR Biology OR Chemistry OR Geology OR Physics OR STEM) AND (“Inquiry*”) AND (“Secondary education” OR “High school” OR “Middle school”).

Table 1. Synonyms and alternative terms for the major search terms

Major search term	Inquiry-based	Science	Mobile learning	Secondary education
Synonyms and alternative terms	Inquiry* (Inquiry-based, Inquiry based, Inquiry learning)	Sciences Biology Chemistry Geology Physics STEM	M-Learning mLearning Ubiquitous learning Wireless learning Seamless learning Situated learning Digital learning Mobile technology enhanced learning	High school Middle school

3.1.3 Selection of databases and outlets

In this review, we used 20 databases as the initial resources for the search as advised by other review studies in this field (see Figure 1). By using these 20 databases (see Figure 1), an exhaustive view on the field could be established. With the search strings, we searched the publications in Title, Abstract, and Keywords using the online databases to centralise our search. Our search is also customised with search strings in different databases to obtain an initial list of papers. We included a list of specific conferences and journals for search in this SLR as advised by authors of other SLRs in this field (see Figure 1). These journals and conferences have served as essential manual search sources in previous surveys and reviews of m-learning in science education.

We also referred to the references provided in existing relevant SLRs (Authors, 2018a; Crompton & Burke, 2015; Crompton et al., 2016; Suárez et al., 2018; Zydney & Warner, 2016) related to m-learning in science education or mIBL, to identify any articles that might be missing in our search. To enrich the study sample for further analysis, backward (i.e. using the reference list to identify new papers) and forward snowballing (i.e. finding citations to the papers) approaches are also used in this review (Kitchenham et al., 2016).

3.2 Selection of relevant studies

The purpose of this activity was to screen relevant studies from the initial searched papers for further analysis. The inclusion criteria adopted in this review were: (1) the articles included were published in English (IC1); (2) the articles were selected with a publication date from January 2000 to August 2019 (IC2). To ensure the search of studies related to contemporary pedagogical uses of mobile devices, we decided on a time frame of the reviewed literature from 2000 onwards in this SLR; (3) the theme of the articles concerned the use of m-learning applications (or 'apps') to support science learning (IC3); and in the context of the studies involved students and/or teachers in secondary education (IC4). The removal of papers is based on the following exclusion criteria: (1) the studies do not provide robust empirical findings (EC1); (2) the articles are not peer-reviewed research publications (e.g. thesis, editorial letters, and book reviews) (EC2); (3) the papers are not accessible online (EC3); (4) the papers are duplicates (EC4); or (5) the papers do not address our research questions (EC5).

In this review, 371 articles were identified (325 from online databases, 33 from specific outlets, and 13 from previous literature reviews), of which 320 were removed upon title and abstract review, based on our inclusion and exclusion criteria. After full-text review, we further discarded 21 papers based on EC(5). In the snowballing process, we identified an additional 12 papers of which 4 papers then remained after the abstract and full-text review, based on inclusion and exclusion criteria. 34 papers appeared to be eligible for further analysis, as shown in Figure 2. Each paper was given a unique identifier (the letter S followed by a number) so the paper could be referenced in the analysis and reporting of the findings. If more than one paper reported results from the same empirical study, they were treated as one study and given a sole identifier. All 31 studies included in this SLR are listed in Appendix A.

3.3 Extraction, synthesis, and analysis of data from included studies

We used a spreadsheet to design a data extraction form to extract the demographic data from the included studies, such as title, authors, type of outlet (journal or conference), name of outlet, publication year, number of citations in Google Scholar, duration of study, type of participants (students, teachers or parents), and number of participants. We then analysed and coded the description and details in the text of each selected study relevant to our RQs using content analysis technique. However, not every article addressed both of our RQs. We thus extracted and recorded relevant responses from the included studies for the RQs into the form. Thereafter, we conducted the frequency analysis for the extracted data, grouped similar content based on each RQ and gave each group an appropriate name through thematic analysis.

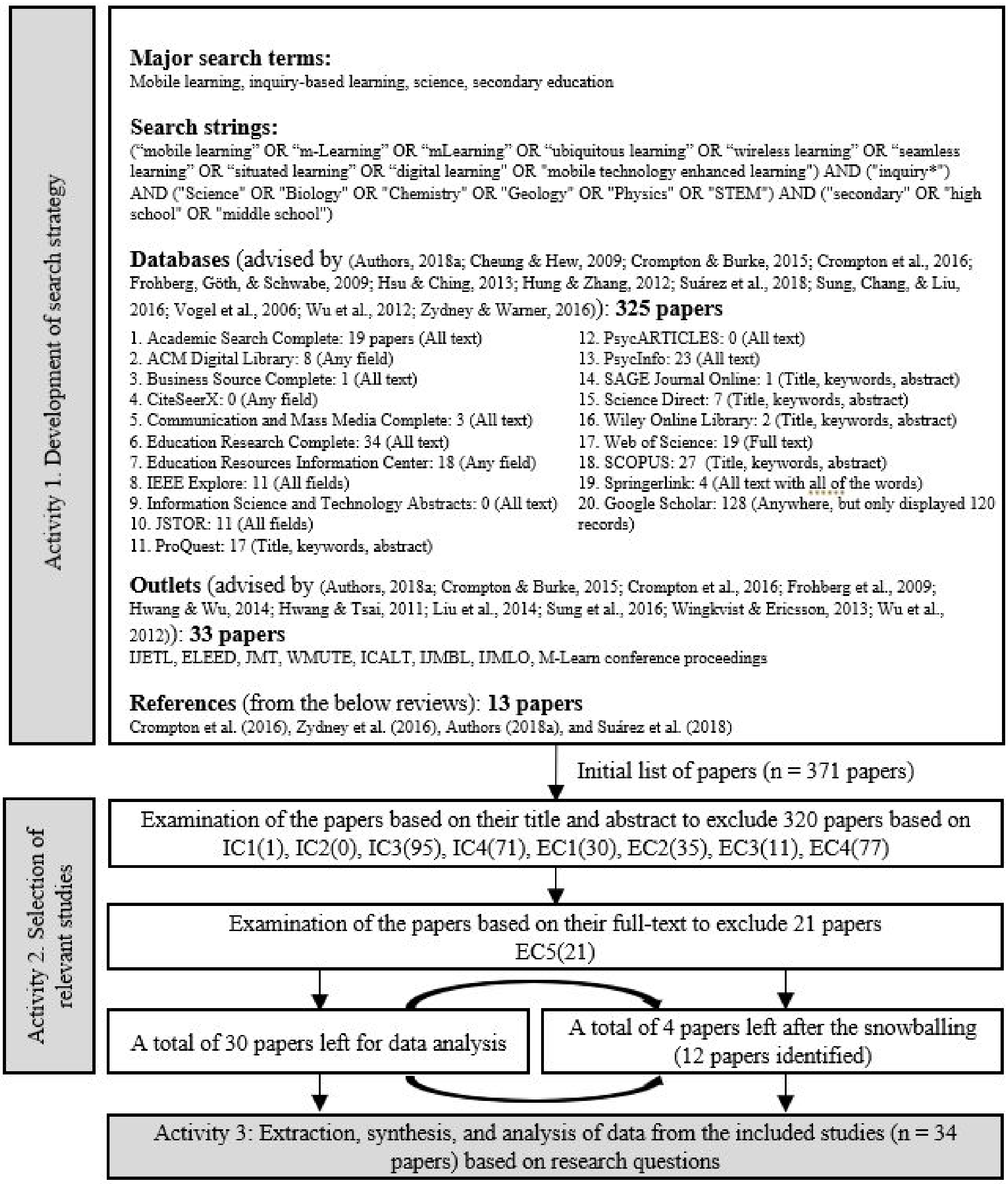

Figure 2. The research process of this SLR

4. Results

In this section, the results of the analysis are presented. First, the demographics of the studies in this review are described to better understand the characteristics of the studies on mIBL in secondary science education. Then, the findings derived from synthesis of the reviewed studies based on our RQs are presented.

4.1 The characteristics of the reviewed studies

This subsection gives an overview of the characteristics of the reviewed studies from three perspectives including: publication trends (see Section 4.1.1), research designs (see Section 4.1.2) and study participants (see Section 4.1.3). As mentioned in Section 3.2, in this SLR 31 studies are analysed.

4.1.1 Publication trends

We observe the number of mIBL publications focusing on secondary science education contexts. Although the m-learning literature contained many *articles* with a focus on m-learning in secondary science education, the more specific focus on IBL activities in this context has only become a more prevalent research topic since 2012, as shown in Figure 3. This phenomenon may be due to (1) new ways that emerged to deal with science inquiry using m-learning technology such as abductive science inquiry [S3, S18, S24] (detailed in Section 4.2.1), (2) the promotion of augmented reality (AR) technology, widely used in science inquiry learning activities [S15, S30], and (3) the increased connection of classroom and field learning contexts in science inquiry activities within projects (e.g. LETS GO [S16] and Zydeco [S21, S22] projects). The majority of the *articles* were published in education technology journals and conferences, rather than science education outlets, as listed in Appendix B.

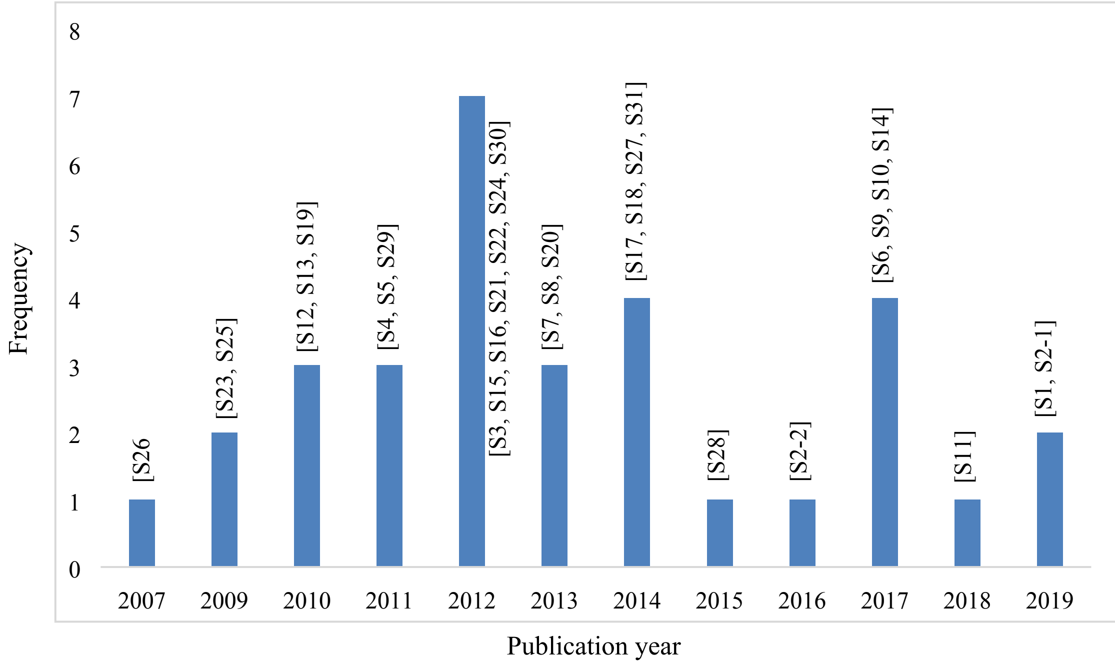

Figure 3. Number of *papers* on mIBL from 2007 to 2019 August

4.1.2 Research designs

We examined the research designs used in the included 31 studies. These research designs that have been explicitly described and/or mentioned by the respective authors in their studies are: case study, experiment, field study, quasi experiment, survey, and multiple research design. Table 2 gives the frequency of the research designs used in the included studies. Investigating the characteristics of research designs that determine the strength of causal inferences being drawn from research findings, contributes to understanding what kinds of research design have been used and providing guidelines for those researchers who are undertaking similar studies. We could also learn experiences from prior research to improve future studies based on the disclosed limitations and propose potential research areas.

Table 2. Distribution of the research designs used in the reviewed *studies*

Research designs	Number of the reviewed *studies* (percent)	References
Case study	8 (26%)	[S2, S8, S18, S23, S25, S26, S29, S31]
Experiment	7 (23%)	[S3, S10, S13, S14, S15, S19, S20]
Field study	7 (23%)	[S1, S4, S5, S12, S21, S22, S30]
Multiple	1 (3%)	[S17]
Quasi experiment	2 (6%)	[S6, S9]
Survey	6 (19%)	[S7, S11, S16, S24, S27, S28]
Total	31	

Researchers in the selected studies collected data to address their research questions using various methods, as shown in Table 3. They conducted interviews with teachers and/or students and administrated questionnaires or tests to gather their participants' experiences of using mobile technology in inquiry-based science learning, and for capturing their science understandings. Observations were used to investigate what happened in the classroom and/or on fieldtrips, and field notes were taken as supplementary materials. Researchers also examined students' work, such as group posters, and tracked system logs to investigate how science students used mobile technology in their inquiry activities.

We identified the duration of research for the included studies and divided them into groups, as advised by Authors (2018a). Most of the reviewed studies (58% of the total studies) were conducted in less than one month. The duration of 7 studies was between one and three months (23% of the total studies). Only 4 studies reported the duration of their research as exceeding three months (13% of the total studies). See Table 4.

Table 3. Distribution of the methods of data collection used in the reviewed *studies*

Method of data collection	Number of reviewed *studies*	References
Interviews	17	[S2, S3, S6, S7, S8, S9, S13, S14, S15, S16, S18, S22, S23, S25, S26, S28, S29, S30]
Questionnaires	16	[S3, S6, S9, S10, S11, S12, S13, S14, S20, S23, S24, S26, S27, S28, S29, S30]
Observations	12	[S1, S2, S4, S5, S8, S13, S17, S21, S23, S25, S26, S29, S31]
Field notes	6	[S1, S4, S5, S8, S17, S22, S25]
Students' work	6	[S8, S16, S17, S21, S22, S25, S31]
System logs	4	[S2, S12, S22, S29]
Tests	5	[S3, S14, S20, S28, S30]

Note that one study may use more than one data collection method and cover multiple categories.

Table 4. Timeframe ranges of the reviewed *studies*

Duration of research	Number of the reviewed *studies* (percent)	References
Less than one month	18 (58%)	[S1, S2, S4, S5, S10, S11, S12, S13, S14, S16, S20, S21, S22, S25, S26, S28, S29, S30]
More than one month and less than three months	7 (23%)	[S3, S6, S8, S18, S19, S27, S31]
More than three months	4 (13%)	[S9, S15, S17, S23]
Not given	2 (6%)	[S7, S24]
Total	31	

4.1.3 Study participants

We gained an insight into the characteristics of participants in the SLR. Firstly, regarding the type of participants, as shown in Table 5, 68% of the total studies (21 studies) only recruited students, and 23% (7 studies) included both teachers and students. One study targeted students, teachers, and a museum educator, while one study recruited students, teachers and parents. In one study, the scholars acted as participant researchers by using mobile devices to address a set of inquiry problems in the context of secondary science education [S1]. These results reveal that students were the most prevalent subjects targeted in the literature and the next most prevalent subjects were teachers. Furthermore, the research diverged their trends by involving multiple participants from community such as museum educators and parents. While the perspective of community-based participants on mIBL in secondary science education has received attention in the research [S1, S8, S23], this evident lack of emphasis on community-based participants (only 3 out of 31 studies) is still in agreement with the result reported from Authors (2019).

Table 5. Demographics of participants based on their type

Type of participants	Number of the reviewed *studies* (percent)	References
Students only	21 (68%)	[S2, S3, S4, S5, S6, S7, S9, S10, S11, S12, S13, S14, S17, S19, S20, S21, S22, S24, S27, S28, S31]
Students and teachers	7 (23%)	[S15, S16, S18, S25, S26, S29, S30]
Students, teachers, and a museum educator	1 (3%)	[S23]
Students, teachers, and parents	1 (3%)	[S8]
Researchers	1 (3%)	[S1]
Total	31	

Secondly, we examined the characteristics of participants recruited in the studies from the sample size perspective. Table 6 outlines the distribution of sample size used in the studies in this review, based on different size groups.

Table 6. Size ranges of study sample

Size of sample	Number of the reviewed studies	References
1 – 50 participants	14 (45%)	[S2, S5, S7, S9, S12, S13, S14, S16, S19, S21, S23, S24, S26, S29]
51 – 100 participants	12 (40%)	[S4, S8, S10, S11, S15, S18, S20, S22, S27, S28, S30, S31]
101 – 200 participants	2 (6%)	[S3, S6]
> 200 participants	1 (3%)	[S17]
Not given	2 (6%)	[S1, S25]
Total	31	

4.2 Findings addressing the research questions

This subsection presents our findings derived from the reviewed studies based on our RQs. Section 4.2.1 answers RQ1 summarising the types of mIBL in the context of secondary science education. Section 4.2.2 addresses RQ2 presenting the benefits and constraints on mobile technology supported inquiry.

4.2.1 Types of mIBL

In this review, we identified five main types of mIBL from the included studies, and these types are: (1) authentic scientific inquiry, (2) abductive science inquiry, (3) collaborative inquiry, (4) collective whole-class inquiry, and (5) inquiry with a game component, as shown in Table 7. These terms are used because they have been explicitly mentioned in the reviewed studies to describe the types of mIBL. Table 7 also lists a description for each type with relevant literature that helps better understand these types.

4.2.1.1 Authentic scientific inquiry (AUI)

Authentic scientific inquiry was the most frequently used type of mobile technology supported IBL in this review (a total of 28 studies), being an area of focus in 90% of the included studies. Authentic scientific inquiry occurred when students took advantages of mobile technology to collect and analyse data in hands-on practices and make a conclusion towards a real-life problem. Among these studies concerning authentic scientific inquiry, in 14 studies students addressed a given investigation problem by using their designed or selected procedures, and in 10 studies students proposed their own research problems or hypotheses and selected or designed procedures.

Table 7. Types of mIBL identified in this review

Type of mIBL	Description	References
Authentic scientific inquiry (AUI)	Students conduct hands-on investigations using mobile technology that parallel scientists' practices for a real-life problem (Chinn & Malhotra, 2002; Marlow & Stevens, 1999)	[S1, S2, S3, S4, S5, S6, S8, S10, S11, S12, S13, S14, S15, S16, S17, S18, S19, S20, S21, S22, S23, S24, S25, S26, S28, S29, S30, S31]
Abductive science inquiry (ABI)	Students develop plausible hypotheses based on theories and observation (Råholm, 2010) with assistance of mobile technology. New explanations emerge based on the observed phenomena (Oh, 2011).	[S3, S18, S24]
Collaborative inquiry (CAI)	Students in groups/pairs engage in investigations with mobile devices to answering a question of importance to them (Bray, Lee, Smith, & Yorks, 2000; Kasl & Yorks, 2002)	[S2, S4, S6, S7, S8, S9, S10, S11, S12, S13, S16, S17, S19, S21, S25, S26, S27, S28, S29, S30, S31]
Collective whole-class inquiry (CEI)	Students engage as a whole class in jointly negotiating problems and working for a common goal [S31] (Jeong & Hartley, 2018) with the assistance of mobile technology	[S31]
Inquiry with a game component (GCI)	Students use a game as learning materials and conduct investigations for addressing a problem with the assistance of mobile technology (Srisawasdi & Panjaburee, 2019)	[S25, S26, S27, S30]

Note that one study may involve more than one inquiry type.

These real-life problems covered various science subjects, such as biology (the problems were related to figuring out the organisms in rainforest stations [S31]), botany (the problems were, for example, identifying the part of a Lotus flower typically used to protect the flower in the bud [S14]), chemistry [S10], environmental science (the problems concerned the decline of the mallard duck population [S2], mosquito borne diseases [S6], plant morphology and biodiversity [S11], water quality [S12, S13, S16, S17, S19, S30], and Ivan's death [S26]), food science (the problems were about decomposition of food S8] and health diets [S29]), geosciences (the problems involved the features of rocks [S20]), math and science [S15, S25], physics (the problems referred to sound pollution [S1], heat energy transfer [S3, S18, S24], Ohms' law in electricity [S11] and trajectories of the balls [S28]), and archaeology (the problems concerned artifacts and biofacts for example [S4, S21, S5, S22, S23]). The majority of these inquiry activities (13 studies) took place in seamless learning contexts covering both inside and outside of classroom settings [S5, S6, S11, S12, S13, S15, S16, S17, S19, S22, S23, S29, S30]. Eight studies reported authentic inquiry activities happening only outside of the classroom [S1, S2, S4, S8, S14, S21, S25, S26], while 7 studies reported on classroom contexts [S3, S10, S18, S20, S24, S28, S31].

4.2.1.2 Abductive science inquiry (ABI)

Abductive science inquiry refers to inquiry activities supporting science students' generation of hypotheses based on theories and observations and their explanation of the observed phenomena using critical thinking [S3, S18, S24]. Ahmed and Parsons [S3, S18] developed a mobile web application "ThinknLearn" that helped the students generate hypotheses in inquiry activities for understanding heat energy transfer. The students measured and recorded the temperature of the three tins with different surface colors (white, black and silver/shiny) using the "ThinknLearn" at a particular time. Then these students were asked to answer a set of multiple choice questions on the collected values of the measures, assisting them in developing hypotheses about the observed measures. Thereafter, the students selected one plausible hypothesis based on the given question, and also proposed their explanations. These inquiry activities were conducted in the classroom.

4.2.1.3 Collaborative inquiry (CAI)

Collaborative inquiry was the second most commonly used type of mobile technology-assisted inquiry identified in this review (21 studies). This inquiry pertains to "*a process consisting of repeated episodes of reflection and action through which a group of peers strives to answer a* *question of importance to them*" (Bray et al., 2000) (p. 6). Students worked in groups/pairs to collect and interpret data (either quantitative or qualitative data), shared the collected data, and generated evidence-based explanations in discussion toward the investigation problems. Most studies in this category [S2, S4, S6, S8, S10, S12, S13, S16, S17, S19, S21, S25, S26, S28, S29, S30, S31] were also in the authentic scientific inquiry category (see Section 4.2.1.1), and covered different science subjects with learners in a variety of locations either inside and/or outside of the classroom. We present two studies that are not included in authentic scientific inquiry but were classified in this collaborative inquiry genre. DeWitt et al. [S7] evaluated the strengths and weakness of the CmL Science module that contributed to learning the concept of food in inquiry activities. In this study, the students worked in groups and discussed the given online questions outside the science classroom. While Laine et al. [S9] assessed the students' interests toward science (i.e. math, chemistry and physics, and biology) in an mIBL environment. These students were asked to set individual goals and collaboratively solve problems with peers both inside and outside of the classroom.

4.2.1.4 Collective whole-class inquiry (CEI)

Collective whole-class inquiry involves the entire class of students working as a whole towards a common goal and developing community knowledge based on each other's ideas [S31] (Lakkala, Lallimo, & Hakkarainen, 2005). We distinguish collaborative inquiry and collective whole-class inquiry from the focus of interaction between participants in the mobile technology supported inquiry process. According to Lui et al. [S31], the focus of collaborative inquiry is on interactions in pairs or groups of students with the support of mobile technology, while in collective whole-class inquiry, students develop their understanding "*with an emphasis on collective knowledge* *or progress over individual contributions*" [S31] (p. 2104). Students may work in groups but they generate their own ideas and comment on their peer's ideas in order to improve the consistency of the shared knowledge in the whole class [S31]. In this SLR, only one study took into account collective whole-class inquiry [S31]. In the designed smart classroom environment (i.e. EvoRoom) presented in [S31], the authors investigated how students collected and explored the data for understanding biodiversity through collective whole-class inquiry.

4.2.1.5 Inquiry with a game component (GCI)

Inquiry with a game component pertained to student participants using a games-based learning resource, and solving a problem based on collected evidence [S25, S26, S27, S30]. For instance, Dunleavy, Dede and Mitchell (2009) [S25] developed a mobile application "Alien Contact!" based on AR to explore how students made sense of and used the AR at the mobile simulation outside of classroom to address why the aliens landed. In the inquiry activities, the students with different roles in teams had to explore the AR world, collecting digital evidence and answering math and science quizzes. Similarly, in Squire and Jan's (2007) study [S26], the students were required to play roles in the story in the classroom for addressing why Ivan died, interviewing virtual characters at the AR-based mobile simulation and synthesising their findings based on the collected evidence. In Kalz et al.'s study [S27], the students worked in small groups in the classroom to conduct inquiry activities in the form of a game on the topic of energy consumption and used mobile technology to collect and analyse data for answering their proposed questions, while Kamarainen et al. [S30] investigated how the students in pairs played with the developed EcoMOBILE game to address ecosystem science problems in the field trip.

4.2.2 Benefits and constraints of mIBL

This SLR analysed different foci of mIBL uncovered in the included studies. There were a number of themes in relation to benefits and constraints of mIBL evaluated by the included studies identified in the SLR, and we needed a way to study and understand them. Three of the included studies adopted the M3 evaluation framework to evaluate mIBL [S3, S18, S23]. The M3 evaluation framework (Vavoula, Sharples, Rudman, Meek, & Lonsdale, 2009) addresses three levels (i.e. micro, meso, and macro) and provides a more inclusive theoretical lens to evaluate m-learning than other frameworks such as (Motiwalla, 2007) framework and the TAM framework (Davis, Bagozzi, & Warshaw, 1989) that are only used a single level (i.e. micro or meso level) (Ahmed, 2014). Hence, we utilised the M3 evaluation framework (Vavoula et al., 2009) to categorise aspects of mIBL evaluated in the included studies for understanding the advantages and disadvantages of mIBL. The M3 evaluation framework concerns usability of mobile technology (micro level), learning experience with the support of the technology (meso level), and longer-term impact of the technology on learning practices (macro level) (Vavoula et al., 2009). We categorised evaluated aspects of mIBL that were explicitly mentioned in the reviewed studies at these three levels, based on content and theme analysis. Furthermore, we examined these aspects from both positive and negative viewpoints between teachers and students, as shown in Table 8 (the examples quoted in the reviewed articles to support our summary in Table 8 can be accessed via our online analysis document[1]). Using the M3 framework as a lens to examine the evaluated aspects of mIBL

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[1] The online link is available at https://www.dropbox.com/scl/fi/lbfmkmbvfxq5lgko92o1e/Quotes-in-the-studies-for-evaluation-perspectives.docx?dl=0&rlkey=q5xodxybb1lnuewnpmxs8yvic

in secondary science education, we could identify the benefits and constraints (see ‘positive’ and ‘negative’ columns in Table 8) of mobile technology supported IBL.

Table 8. Positive and negative aspects of mIBL in science education

Level	Aspects		Positive		Negative	
			Learner perspective	Teacher perspective	Learner perspective	Teacher perspective
Micro	Efficiency		[S13]			
	Effectiveness		[S1, S2, S3, S6]	[S30]		
	Learnability		[S3, S5, S13, S14, S15, S18, S23, S29]	[S18, S29]	[S3, S5, S14, S18, S20]	[S23]
	Perceived usefulness		[S14, S20, S22]	[S18, S29]	[S14]	[S18]
	Cognitive load				[S25]	[S25]
Meso	Attitude		[S20]		[S8, S29]	
	Attention		[S3, S4, S21, S23, S30]	[S25, S30]	[S22, S25]	
	Motivation		[S2, S3, S4, S5, S6, S7, S8, S9, S10, S11, S12, S13, S14, S15, S17, S23, S25, S26, S29, S30, S31]	[S18, S23, S25, S26, S30]	[S3, S6, S14]	
	Learning performance		[S3, S6, S20, S27, S28, S29, S30]			
	Group work		[S4, S6, S7, S19, S21, S25, S31]	[S25, S30]	[S7, S25, S31]	[S29]
	Cognitive process	Remember	[S9, S20, S23]			
		Understand	[S5, S6, S7, S12, S21, S24, S28, S30, S31]		[S14, S15]	[S15]
		Apply	[S6, S20, S21, S30]			
		Analyse	[S5, S20, S28]			
		Evaluate	[S20, S22, S26]			
		Create	[S3, S4, S6, S24, S31]	[S18]		
Macro	Motivation		[S23]	[S23]		

4.2.3.1 The evaluation perspective at a micro level

According to Vavoula et al. (2009), the micro level deals with individual activities of technology users, addressing usability and utility of mobile technology for learning. In this review's 31 studies, we identified five main evaluation aspects at the micro level: Efficiency, Effectiveness, Learnability, Usefulness, and Cognitive load as depicted below.

Efficiency is the ability of a mobile application/device that takes users less time to complete a task (Nayebi, Desharnais, & Abran, 2012). As noted in Vogel [S13], students found that using mobile devices to capture the data saved their time to complete the experiment instead of via paper, thus, in the contexts of mIBL, speeding up the data collection process in IBL.

Effectiveness was the ability of a mobile application/device that helps users to complete a task in a specified context (Harrison, Flood, & Duce, 2013). For instance, mobile devices enabled users to complete a set of measurement tasks in scientific inquiry (e.g. measuring sound at the bus stops for a given problem) [S1]. Teachers also agreed with the effectiveness of these devices for supporting data collection in IBL [S30]. However, the use of mobile technology related to capturing, annotating, and organising data seemed to be more effective when this was combined with students' reflective and problem-solving discussions for data collection [S2]. When the students completed a set of tasks in the inquiry process using mobile devices, they considered that mobile technology is effective for learning science [S3], and this is especially true for the slow learners [S6].

Learnability pertained to the ease of which users can learn to use a mobile application/ device, addressing how long it takes users to be able to use the technology at an expected level of proficiency (Harrison et al., 2013). Learnability was the most frequently addressed aspect in this review, at the micro level. On the one hand, when the application/device is user-friendly [S1] and easy to use [S3, S5, S13, S14, S15, S18, S23, S29], this could save students' time and help them learn to use it without lengthy tutorials and manuals [S23], increase their interest and pleasure in mIBL toward science [S5, S14, S15], and help them better understand the learning process [S3, S18, S29] as well as collect and analyse data [S1, S13]. On the other hand, a difficulty to use the application costed students more effort in learning activities [S20] and made them confused, with a lack of understanding of the learning problems [S3, S5, S18], or even made them distracted while using it [S14]. For teachers, an additional load was placed on them, such as taking training sessions that can be expensive and time-consuming [S23].

Perceived Usefulness refers to the extent to which a user believes that the use of mobile technology will enhance his or her learning performance (adapted from (Davis, 1989). Perceived usefulness was the second frequently addressed aspect of the micro level in this review. Some students found that mobile technology was useful since it allowed them to learn science in a better way [S14, S20], such as identifying required information by automatic search [S22]. Teachers also appreciated the usefulness of mobile technology in IBL because it enabled them to manage the inquiry process [S29] and help generate an enjoyable learning experience for their students [S18]. However, a few students considered that the mobile application was not useful since it was inconvenient to hold the devices for a long period of time and found it difficult see the screen in the outdoor environment [S14].

Cognitive load concerned the amount of cognitive processing required by users in using a mobile application/device (Harrison et al., 2013). In a mobile context, users may be required to perform additional tasks (e.g. walking), and this could have an impact on the completion of the primary task (Harrison et al., 2013; Wang, Fang, & Miao, 2018). In this review, only one study [S25] paid attention to this evaluation aspect and indicated that using mobile technology while addressing an inquiry problem in an outdoor environment was challenging for secondary school students due to cognitive overload.

4.2.3.2 The evaluation perspective at a Meso level

The meso level analysis emphasises an examination of the learning experience to identify learning breakthroughs and breakdowns (Vavoula et al. 2009). In the context of this study, learning experience refers to having both a process and an outcome where learners engage in the inquiry process and have outcomes or results through this process (adapted from Fink (2013). The outcomes or results could be new knowledge, skills, behaviors, or preferences developed in mIBL. As Vavoula et al. (2009) did not give specific aspects at this level, we analysed and divided the learning experiences about mIBL into six main groups: Attitude, Attention, Motivation, Learning performance, Teamwork, and Cognitive process. Furthermore, we use the revised Bloom's taxonomy (Anderson & Krathwohl, 2001) as the lens to better understand the students' learning achievements in terms of cognitive process.

Attitude concerns students' favorable or unfavorable feelings toward science learning or inquiry activities [S8, S20] (adapted from (Koballa, 1988)). Wu, Hwang and Tsai [S20] revealed that the students who used mobile technology in inquiry activities showed better learning attitudes than those without using the technology. However, a few students found that their attitudes toward inquiry activities supported by mobile technology was not as positive as expected [S8]. This may be due to the requests to be protective appropriation of the technology by their parents and inconvenience of carrying mobile devices between home and classroom [S29].

Attention addressed the extent to which students were focused on their science learning [S3, S4, S21, S30]. From the perspectives of both students [S3, S4, S21, S23, S30] and teachers [S25, S30], the use of mIBL enhanced the focus of students and helped students to navigate their science learning. However, the limitations of mobile technology could distract students' attention from the learning content. For example, repeatedly playing audio notes disrupted students nearby [S22]. In one study [S25], participants reported on difficulties hearing audio information in an open noisy environment, while the dangers of ignoring the physical environment due to intense focus on devices presented a threat to students' safety [S25].

Motivation was defined for this study as an individual's desire to learn concepts or complete learning tasks in mIBL (adapted from (Bakar, Ayub, Luan, & Tarmizi, 2010; McMillan, Forsyth, & learning, 1991)). In this SLR, 'motivation' was the most frequently mentioned aspect at the meso level. Students were motivated toward science learning when they had an enjoyable learning experience using mobile technology [S7, S14, S15, S23, S25]. To specify, the use of mobile technology that provides data visualization and collaborative opportunities in teams fostered their interests in science [S4, S5, S6, S7, S9, S12, S13, S15, S17, S25] and created feelings of excitement in their learning [S15, S23, S31], leading to enhanced engagement in addressing the inquiry problem [S2, S3, S4, S5, S6, S8, S10, S17, S26, S29, S30, S31]. The autonomy that students enjoyed in their mIBL activities drove them to be more participative in the science learning process [S11]. Furthermore, the psychological need to develop competence, and engaging in a relevant inquiry problem, positively motivated students to perform mIBL activities [S11]. These student perceptions of learning were also affected by teachers' feedback [S18, S23, S25, S26, S30].

However, a small number of studies reported on students who found mIBL boring and tiring [S3, S6, S14].

Learning performance was defined by the studies in this review as the improvement of students' learning as measured by the development of science knowledge (adapted from (Katuk, Zakaria, Omar, & Romli, 2014)). The use of mobile technology to support science inquiry tasks had a positive impact on learning performance (knowledge gains were measured by questionnaires and tests) in these studies [S3, S6, S20, S27, S28, S29, S30]. Researchers in these studies emphasised that the student participants in mIBL activities gained better scores in the tests than those studying without mobile devices [S3, S6, S28, S29]. This could be due to enhanced student motivation, engagement and participation (as previously discussed) in these hands-on investigations [S29], and effective guidance of students in going beyond just finding facts to synthesise and develop new knowledge [S6].

Group work referred to an interaction where students work together for completing a learning task or answering an inquiry problem using mobile technology (adapted from (Van der Haar, Segers, & Jehn, 2013; Pietarinen et al., 2019)). In this SLR, a body of literature pointed out that data sharing and visualisation supported by mobile technology allowed students to exchange and discuss their findings, and facilitated interaction and group work among students, through observing their learning activities [S4, S6, S7, S19, S21, S25, S31]. Teachers highlighted the role of mobile technology in promoting and mediating students' interaction and group work during the IBL activities [S25, S30]. When students had different roles in addressing a common inquiry problem, they needed each other more and exhibited better teamwork [S25]. Although mobile technology could have a positive impact on collaboration among students in IBL, it could also impede group work in some ways. For example, the difficulties in using mobile technology could discourage students' participation in peers' discussion and collaboration [S7]. The mobile applications (or 'apps') could disclose students' privacy to some degree when conducting personalised inquiry (e.g. health diets), and thus students were reluctant to share information with their team members [S29]. Furthermore, the over-reliance on mobile devices could interrupt interactions with peers because students were distracted by specific external 'off-task' interventions from their devices [S31]. Interestingly, mobile technology that generated collaboration *and* competition (at the same time) between peers during inquiry- based science learning may positively influence their engagement [S25]. However, researchers found that some students in groups avoided sharing findings with other groups as they wanted to win, thus rushing and skipping essential text-based information [S25].

Cognitive process concerned the ways in which information is received, processed and used (Walsh, 1995) by learners. Using the mobile technology in IBL could change or enhance learner' cognitive process that could be considered as a form of learning experience. First, for *remember* (locate (or retrieve) knowledge in (or from) memory (Anderson & Krathwohl, 2001)), mobile technology helped students better memorise the knowledge as they could see, do and interact with real world for constructing the knowledge than just reading textbooks [S9, S15, S20, S23]. Second, in terms of *understand* (construct meaning from instructional messages (Anderson & Krathwohl, 2001)), scaffolding tools that help perform data collection, reflection and annotation [S5, S21] and establish the links between students' physical observations and explanations [S6, S24, S30, S31] could strengthen the understanding of the inquiry problem [S7, S12, S28]. However, if the designed mobile applications/software systems were confusing, this could make the learning content difficult to understand [S14, S15]. Teachers also concerned that the mobile applications/software systems could generate misconceptions of the scientific thinking as this is a model of visualising the real world and they had to explain to the students that "*it might not be the totally accurate representation*" [S15, p. 219]. Third, *apply* concerns students executing or using a procedure to complete a task (Anderson & Krathwohl, 2001). It was reported that mobile technology could enhance students' application skills because the technology guided them to carry out hands-on and mind-on activities in inquiry-based science learning [S6, S20, S21, S30]. Fourth, from the *analyse* aspect (distinguish and organise elements within a structure (Anderson & Krathwohl, 2001)), mobile technology had a positive impact on the analytical process as some functional features (e.g. tagging data) could help students differentiate and organise the collected data [S5, S20, S28]. Fifth, tagging data also assist in reviewing and determining the data based on the defined criteria [S20, S22, S26] (the *evaluate* aspect). Last, the *create* aspect addresses constructing elements into a new structure (Anderson & Krathwohl, 2001). With scaffolding tools and hints provided by mobile technology, students could have great potential to build new knowledge and formulate hypotheses based on the observed evidences in inquiry-based science learning [S3, S4, S6, S18, S24, S31].

4.2.3.3 The evaluation perspective at a Macro level

The macro level refers to the longer-term impact of the technology on established learning practices (Vavoula et al. 2009). We only identified one aspect related to this level: motivation. Authors of the study [S23] explicitly pointed out that they adopted the macro level to evaluate the learning activities. An enjoyable learning experience in using mobile technology contributed to students wanting to go back to classroom or field (e.g. museum) to learn science. High-levels of device usability helped students to bridge classroom and field-based learning and sustain their enthusiasm for learning science [S23].

5. Discussion

In this section, we present the findings of this review and the extent to which they answer our RQs. We generate insights into these findings and present areas that require further exploration. The implications and limitations of this study are also outlined.

5.1 Trends in mIBL studies in science education

Our review reveals that the frequency of empirical research in mIBL is increasing in the field of secondary science education during the last two decades (2000-2019). As shown in Figure 3, 91 percent of the included articles in this review were published in the second decade (from 2010 to 2019). There were approximately equal numbers of journal articles and conference papers in this review, as listed in Appendix B. These publication outlets can now be used by other researchers conducting SLR studies in this area of mIBL in science education.

We established links among research designs, data collection methods, and duration of studies identified in this review, as shown in Appendix C. In this light, we explored the characteristics of research studies in the literature and provided implications for future research designs, including selection of suitable data collection methods.

Case study was the most popular research design adopted in studies in this review. The majority of researchers adopted case study research design for achieving a deeper understanding of processes toward the use of mobile technology in science inquiry. Thus, interviews of participants and observations of students' inquiry activities were the most frequently used data collection methods (see Appendix C). These two methods allowed researchers to generate insights into the learning process [S2, S25, S26, S29]. Furthermore, many of the included studies did not consider longer-term impact of the technology use on science inquiry practices (e.g. due to time or funding limitation), and the research duration was typically limited to less than one month. This was especially true for field study research design (see Appendix C) since organising students in field trips requires additional workload and preparation [S23] and visiting the fields multiple times is expensive.

To facilitate better empirical results, combinations of multiple data collection methods are recommended in future research on mIBL. This allows researchers to validate findings by triangulation and overcome potential bias. For example, field notes and system logs combined with observations should yield more details on critical processes of using mobile technology in science inquiry. Both tests (pre and post) and analysis of students' work can help better investigate learning performances. The study based on a single inquiry context needs to be repeated in similar contexts, assisting to validate the results [S3]. In addition, our review discloses that the majority of the included studies had relatively short research durations and therefore may not sufficiently probe the longer term benefits of mIBL in this secondary science context [S8, S26]. A longer timeframe is needed to fully investigate the experiences of mIBL for science learning in future studies [S3, S12, S22].

5.2 Extending our understanding of mIBL in science education

After discussing the findings and implications based on the characteristics of the reviewed studies, we now discuss findings associated with the two RQs for this study.

5.2.1 Types of mIBL

The types of mIBL for science secondary education in this SLR included: (1) authentic scientific inquiry; (2) abductive science inquiry; (3) collaborative inquiry; (4) collective whole-class inquiry; and (5) inquiry with a game component.

While Suárez et al. (2018) have distinguished the types of mobile activities in IBL that *provide guidance for learners to carry out inquiry processes*, little is known about what types of mIBL have been used. We explored the relationships between these types, as shown in Figure 4, and found that some studies involved more than one type of mIBL. For example, approximately 50% of the included studies adopted both authentic science inquiry and collaborative inquiry with the support of mobile technology in secondary science education. Abductive science inquiry was used with a combination of authentic scientific inquiry [S3, S18, S24]. An inquiry type with a game component was combined with both authentic science inquiry and collaborative inquiry in mobile technology supported science learning, as students in these studies played different roles in the narrative and worked in groups to conduct hands-on mIBL investigations to address a real-life problem [S25, S26, S30]. Collective whole-class inquiry could be enacted by students while also carrying out authentic science inquiry and collaborative inquiry in a mobile technology supported learning environment [S31]. Thus, the types of mIBL identified in this review overlap with each other, and the relationships between these types are not mutually exclusive. Teachers could customise the combinations of these types in science learning for their own purposes.

Based on the summary of the mIBL activities (see the online document[2]), we gained insights into what has been addressed and possible gaps in the literature.

Firstly, only a small number of studies acknowledged the level of inquiry being used in the research [S10, S12, S13, S14]. The level of inquiry (Pedaste et al., 2015) is critical to declare as it reveals the likely level of autonomy in students' roles in the mIBL activities. For example, in guided

[2] The summary of the reviewed studies addressing mIBL activities is available via the following link: https://www.dropbox.com/s/0qk1lt2qyfvgmkx/A%20summary%20on%20the%20reviewed%20studies%20addressing%20mIBL%20activities%20.docx?dl=0

inquiry, students were required to solve a given inquiry question [S10, S14]. While in open inquiry, students proposed and validated their own hypotheses [S12, S13]. We found that for guided inquiry, mobile technology helped students engage with the inquiry questions [S14] and mediated their involvement in data collection (e.g. using camera) and analysis [S10]. Furthermore, students in guided inquiry were allowed to choose an answer using their mobile devices, providing the solutions to questions [S14]. During the learning process, the collected data can be also visualised using mobile technology, helping students to present and share their findings with peers [S10]. As to open inquiry, mobile technology also played a similar role in supporting students' IBL activities carried out [S12, S13]. While the open inquiry process supports students in proposing their own inquiry questions (Banchi & Bell, 2008) and mobile technology at this time evidently helped them pose questions [S12, S13].

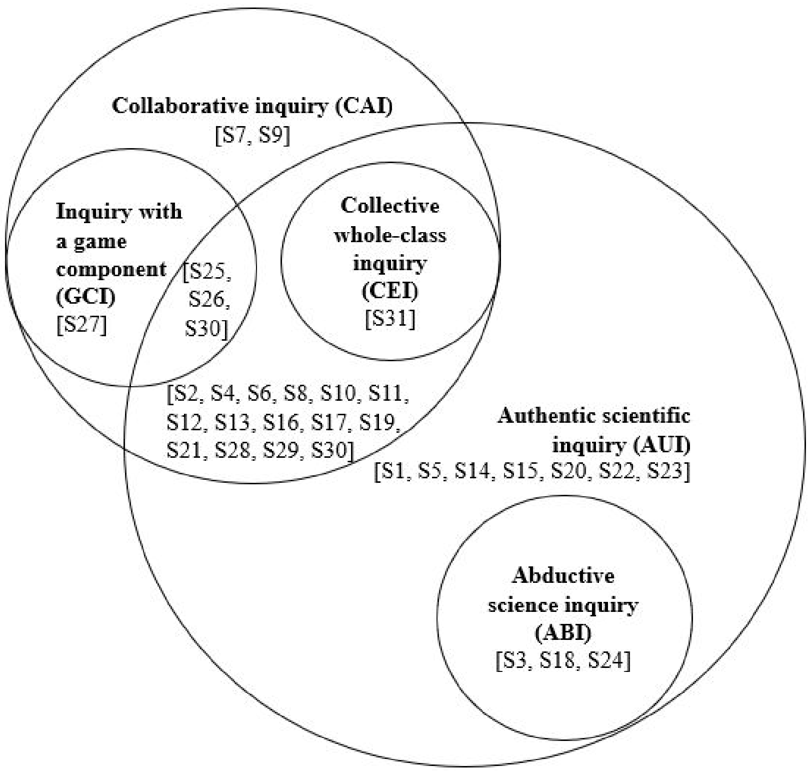

Figure 4. Relationships among the types of mIBL used in the studies in this review

Secondly, only ten studies explicitly pointed out the nature of *the settings used in their* mIBL activities. From these reviewed studies, we identified four groups: informal context only [S2, S4, S7, S21], a combination of both formal and informal contexts [S15, S22, S29], formal context only [S27, S31], and a combination of both informal and semiformal [S8] contexts. The use of mobile devices can potentially leverage a strong sense of student agency and ownership of mIBL activities [S8, S11], for example, freedom to define tasks and organise activities to achieve their goals, mobile technology has been welcomed to informal learning (Jones et al., 2006). In the studies that mentioned informal contexts, the settings of IBL activities referred to outside of classroom settings, such as museum [S4, S21, S22, S29] and home [S8, S15]) settings. From the studies using formal contexts, the mIBL activity settings involved indoor classrooms [S15, S22, S27, S29, S31]. Thus, the spectrum of learning (formal-informal) could have a tight relationship with the activity settings (indoor classroom or outside of school).

Mobile technology can help students collect and store data from mIBL activities, and access it at anytime and anywhere [S22]. When students captured data from field trips, they can later access and use it back in the classroom [S5, S22, S23]. Similarly, annotated and tagged data from IBL activities in formal settings can be accessed later by students to complete relevant inquiry tasks in less formal after-school settings. Mobile technology thus enables seamless learning experiences across formal and informal learning contexts (Hwang, Lai, & Wang, 2015; Jagušt, Botički, & So, 2018; Wong & Looi, 2011), enhancing students' science learning experience in IBL. The application of mIBL in the contexts of informal learning and combination of formal and informal learning will be future research directions. We also found that environment science was considered as the most popular subject in this review [S2, S6, S11, S12, S13, S16, S17, S19, S26] and the inquiry activities related to this subject were mainly conducted at both classroom and outside of school.

Finally, we found that development and use of m-learning ‘apps’ based on AR platforms has become a trend in secondary science education [S2, S14, S15, S25, S26, S27, S30]. Future research could further affordances and limitations of mobile AR technology and its outdoor inquiry investigations [S2, S30], and look into scaffolds in more depth by specifying the technical characteristics that students find engaging or disengaging, in order to better develop AR curricula [S2, S25, S27]. Additionally, mIBL can be extended and integrated with other emerging technologies such as robots and artificial intelligent (AI). For example, learners could interact with robots to complete a set of inquiry activities or could be guided to address a given inquiry problem with AI supported m-learning systems (e.g. students can call a variety of resources using the systems (Liu, Diao, & Tu, 2010)).

This section indicates an overlap among different types of mIBL in the reviewed studies, as shown in Figure 4. The relationships between these types are not mutually exclusive and customisation of the combinations relies on specific purposes. Authentic scientific inquiry and collaborative inquiry were the most frequently used types of mIBL in secondary science education in this SLR. The SLR shows an increasing trend of carrying out mIBL activities across both formal and informal contexts in secondary science education, for enhancing students’ seamless learning experiences, especially toward the ‘environmental science’ subject. Regarding mobile technologies/applications used in IBL, teachers and researchers have presented a growing interest on the use of mobile AR technology in inquiry-based science education.

5.2.2 Benefits and disadvantages of mIBL in science education

The results for our second RQ have been presented in Section 4.2.2.The majority of the reviewed mIBL science education studies reported positive perspectives more frequently than negative perspectives, as shown in Table 8. This finding is similar with the results reported by Authors (2018a). One reason for this result is that most mobile applications/ software systems featuring in the SLR were developed by researchers (77% of the total 31 studies) and they wanted to highlight the advantages of their technologies in the literature. Furthermore, we found out that researchers preferred to evaluate 'efficiency', 'effectiveness', and 'learnability' of mobile technology use in mIBL based on participant self-assessment questionnaires and interviews. More diverse methods (e.g. refer to Harrison et al. (2013)) are needed to evaluate these aspects in future research.

Similarly, we link the types of mIBL and the benefits and constraints of mIBL (see Appendix D), that could help teachers select types of mIBL in practice based on the affordances and limitations for achieving expected outcomes. It can be observed that researchers have paid much attention to evaluating the authentic scientific inquiry supported by mobile technology, addressing a broad range of aspects at both meso and macro levels. A few studies pointed out the negative perspectives of using the technology in authentic scientific inquiry. For example, a small group of students experienced cognitive overload [S14] and some students were used to learning science in more traditional ways [S3, S6]. However, more benefits from mIBL were evidenced in this review (see Appendix D).

Students and teachers need to be aware of potential constraints. This requires teachers to appropriately design an mIBL activity based on rich contexts to stimulate student interests. If an inquiry problem is not relevant to students themselves, they will feel less powerful to address the problem affecting their attitude toward learning [S8]. While if the inquiry problem is too personalised, students may feel embarrassed and uncomfortable to expose potentially private information so that they would not like to participate in inquiry activities [S29]. Finally, mobile apps used in mIBL to enhance authentic learning often only provide a model for visualising the real world. Therefore, teachers need to explain this epistemology to their students in the process of addressing misconceptions in their science thinking [S15]. Abductive scientific inquiry supported by the technology was evaluated using similar aspects. Appendix D outlines other foci for ABI (e.g. attitude) that have not been addressed in the literature and could be further explored, in order to improve the understanding of the outcomes of this type of mIBL.

Collaborative inquiry supported by mobile technology accounted for the second broadest range of evaluation aspects at both the meso and macro levels in this review. Collaborative mIBL activities supports data sharing and visualisation that enable students to reflect and discuss their findings [S4, S6, S7, S19, S21, S25, S30, S31]. On the other hand, difficulties in using mobile technology in collaborative inquiry could jeopardise the teamwork among students [S7] and using the technology in inquiry activities may disclose the students' privacy [S29] and disturb interactions between students [S31], resulting in challenges in performing collaborative inquiry. Collaborative mIBL activities at the same time could induce an unanticipated competition among students [S25] (see Section 4.2.3). Hence, teachers need to give appropriate instructions and guidance for students using mobile technologies to support their collaborative inquiry. As shown in Figure 4, collaborative mIBL activities were often used in secondary science education in a combination with authentic scientific inquiry (there were 15 studies in the 2 categories).

Our review also shows that mIBL with a game component has positive impacts on learning experience [S25, S26, S27, S30], covering a broad range of aspects at the meso level (see Appendix D). However, little attention has been paid to evaluating the macro level for this inquiry type. Use of jigsaw pedagogy embedded in mobile AR technology highlighted the unique role of each student in a group, while the mobile apps mediated the differentiation of information to each student in the role games [S25]. On the one side, students in groups need each other more to complete learning activities that contribute to enhancing collaboration among the group members (Bressler, Bodzin, & Tutwiler, 2019). On the other side, if one of the roles is absent, it severely affects the entire game play [S25]. Hence, future developments of mIBL with a game component need to further explore the use of student roles in these games-based learning science activities.

The facilitation of motivation toward science was the most prevalent benefit to students as evidenced in the selected studies. However, little attention has directed to the longer-term impacts of mIBL on learning practices. This could raise awareness from teachers, researchers and developers of mobile technologies/software systems about the importance of probing longer-term impacts of mIBL activities.

5.3 Limitations of this SLR

While we have consistently followed the guidelines of the PRISMA statement (Liberati et al., 2009) and Evidenced Based paradigm (Kitchenham et al., 2016) to search and select relevant articles in order to ensure the completeness of our sample, there may still be some publications that have not been included in our final selection. There are three issues to consider. *Firstly*, the review process was limited to the online databases as advised by previous scholars in this area conducting SLRs (See Figure 1). We also used restricted keywords as advised by (Authors, 2018a; Crompton & Burke, 2015; Crompton et al., 2016; Hwang & Tsai, 2011; Suárez et al., 2018). There could potentially be articles, in different languages for example, not included in the databases or identified by using our keywords. However, these are the primary sources for academic studies of mIBL in secondary science education to ensure an exhaustive scope on the topic of interest, addressing the potential largest set of peer-reviewed, relevant literature from English language sources. *Secondly*, we only focused on empirical studies, and thus we might have underestimated the current state of IBL studies in secondary science education. *Thirdly*, the articles screened based on our inclusion and exclusion criteria and the data was extracted from the articles based on our RQs. To ensure quality of coding, multiple researchers of this study reviewed and evaluated the coding results. For example, each of the three co-authors randomly selected and reviewed five papers from the data sample (in other words, 44% papers have been triangulated), to compare with the results of the main coder. The results of inter-rater coding agreement showed a high level of concordance (99%). Any uncertain coding was discussed for resolution. Also, there is plethora of definitions for the Education concepts extracted from the selected studies (e.g. attitude, attention, motivation). We had to remain faithful to the description of these concepts given in the selected studies. At the same time, we concede that these definitions may vary from those published in extant literature.

6. Conclusion

This study presents a systematic review of the empirical studies of mIBL in secondary school science education. Our review not only explores fundamental research trends of mIBL but also answers two specific RQs, based on the data extracted from 34 research articles (31 studies) from 2000 to 2019.

The SLR also shows that the major focus of mIBL is on guided and open inquiry, with minimal attention given to the more teacher-centric confirmation and structured inquiry approaches. The study provides a novel synthesis leading to a categorisation of types of mIBL: authentic scientific inquiry, abductive science inquiry, collaborative inquiry, collective whole-class inquiry, and inquiry with a game component. By using the M3 evaluation framework (Vavoula et al., 2009), we divided the pros and cons of mIBL into three main groups: micro, meso, and macro levels. Different themes emerged under these three levels. At the micro level themes included efficiency, effectiveness, learnability, perceived usefulness, and cognitive load. At the meso level, themes focused on attitude, attention, motivation, learning performance, group work, and cognitive processes; and the only macro-level theme focused on motivation. Therefore, this review contributes a systematic review of types of mIBL and benefits and constraints of mIBL, delineating the settings and contexts of mIBL in secondary school science education and trends of this field. In addition to these academic contributions, the practical implication of our study is twofold. Firstly, the SLR can raise awareness of teachers about selecting types of mIBL according to their affordances and limitations to achieve desired outcomes, and organising relevant activities to address the desired outcomes. Secondly, it presents an analysis of mobile technology trends in IBL, and positive and negative perspectives that will benefit developers and policymakers in decision making on further developments of mIBL in secondary school science education.

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Appendices

Appendix A. The list of the reviewed 31 studies

Study No.	Citations
S1	Sullivan, T., Slater, B., Phan, J., Tan, A., & Davis, J. P. J. T. S. (2019). M-learning: Exploring mobile technologies for secondary and primary school science inquiry. *Teaching Science*, 65(1), 13-16.
S2	P1: Kyza, E. A., & Georgiou, Y. (2019). Scaffolding augmented reality inquiry learning: the design and investigation of the TraceReaders location-based, augmented reality platform. *Interactive Learning Environments*, 27(2), 211-225. P2: Kyza, E. A., & Georgiou, Y. (2016). Digital tools for enriching informal inquiry-based mobile learning: The design of the TraceReaders location-based augmented reality learning platform. Paper presented at the *Proceedings of the 3rd Asia-Europe Symposium on Simulation & Serious Gaming*, 195-198.
S3	P1: Ahmed, S., & Parsons, D. (2013). Abductive science inquiry using mobile devices in the classroom.

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Study No.	Citations
	Computers & Education, 63, 62-72. P2: Ahmed, S., & Parsons, D. (2012). Evaluating ThinknLearn: A mobile science inquiry based learning application in practice. Paper presented at the *mLearn*, 17-24.
S4	Cahill, C., Kuhn, A., Schmoll, S., Lo, W.-T., McNally, B., & Quintana, C. (2011). Mobile learning in museums: How mobile supports for learning influence student behavior. Paper presented at the Proceedings of *the 10th International Conference on Interaction Design and Children*, 21-28.
S5	Kuhn, A., Cahill, C., Quintana, C., & Schmoll, S. (2011). Using tags to encourage reflection and annotation on data during nomadic inquiry. Paper presented at the *Proceedings of the 11th SIGCHI Conference on Human Factors in Computing Systems*, 667-670.
S6	Leelamma, S., & Indira, U. D. (2017). My pocket technology: Introducing a Mobile Assisted Inquiry Learning Environment (MAILE) to promote inquiries among secondary students. *Journal of Education Learning*, 6(3), 107-117.
S7	DeWitt, D., Siraj, S., Alias, N., & Leng, C. H. (2013). Retrospective evaluation of a collaborative learningscience module: The users' perspective. *Malaysian Online Journal of Educational Technology*, 1(2), 33-43.
S8	P1: Jones, A. C., Scanlon, E., & Clough, G. (2013). Mobile learning: Two case studies of supporting inquiry learning in informal and semiformal settings. *Computers & Education*, 61, 21-32. P2: Jones, A., Scanlon, E., Gaved, M., Blake, C., Collins, T., Clough, G., Petrou, M. (2013). Challenges in personalisation: Supporting mobile science inquiry learning across contexts. *Research Practice in Technology Enhanced Learning*, 8(1), 21-42.
S9	Laine, E., Veermans, M., Lahti, A., & Veermans, K. (2017). Generation of student interest in an inquiry-based mobile learning environment. *Frontline Learning Research*, 5(4), 42-60.
S10	Premthaisong, S., Srisawasdi, N., & Pondee, P. (2017). Development of smartphone-based inquiry laboratory lessons in chemistry learning of solution and concentration: An evidence- based practice. Paper presented at the *6th IIAI International Congress on Advanced Applied Informatics (IIAI-AAI),* 579-584.
S11	Nikou, S. A., & Economides, A. A. (2018). Motivation related predictors of engagement in mobile-assisted inquiry-based science learning. Paper presented at the *2018 IEEE Global Engineering Education Conference (EDUCON)*, 1222-1229.
S12	Maldonado, H., & Pea, R. D. (2010). LET's GO! to the Creek: Co-design of water quality inquiry using mobile science collaboratories. Paper presented at the *6th IEEE International Conference on Wireless, Mobile, and Ubiquitous Technologies in Education*, 81-87.
S13	Vogel, B., Spikol, D., Kurti, A., & Milrad, M. (2010). Integrating mobile, web and sensory technologies to support inquiry-based science learning. Paper presented at *the 6th IEEE International Conference on Wireless, Mobile, and Ubiquitous Technologies in Education*, 65-72.
S14	Umer, M., Nasir, B., Khan, J. A., Ali, S., & Ahmed, S. (2017). MAPILS: Mobile augmented reality plant inquiry learning system. Paper presented at *the 2017 IEEE Global Engineering Education Conference (EDUCON)*, 1443-1449.
S15	Davidsson, M., Johansson, D., & Lindwall, K. (2012). Exploring the use of augmented reality to support science education in secondary schools. Paper presented at *the 7th IEEE International Conference on Wireless, Mobile and Ubiquitous Technology in Education*, 218-220.
S16	Spikol, D., & Otero, N. (2012). Designing better mobile collaborative laboratories for ecology field work

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Study No.	**Citations**
	for upper secondary schools. Paper presented at *the 7th IEEE International Conference on Wireless, Mobile and Ubiquitous Technology in Education*, 77-81.
S17	Vogel, B., Kurti, A., Milrad, M., Johansson, E., & Müller, M. (2014). Mobile inquiry learning in Sweden: Development insights on interoperability, extensibility and sustainability of the LETS GO software system. *Journal of Educational Technology Society*, 17(2), 43-57.
S18	Ahmed, S., & Parsons, D. (2014). A comparative analysis in evaluating 'ThinknLearn' from science educators and high school students perspectives. Paper presented at *the 13th International Conference on Mobile and Contextual Learning*, 228-237.
S19	Vogel, B., Kurti, A., Spikol, D., & Milrad, M. (2010). Exploring the benefits of open standard initiatives for supporting inquiry-based science learning. Paper presented at *the 5th European Conference on Technology Enhanced Learning*, 596-601.
S20	Wu, P.-H., Hwang, G.-J., & Tsai, W.-H. (2013). An expert system-based context-aware ubiquitous learning approach for conducting science learning activities. *Journal of Educational Technology Society*, 16(4), 217-230.
S21	Lo, W.-T., Delen, I., Cahill, C., Kuhn, A., Schmoll, S., & Quintana, C. (2012). A new type of learning experience in nomadic inquiry: Use of Zydeco in the science center. Paper presented at *the 7th IEEE International Conference on Wireless, Mobile and Ubiquitous Technology in Education*, 57-61.
S22	Kuhn, A., McNally, B., Schmoll, S., Cahill, C., Lo, W.-T., Quintana, C., & Delen, I. (2012). How students find, evaluate and utilize peer-collected annotated multimedia data in science inquiry with Zydeco. Paper presented at *the Proceedings of the 12th SIGCHI Conference on Human Factors in Computing Systems*, 3061-3070.
S23	Vavoula, G., Sharples, M., Rudman, P., Meek, J., & Lonsdale, P. (2009). Myartspace: Design and evaluation of support for learning with multimedia phones between classrooms and museums. *Computers & Education*, 53(2), 286-299.
S24	Ahmed, S., Parsons, D., & Mentis, M. (2012). An ontology supported abductive mobile enquiry based learning application. Paper presented at *the 12th IEEE International Conference on Advanced Learning Technologies*, 66-68.
S25	Dunleavy, M., Dede, C., & Mitchell, R. (2009). Affordances and limitations of immersive participatory augmented reality simulations for teaching and learning. *Journal of Science Education and Technology*, 18(1), 7-22.
S26	Squire, K. D., & Jan, M. (2007). Mad City Mystery: Developing scientific argumentation skills with a place-based augmented reality game on handheld computers. *Journal of Science Education and Technology*, 16(1), 5-29.
S27	Kalz, M., Firssova, O., Börner, D., Ternier, S., Prinsen, F., Rusman, E., Specht, M. (2014). Mobile inquiry-based learning for sustainability education in secondary schools. Paper presented at *the 14th IEEE International Conference on Advanced Learning Technologies*, 644-646.
S28	Wang, J.-Y., Wu, H.-K., Chien, S.-P., Hwang, F.-K., & Hsu, Y.-S. (2015). Designing applications for physics learning: Facilitating high school students' conceptual understanding by using tablet pcs. *Journal of Educational Computing Research*, 51(4), 441-458.
S29	Anastopoulou, S., Sharples, M., Ainsworth, S., Crook, C., O'Malley, C., & Wright, M. (2012). Creating personal meaning through technology-supported science inquiry learning across formal and informal

Appendix A. The list of the reviewed 31 studies

Study No.	Citations
	settings. *International Journal of Science Education*, 34(2), 251-273.
S30	Kamarainen, A. M., Metcalf, S., Grotzer, T., Browne, A., Mazzuca, D., Tutwiler, M. S., & Dede, C. (2013). EcoMOBILE: Integrating augmented reality and probeware with environmental education field trips. *Computers & Education*, 68, 545-556.
S31	Lui, M., Kuhn, A. C., Acosta, A., Quintana, C., & Slotta, J. D. (2014). Supporting learners in collecting and exploring data from immersive simulations in collective inquiry. Paper presented at *the Proceedings of the 14th SIGCHI Conference on Human Factors in Computing Systems*, 2103-2112.

Appendix B. Distribution of *papers* based on outlets

Type of outlet	Title of the outlet	Number of *papers*
Journal	Computers & Education	4
	Frontline Learning Research	1
	Interactive Learning Environments	1
	International Journal of Science Education	1
	Journal of Education and Learning	1
	Journal of Educational Computing Research	1
	Journal of Educational Technology & Society	2
	Journal of Science Education and Technology	2
	Malaysian Online Journal of Educational Technology	1
	Research and Practice in Technology Enhanced Learning	1

	Teaching Science	1
Conference	SIGCHI Conference on Human Factors in Computing Systems	1
	Asia-Europe Symposium on Simulation & Serious Gaming	1
	International Conference on Interaction Design and Children	1
	SIGCHI Conference on Human Factors in Computing Systems	2
	IIAI International Congress on Advanced Applied Informatics	1
	IEEE Global Engineering Education Conference	2
	IEEE International Conference on Wireless, Mobile, and Ubiquitous Technologies in Education	5
	International Conference on Mobile and Contextual Learning	1
	European Conference on Technology Enhanced Learning	1
	IEEE International Conference on Advanced Learning Technologies	2
Workshop	CEUR Workshop Proceedings	1
Total		34

Appendix C. Cross analysis based on the characteristics of research design

Method of data collection	Duration of research	Research designs					
		Case study	Experiment	Field study	Multiple	Quasi experiment	Survey
Interviews	< 1 month	[S2, S25, S26, S29]	[S13, S14]	[S22, S30]			[S16, S28]
	1 < T < 3 months	[S8, S18]	[S3]			[S6]	
	> 3 months	[S23]	[S15]			[S9]	
	Not given						[S7]
Questionnaires	< 1 month	[S26, S29]	[S10, S13, S14, S20]	[S12, S30]			[S11, S28]
	1 < T < 3 months		[S3]			[S6]	[S27]
	> 3 months	[S23]				[S9]	
	Not given						[S24]

Appendix C. Cross analysis based on the characteristics of research design

Method of data collection	Duration of research	Research designs					
		Case study	Experiment	Field study	Multiple	Quasi experiment	Survey
Observations	< 1 month	[S2, S25, S26, S29]	[S13]	[S1, S4, S5, S21]			
	1 < T < 3 months	[S8, S31]					
	> 3 months	[S23]			[S17]		
	Not given						
Field notes	< 1 month	[S25]		[S1, S4, S5, S22]			
	1 < T < 3 months	[S8]					
	> 3 months				[S17]		
	Not given						
Students' work	< 1 month	[S25]		[S21, S22]			[S16]
	1 < T < 3 months	[S8, S31]					
	> 3 months				[S17]		
	Not given						
System logs	< 1 month	[S2, S29]		[S12, S22]			
	1 < T < 3 months						
	> 3 months						
	Not given						
Tests	< 1 month		[S14, S20]	[S30]			[S28]
	1 < T < 3 months		[S3]				
	> 3 months						
	Not given						

Appendix D. Cross analysis of inquiry types and evaluation perspectives based on meso and macro levels

Level	Aspect	Types of mIBL									
		AUI		ABI		CAI		CEI		GCI	
		P	N	P	N	P	N	P	N	P	N
Meso	Attitude	[S20]	[S8, S29]			[S8]	[S29]			[S30]	
	Attention	[S3, S4, S21, S23, S25, S30]	[S22, S25]	[S3]		[S4, S21, S25, S30]				[S25, S30]	[S25]

Appendix D. Cross analysis of inquiry types and evaluation perspectives based on meso and macro levels

Level	Aspect		Types of mIBL									
			AUI		ABI		CAI		CEI		GCI	
			P	N	P	N	P	N	P	N	P	N
	Motivation		[S2, S3, S4, S5, S6, S8, S10, S11, S12, S13, S14, S15, S17, S18, S23, S25, S26, S29, S30, S31]	[S3, S6, S14]	[S3, S18]	[S3]	[S2, S4, S6, S7, S8, S9, S10, S11, S12, S13, S17, S25, S26, S29, S30, S31]	[S6]	[S31]		[S25, S26, S30]	
	Learning performance		[S3, S6, S20, S28, S29, S30]		[S3]		[S6, S27, S29, S30]				[S27, S30]	
	Group work						[S4, S6, S7, S19, S21, S25, S30, S31]	[S7, S25, S29, S31]	[S31]	[S31]	[S25, S30]	[S25]
	Cognitive process	Remember	[S20, S23]				[S9]					
		Understand	[S5, S6, S12, S21, S24, S28, S30, S31]	[S14, S15]	[S24]		[S6, S7, S12, S21, S28, S30, S31]		[S31]		[S30]	
		Apply	[S6, S20, S21, S30]				[S6, S21, S30]				[S30]	
		Analyse	[S5, S20, S28]				[S28]					
		Evaluate	[S20, S22, S26]				[S26]				[S26]	
		Create	[S3, S4, S6, S18, S24, S31]		[S3, S18, S24]		[S6, S31]		[S31]			
Macro	Motivation		[S23]									

P indicates positive perspective, while N indicates negative perspective.

Practitioner Notes

What is already known about this topic:

- Inquiry-based learning (IBL) is a pedagogical approach in which students are driven by a question and carry out investigations to create new knowledge.
- Mobile technologies create collaboration, in-situ data collection and sharing, and customisation of learning opportunities in science education.
- Inquiry-based mobile learning (mIBL) facilitates learners' curiosity and motivation toward science and enables seamless science learning experiences across formal and informal learning contexts.

What this paper adds:

- A systematic review of the empirical studies focusing on mIBL in secondary school science education is conducted.
- Describes the fundamental research facets and the settings and contexts of mIBL.
- Develops a synthesis leading to a categorisation of types of mIBL; and
- Benefits and constrains of mIBL.

Implications for practice and/or policy:

- Provide opportunities for teachers to rethink the use of types of mIBL based on their affordances and limitations for achieving expected outcomes; and
- Organise activities for implementing these types of mIBL.
- Draw attention from developers and policymakers to the ways of using mobile technologies in IBL have been addressed; and
- Future developments of mIBL in secondary science education.