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Effects of Digital Game-Based Learning on Elementary Science Learning: A Systematic Review

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ABSTRACT Digital game-based learning (DGBL) has been perceived as an engaging teaching approach to foster students' learning and motivation. There are different opinions about the potential benefits of gaming on students' academic achievements, motivation, and skills in science courses due to the lack of empirical evidence and mixed results. To address this issue, this paper provides a review of relevant literature from 2006 to 2017 to examine the effects of using educational computer games in teaching science at the elementary education level. This paper employed a multidimensional framework to classify learning outcomes from studies of DGBL applications in the area of elementary science education. The findings of this review show a promising potential of DGBL, particularly in the area of content understanding. However, the findings of the review also suggest that there is a need to provide additional research in order to gain a more comprehensive picture of the educational effectiveness of DGBL. Hence, researchers are advised to conduct more randomized controlled trials (RCTs), various learning modes (e.g., collaborative and individual), and comparisons of DGBL to traditional methods of teaching. Furthermore, the researchers are highly encouraged to examine the effectiveness of DGBL applications in other areas, such as problem-solving and critical thinking. The findings of this review can benefit educational computer game designers, educators, and practitioners in the area of science education, particularly at the elementary level.

INDEX TERMS Digital game-based learning, science education, serious games, systematic review.

I. INTRODUCTION

Computer games are one of the most popular leisure activities among children and adolescents [1], [2]. The earliest trends in research assessing the psycho-social effects of computer games focused on their negative effects such as addiction [3], aggressive behavior [4], and poor academic performance [5].

The prevalence of computer games henceforth collectively and interchangeably called serious games or Digital Game-Based Learning (DGBL) [6]) prompted researchers and educators to use this medium in education [7]–[9]. A serious game is a computer game designed for learning, training, and behavior change [7], [10], [11]. It is suggested by a number of scholars that the utilization of serious games could benefit students' learning engagement [11], learning performance [12], and motivation [13]. However, other studies showed the contrary, namely that DGBL environments did not produce positive learning outcomes [14], [15].

In response to the contradictions of previous findings, this study synthesized several literature reviews to examine the empirical effectiveness of the DGBL approach. Some of the studies provide support to the claim that DGBL is a promising instructional style. For example, Vogel *et al.* [16] performed a quantitative meta-analysis with 32 articles spanning from 1986 to 2003 and revealed that learners who used DGBL obtained greater cognitive gains and demonstrated better attitudinal outcomes than students who learned via the traditional teaching method. Similarly, Connolly *et al.* [7] and Boyle*et al.* [17] analyzed 129 papers ranging from 2004 to 2009 and 143 papers from 2009 to 2014, respectively and

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found that using serious games promoted students' knowledge acquisition/content understanding and led to positive behavioral changes. In contrast to these promising findings, in their meta-analysis, Wouters *et al.* [18] synthesized results from 39 studies covering the years 1990 to 2012. They found no evidence that serious games were more motivating than the traditional method of teaching.

Although previous research works have provided valuable insights regarding the academic value of DGBL, there are areas that require further examination. For example, a number of educators have pointed out that science learning mainly occurs in laboratory settings [19], or observed in its natural habitat [20], and through these activities, young learners will develop their scientific ideas, and foster their cognitive abilities [21]. However, science is a subject that is inherently rich with abstract concepts and complex problems which might cause students to develop a sense of anxiety, and experience difficulties in learning [22]. Therefore, a growing number of scholars have recognized DGBL as a promising platform to foster students' science knowledge [23]. As a consequence, DGBL is being used extensively to enable the learner to conduct experiments and test hypotheses while being engaged in an interactive and immersive learning environment [24], [25].

Despite researchers' increased interest in utilizing DGBL applications in science learning, several scholars have indicated that there is a lack of empirical evidence pertaining the academic value of serious games [7], [8]. Specifically, Young *et al.* [26] found that the effects of serious games on science are not clear and more research is required in that area. Hence, based on the inconclusive results with respect to the impact of serious games on students' learning and understanding of scientific concepts, and the potential of using games in science education, there is a need to provide evidence-based research to address the lack of comprehensive evidence.

Science is a knowledge discipline that is closely related to our daily lives. In addition, competence in science allows students to understand the underlying principles of the natural world [27], [28].

Science in previous DGBL reviews was studied along with other curricular subjects [7], [8], [17], [26]. In addition, there have been only a limited number of research studies that systematically reviewed the effects of serious games on students' science understanding [23], [29]. In these reviews, the scope of investigation and analysis was vast and covered all educational levels (e.g., preschool to undergraduates). The broad scope of these reviews impedes researchers to conduct an in-depth investigation and form a clear consensus regarding the effects of DGBL applications on students' science understanding, particularly at the elementary level. Therefore, this study seeks to narrow the coverage area of previous reviews by producing a synthesis of research on the use of serious games in science learning at the elementary level. Thus, the purpose of this study is to synthesize the results of existing studies and produce an updated analysis regarding the effects of integrating serious games in elementary science education. The classification framework proposed by Connolly *et al.* [7] was employed to guide this review. This framework classified the learning outcomes of serious games into four main dimensions: (1) knowledge acquisition, (2) skills acquisition, (3) affective, motivational, and physiological outcomes, and (4) behavior change outcomes. Consequently, three main research questions based on the aforementioned framework are used to direct the analysis of this review:

1. What are the potential benefits of using DGBL in elementary science education?
2. Can the multi-dimensional framework be extended to classify the outcomes associated with DGBL in the area of primary science education?
3. What are the barriers facing this domain of research?

The findings of this review are expected to add to the existing body of literature in science education and serious games by presenting researchers, educators, and policymakers a detailed analysis into the potential of serious games in science education. In addition, the findings of this article could assist practitioners in the educational sector to draw plans to guide their future research endeavors and thus improve the learning and teaching practices.

The remaining of this review is structured as follows: Section II details the research methods that this study used for selecting research articles; section III describes the findings of the current study; section IV discusses the various opportunities, and challenges associated with the use of DGBL in elementary science education; section V concludes the paper.

II. METHOD

The wider purpose of this review is to gain an understanding of the current state of the art of studies on serious games with a special interest in DGBL applications in the domain of science at the elementary education level. Below is the search and review process that was used for the current study.

A. DATABASES

The Web of Science and SCOPUS databases were used to search for game-based learning articles in science education. According to Hwang and Wu [30], DGBL research received increased attention from 2006 and onwards. Hence, this review covered research articles from 2006 to 2017. These online repositories were chosen because they are known to include high quality and high impact studies [20], [23].

1) SEARCH TERMS

The following search terms and keywords were used:

(''game*-based learning'' OR ''computer game*'' OR ''digital game-based learning'' OR ''digital game*'' OR ''educational game*'' OR ''online game*'' OR ''serious game *'' OR ''science learning'' OR ''natural science'' OR ''DGBL'' OR ''MMORPG'').

2) INCLUSION CRITERIA

The aim was to locate high-quality research articles that reported empirical findings on the relative effectiveness of the DGBL approach on elementary age students in the area of science education as compared to the traditional methods of teaching or other technology-enhanced learning approaches. Specifically, the following conditions were implemented to ensure an appropriate selection of papers. To be included in this review, papers had to (a) date from 2006 to 2017 and published in English, (b) include an abstract, (c) explicitly state the digital environment used in the experiment as a *game*, and the term *game* was required to appear in title or the abstract of the publication to avoid confusion with other learning environments (e.g., simulations)[1], (d) include at least one comparison of a serious game versus a nongame condition or an equivalent standard game design[1], (e) provide students with feedback (e.g., score, progress) when the learning activity is completed[11], (f) includes participants from elementary education, and (g) focus solely on science-related topics.

B. DATA ANALYSIS

In the current review, all studies that met the inclusion criteria were systematically analyzed to extend and refine Connolly's *et al.* [7] classification framework, establish a connection with previous studies that employed the same classification framework [8], [17], [31], and synthesize similarities and differences across the discipline of serious games in elementary science education.

The limited number of studies motivated Novak [31] to repurpose the dimensions of Connolly's *et al.* [7] framework. Similarly, in the present study, the number of research articles that focused on students' motivational outcomes and skills acquisitions was limited, therefore these two dimensions were combined together into one category, that is, motivational and skills acquisitions.

Additionally, none of the included studies explored behavioral changes, hence this category was not considered in the current study.

III. RESULTS

This section outlines the screening and selection process of the research articles. When a paper is selected it is classified to the following two main dimensions: knowledge acquisition, or motivational and skills acquisitions.

A. IDENTIFICATION AND SELECTION OF RESEARCH ARTICLES

Figure 1 shows the number of research articles retrieved from each database in the initial search process, screening process the studies for potential inclusion, and the studies that ultimately met the inclusion criteria.

1) KNOWLEDGE CONSTRUCTION/CONTENT UNDERSTANDING OUTCOMES

Seventeen studies focused primarily on knowledge acquisition/content understanding. Therefore, they were found appropriate for inclusion in this category. 6 out of 17 studies were randomized controlled trials (RCT).[2] In regards to the effects of DGBL on students' understanding of science-related concepts, all the studies reported positive knowledge construction gains [33]–[38] while none of these studies compared the DGBL approach to the traditional method of science teaching.

The majority (4 studies) of serious games in this section were utilized to teach students light and shadow concepts, three of these studies employed 3D technology [33]–[35] which were single-player, and non-collaborative, but one study utilized 3D technology in a collaborative DGBL environment [36]. When considering the effects of different learning dynamics (e.g., collaborative, and individual) only two studies looked at this issue and reported mixed outcomes, one study reported positive results for the individual learning condition [36], however, the other study reported positive results for the collaborative learning condition [37].

Eleven studies followed a quasi-experimental design and they all reported positive findings. However, only two studies compared a DGBL approach to a traditional method of science teaching [39], [40]. The results showed that the DGBL applications were mainly used to teach students plants' characteristics [41]–[43]. Additionally, the majority (10 studies) were 2D, individual, and non-collaborative and only one study explored collaborative and individual interactions with DGBL application, with the results indicating positive learning gains for the collaborative learning condition [43]. Table 1 shows the 17 studies included in this category classified along the dimensions of the topic, genre, DGBL type, design of the study, platform and implementation setting.

2) MOTIVATIONAL AND SKILLS ACQUISITIONS

Six studies were included in this category, five of which were quasi-experimental. Only one study followed an RCT design, [49] with 3D, single-player and non-collaborative conditions. For the positive effects of serious games on motivational and skills acquisitions, every article in this section reported positive findings. However, only two articles adopted a traditional method of science teaching [50], [51]. The majority (5 studies) were 2D. Three employed 2D collaborative games [50], [52]. However, one of these studies ran on a mobile platform [51], the other two were individual and non-collaborative [53], [54]. In addition, the same three studies looked at the effects of DGBL applications on collaborative and individual playing conditions with the results indicating positive outcomes for the collaborative learning condition. Table 2 shows the 6 studies included in this category classified along the dimensions of the topic, genre, DGBL type, design of the study, platform and implementation setting.

[1]Marked conditions are adapted from [32]

[2]According to numerous scholars and research organizations, RCT is considered the "gold standard" for scientific research [55]

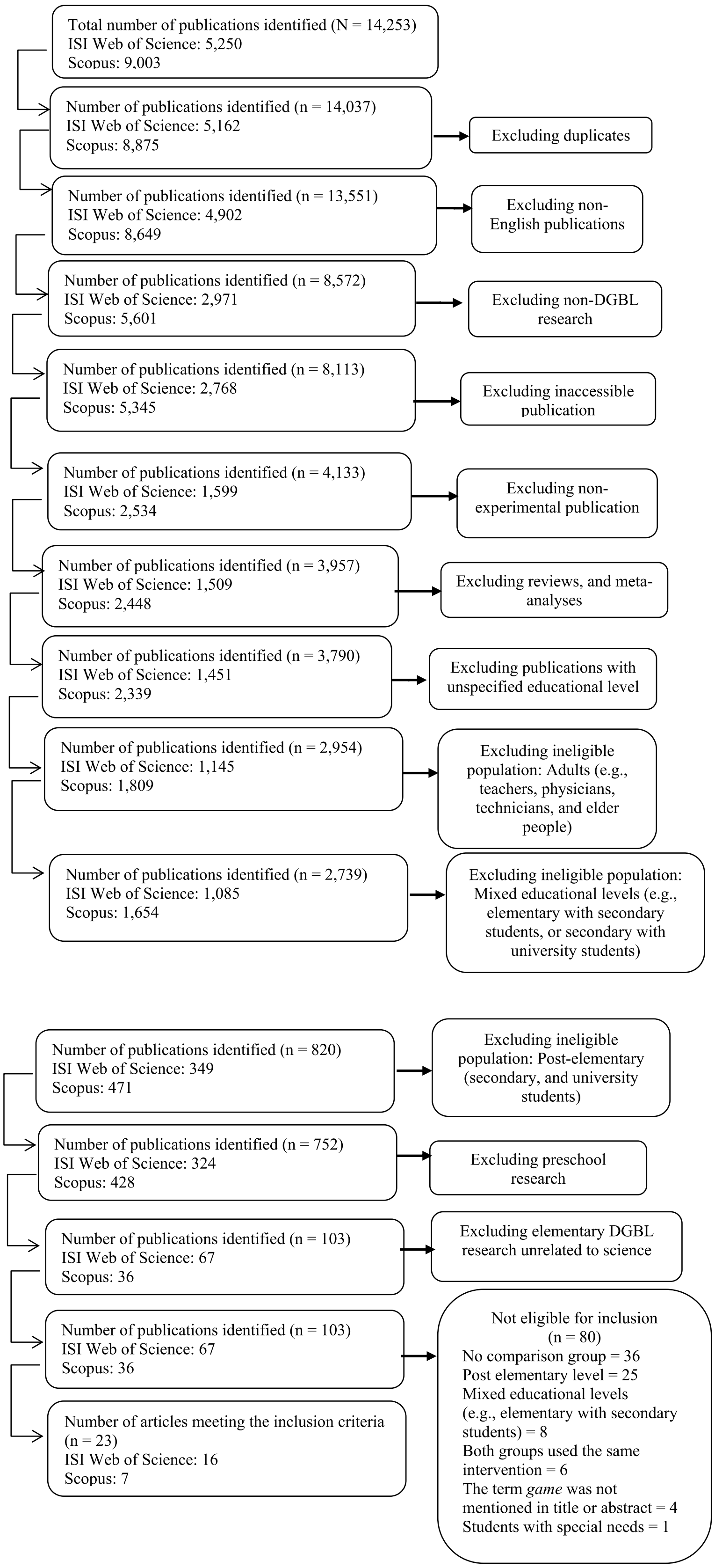

FIGURE 1. Study identification and inclusion diagram.

TABLE 1. Summary of research articles investigating the effects of serious games on knowledge construction.

Study	Topic	Genre	Game environment	Study design	Platform	In class/out of class
Chen [39]	Multidisciplinary	Role-Playing Game (RPG)	2D (individual)	Quasi-experimental	Computer	In class
Chu [12]	Birds	RPG	2D (individual)	Quasi-experimental	Online	In class
Chung [40]	Multidisciplinary	RPG	2D (individual)	Quasi-experimental	Computer	In class
Hsu [33]	Light and shadow	RPG	3D (individual)	Experimental	Computer	In class
Hsu [34]	Light and shadow	RPG	3D (individual)	Experimental	Computer	In class
Hsu [35]	Light and shadow	RPG	3D (individual)	Experimental	Computer	In class
Hsu [36]	Light and shadow	RPG	3D (collaborative)	Experimental	Computer	In class
Hung [45]	Nutrition	Strategy	2D (individual)	Quasi-experimental	Online	In class
Hwang [38]	Insects	Board game	2D (individual)	Experimental	Mobile	Out of class
Hwang [41]	Plants	RPG	2D (individual)	Quasi-experimental	Computer	In class
Hwang [42]	Plants	RPG	2D (individual)	Quasi-experimental	Computer	In class
Hwang [44]	Insects	RPG	2D (individual)	Quasi-experimental	Computer	In class
Hwang [46]	Insects	Board game	2D (individual)	Quasi-experimental	Online	In class
Molnar [47]	Health	Platform	2D (individual)	Quasi-experimental	Online	In class
Sung [37]	Plants	RPG	2D (collaborative)	Experimental	Computer	In class
Sung [43]	Plants	RPG	2D (collaborative)	Quasi-experimental	Computer	In class
Yien [48]	Nutrition	Strategy	2D (individual)	Quasi-experimental	Online	In class

TABLE 2. Summary of research articles investigating the effects of serious games on motivational and skills acquisitions.

Study	Topic	Genre	Game environment	Study design	Platform	In class/out of class
Boonsamuan [53]	Space	Board game	2D (individual)	Quasi-experimental	Mobile	In class
Hsiao [50]	Electrical science	RPG	2D (collaborative)	Quasi-experimental	Computer	In class
Kuo [49]	Insects	Strategy	3D (individual)	Experimental	Online	In class
Sung [52]	Plants	RPG	2D (collaborative)	Quasi-experimental	Computer	In class
Sung [54]	Plants	RPG	2D (individual)	Quasi-experimental	Computer	In class
Yen [51]	Ecology	Simulation	2D (collaborative)	Quasi-experimental	Mobile	Out of class

IV. DISCUSSION

The search terms used in this review provided 14,253 studies. The high volume of research articles found suggests a growing interest in using DGBL in education. 91 studies were fully screened to determine their eligibility for inclusion. However, when the inclusion criteria were applied, only 23 were considered relevant for this review.

TABLE 3. Knowledge acquisition/content understanding outcomes.

Author(s)	Aims/Objectives of study	Methods	Conclusion
Chen [39]	Assessing the influence of a multi-faceted serious game called *FORmosaHope* (FH) on students' material, societal, spiritual, scientific cultural identities.	130 (71M, 59F) (aged 11-12) from four sixth grade classes. The research sample was divided into two sections, the experimental group (N= 64, 35M, 29F) utilized the proposed FH environment, while the comparison group (N= 66, 36M, 30F) was guided by the traditional method of teaching.	The study found that the experimental group showed significant improvements in their cultural identities which included scientific cultural identities among other cultural facets.
Chu [12]	To explore the academic benefits of developing a serious game based on the two-tier test approach in promoting students' knowledge construction and learning motivation in the ''migratory bird identification'' chapter.	53 (24M, 29F) (aged 11.8) students from two fifth-grade classes, one class (N= 26, 12M, 14F) was assigned to the experimental group, while the second class (N= 27, 12M, 15F) was assigned to the control group. The experimental group was taught by the two-tier test-based DGBL environment, learners in the comparison group were guided by conventional technology-enhanced learning environment.	The analysis of post-test scores revealed that students who learned with the DGBL environment significantly outperformed their peers in the comparison group in terms of learning acquisition and motivation; additionally, students perceived the proposed DGBL environment as easier and more beneficial than the e-learning system.
Chung [40]	The impact of gender on students learning motivation and acquisition of first aid knowledge and language skills is investigated by a DGBL environment called *Emergency First Aid* (EFA).	100 fourth-grade students were divided equally into two groups; the experimental group (N = 50, 25M, 25F) was guided by the EFA game, while the students in the control group (N = 50, 25M, 25F) were taught by the traditional method of science teaching.	Results showed that the learning achievements of the experimental group were significantly higher than that of the comparison group; the analysis of the learning motivation questionnaire revealed that the EFA game effectively engaged students in learning, however, the learning motivation of female students was significantly better than that of male students. Additionally, the difference between male and female students in learning gains, and game usability did not reach the point of statistical difference.
Hsu [33]	Evaluating the academic value of integrating self-explanation principles with a serious game on students' understanding of light and shadow concepts.	35 third-grade students randomly assigned to one of two conditions: experimental group students 16 (8M and 8F), and control group students 19 (12M and 7F).	The results indicate that students who were assigned to use the game with the self-explanation principles did not outperform students who learned with the standard version of the game. Paired samples *t*-test revealed a significant improvement was identified in the post-test of students in an experimental condition.
Hsu [34]	Whether a serious game with self-explanation prompts could foster students in the acquisition of light and shadow concepts.	Participants were (88, 48M and 40F) third-grade students randomly assigned to a self-explanation version of DGBL application (44, 24M, 20F), or the basic version of the same application without self- explanation prompts (44, 24M, 20F).	The post-test scores and delayed test scores revealed no significant difference between students regardless of their group in terms of acquisition of light and shadow concepts. When students in the experimental group were divided into high engagement and low engagement levels, the post-test findings indicated that there was no significant difference between students regardless of their group; however, it was revealed that learners with high engagement significantly outperformed other students in the low engagement and control groups with regard to their retention test scores.

TABLE 3. ***(Continued.)*** **Knowledge acquisition/content understanding outcomes.**

Hsu [35]	Studying the effects of integrating self-explanation prompts on students' acquisition of light and shadow principles	A sample that consisted of 35 students was randomly assigned into two groups, experimental and control. The former group (N = 16, 8M, 8F) were required to learn by playing the game that incorporated the self-explanation prompts, while the latter group (N = 19, 12M, 7F) played the basic version of the game that did not include the self-explanation prompts.	The analysis of both groups' progress from the pre-tests suggests that the students who played the game with the self-explanation prompt made significant progress, while students in the comparison group who played the basic version of the game did not achieve significant progress. However, the difference between the experimental and control groups did not reach the point of statistical significance. Further, when experimental group student categorized to high accuracy and low accuracy groups, it was revealed that the self-explanation prompts had no significant effects on students regardless of their accuracy affiliation.
Hsu [36]	To determine the impact of collaborative gameplay and self-explanation prompts on students' comprehension of light and shadow concepts.	184 fourth grade students (107M and 77F). Students were randomly assigned to three conditions: (a) students in experimental group 1 (N = 44) individually played *Saving the Princess* embedded with self-explanation prompts, (b) students in experimental group 2 (N = 96) collaboratively played the same game with self- explanation principles, (c) students in the control group (N = 44) individually played a simplified version of *Saving the Princess* without the self-explanation prompts.	The learning achievement of students in experimental group 1 was higher than those in the control or experimental 2 groups. In other words, students who individually played *Saving the Princess* outperformed students who collaboratively played the game in experimental group 2 or those who played the basic version of the game. However, there was no statistical significance in the delayed test after 3 weeks. When students were categorized according to their level of engagements, the post-test scores revealed that high engaging students in experimental group 1 showed significantly better results than low engaging students in the control and experimental 2 groups, while the delayed test findings suggest that high engaging students in experimental groups 1 and 2 significantly outscored low engaging students in the control, and experimental groups 1 and 2.
Hung [45]	To observe the benefits of a number of web-based games on students' nutrition knowledge, nutrition attitude, and dietary behavior.	33 third-grade students (18M and 15F). Experimental group students played Health e-Learning Network's games *Little Nutritionist, Presents Falling Down From the Sky*, and *Save the Kingdom of Nutrition*, while control group students learned about nutrition via multimedia slideshow.	Students in the experimental group demonstrated significant gains in nutrition knowledge and dietary behavior. However, there was no significant difference in students' attitude on nutrition, and there was no significant difference between male players and female players.
Hwang [38]	To explore the impact of an AR-based gaming approach on students' learning achievements and attitude.	57 students from two fifth grade classes. One class (N = 30) was randomly assigned to the experimental group and learned by the AR-based mobile gaming approach, while the other class (N = 27) was assigned to be the control group and was guided by the AR-based mobile approach.	The academic performance and learning attitude of students in the experimental group who interacted with the proposed AR-based mobile gaming approach was significantly higher than their counterparts in the control group who received their instructions via an AR-based mobile approach.

TABLE 3. ***(Continued.)*** **Knowledge acquisition/content understanding outcomes.**

Hwang [41]	To investigate the effectiveness of a serious game designed based on the knowledge engineering approach to help students observe and compare learning targets in the "Knowing Campus Plants" unit.	The sample consisted of two sixth-grade classes and a total of 60 students. (33M, 27F). The two classes were divided into 2 groups; one class was assigned to the experimental group (16M, 14F), while the second class (17M, 13F) was assigned to the control group. The experimental group learned with the proposed DGBL application, whereas students in the control group were taught with slides and videos on computers connected to a projector.	Findings demonstrated that students who learned with the proposed DGBL approach showed significantly better learning gains and attitudes. There was no significant difference between different genders in terms of learning gains and attitudes which seems to indicate that the proposed game equally benefited the students regardless of their gender.
Hwang [42]	To develop a personalized serious game based on the learning style theory to assess its effectiveness on students' learning achievements, motivation, perceived ease of use, and perceived usefulness in the "knowing campus plants" unit.	46 students from two fifth-grade classes. One class (N = 24) learned with a DGBL approach that was designed to meet the learning styles of the research sample, the second class (N = 22) was guided by a standard version of the game that did not meet the learning styles of students.	Students who played the personalized DGBL application showed significant gains in learning achievements and motivation. Moreover, the results indicate that students in the experimental group demonstrated higher degrees of technology acceptance.
Hwang [44]	To evaluate whether the incorporation of concept maps strategy in DGBL environment could promote students' abilities to organize the knowledge they gained from playing a serious game in the unit of "butterfly ecology".	This study included 56 sixth-grade students from two classes. The participants were equally divided between the experimental and the control groups. The experimental group used the proposed DGBL application, that is, students learned with DGBL approach based on the concept maps learning strategy, while the control group used a basic version of the proposed DGBL application that did not include the concept maps as part of the gaming scenario.	The experimental results suggest that students who learned with the proposed approach significantly outscored their peers in terms of their learning achievements, and perceived usefulness of the learning method. In addition, the proposed approach also reduced students' cognitive load. However, no significant difference was identified with regard to students' learning motivation.
Hwang [46]	To develop an online serious game in the unit of butterfly ecology in order to promote students learning and flow experience while engaging in web-based problem-solving activities.	50 students from two fifth-sixth classes. Two groups; one class (N= 29) played a serious game that used the graphic quiz, while the second class (N= 21) was guided by learning sheets and keywords search on the web.	Findings showed a significant difference between the groups of students in terms of learning achievements, attitude, interest, flow experience and technology acceptance, favoring the participants who learned with the proposed web-based DGBL application.
Molnar [47]	To evaluate the effectiveness of game narratives as text, or game mechanics as methods of information delivery via a modified game called *Bugs Kingdom* to promote students' knowledge in the subject of microbes.	60 students (aged 6 to 11) played an augmented version of a game called *Bugs Kingdom*. 30 students played *Harmful Microbes*, a modified level of *Bugs Kingdom* to teach students through texts and game mechanics. The other 30 students played *Useful Microbes*, also a modified level of *Bugs Kingdom* to teach students through texts and game mechanics.	Significant difference were identified between groups, favoring the game mechanics method of information delivery.
Sung [37]	A collaborative knowledge construction tool is embedded into a serious game to investigate its academic effectiveness in facilitating the learning gains of students, and their abilities to organize and share information in the unit of "Identifying plant features and functions".	186 (85M, 81F) (average age 12) students from six sixth-grade classes. Three classes (N= 83, 44M, 39F) were selected as the experimental group and three (N=83, 41M, 42F) were assigned as the control group. The experimental group learned with a DGBL application embedded with the repertory grid and an online discussion forum, while the control group also used a DGBL application and enjoyed access to an online discussion group; however, the repertory grid was replaced with learning sheets.	The learning achievements and problem-solving awareness of students who used the DGBL environment with the repertory grid significantly outperformed their peers in the comparison group. Students in the experimental group also revealed more behavioral patterns of comparing and observing the learning target than the students who learned with the conventional DGBL approach that did not include the repertory grid. However, the self-efficacy ratings of students in the experimental group were equivalent to that of those in the control group.

TABLE 3. ***(Continued.)*** **Knowledge acquisition/content understanding outcomes.**

Sung [43]	To design a collaborative DGBL environment developed based on the grid-based mind tools to assist students in organizing their knowledge to differentiate certain characteristics of plants in the unit of "Identifying the plants on the school campus".	93 students from three sixth-grade classes. The sample was equally divided into three groups; in the experimental group (N = 31) students were collaboratively taught by a serious game that incorporated the repertory grid approach. In control group A (N = 31), learners collaboratively played a standard version of the proposed game that did not include the repertory grid approach. In control group B (N = 31), students individually played the standard version of the game, however, they developed their own repertory grids.	Students' outcome indicated that the learning performance and attitude toward science of students in the experimental group were significantly higher than those in the control groups A and B. Additionally, students in the experimental group showed significant progress in terms of their motivation for science courses and self-efficacy in using computers to learn and learning collaboratively.
Yien [48]	To examine the effects of a web-based DGBL approach on third graders nutrition cognition.	66 students from two third-grade classes (36M and 30F). One class was the experimental group (18M and 15F) and the other class was the control group (18M and 15F). The experimental group learned about nutrition using a number of educational games: *Little Dietician, Gifts from Heaven, Saving Health Kingdom, Health Superman's Delicacy Island*, and *Nutrition Supplement Battle*, while the experimental group was taught using multi-media slideshows.	Results indicated that the DGBL approach significantly improved students' learning achievements and food and drinking habits. No significant difference between students of different genders was found. Additionally, the DGBL application did not improve learners' attitude towards nutrition.

Sixteen studies followed a quasi-experimental research design and 7 studies followed an RCT methodology. The low number of RCT articles identified in this study is consistent with similar observations made by [8], [17], [56], [57]. The notable dearth of RCT methodologies identified in this article along with other reviews is attributed to the difficulty of assigning an appropriate and equally engaging intervention for the students in the comparison group [58], [59].

The findings of this study show that RPGs have been identified as the most popular game genre (15 studies). In RPGs, it is often argued that learning and immersion occur via exploration of the learning environment, interaction with Non-Player Character (NPC), customization and controlling the game avatar [60], [61]. In addition, Twining [62] contended that engaging in RPGs could foster students' real-world competency. The frequent utilization of RPG among numerous researchers suggests that this genre can help students to learn about science and science-related topics. This observation supports what has been reported by other scholars, namely that educational games that allow the learners to assume the role of a king or a magician are helpful to students [29].

Consistent with Hainey *et al.* [8] and Jabbar and Felicia [57] who found that computers were the most popular platforms for DGBL environments, the present review study found that the majority (14 studies) used computers as delivery platforms for serious games dedicated to science learning.

The majority (21 studies) were conducted in classroom or computer laboratory settings under the supervision of a teacher, the research team, or both. The apparent lack of informal studies in this review could be attributed to two main reasons. Firstly, most schools are already equipped with computer laboratories, therefore, out of convenience researchers opt to design their games to run on computers. Secondly, some informal studies require mobility (e.g. handheld devices). However, to avoid distractions, most schools try to limit or control cell phone use, particularly, if the targeted audience is young learners [63].

The articles included in this review focused on a wide range of topics. However, the majority (14 studies) placed a great emphasis on plants (6 studies), light and shadow concepts (4 studies), and insects (4 studies). This observation suggests that if carefully designed, educators can employ DGBL applications to guide students learning in numerous areas of science education.

This review attempted to answer the following questions "What are the potential benefits of using games-based

TABLE 4. Motivational and skills acquisitions outcomes.

Author(s)	Aims/Objectives of study	Methods	Conclusion
Boonsamuan [53]	To examine the effects of key motivation factors of a mobile DGBL application called *It is here* in fostering learners' adversity quotient in the subject of space exploration.	40 fourth-grade students divided equally into two groups, the experimental group (N= 20) played the proposed mobile application *It is here*, the control group (N = 20) was guided by an unspecified learning method.	Statistical analysis revealed that adversity quotient of students in the experimental group was significantly higher than those in the comparison group.
Hsiao [50]	To investigate how a DGBL application called the *ToES* might influence the creativity and manual skills of fifth graders in the unit of "Electrical Science".	The research sample comprised 51 individuals (28M, 23F) recruited from two fifth-grade classes. 27 (15M, 12F) were assigned to be the experimental group and collaboratively learned with the proposed *ToEs* game, while the control group consisted of 24 individuals (13M, 11F) who received traditional instruction.	The findings suggest that the users of the *ToES* system showed significant improvement in their overall creativity assessment, Test of Divergent Thinking (TDT), and Test of Divergent Feeling (TDF). Additionally, there was a significant correlation between the TDF and factors of flow experience, favoring the users of the *ToES* application. Furthermore, the outcomes also demonstrated that students in the experimental group showed more animated and diversified behaviors toward the practical activity than the control group students.
Kuo [49]	To examine the effectiveness of an online DGBL environment called *Go Go Bugs* in fostering students' intrinsic motivation.	46 (26M, 20F) individuals were recruited from two third-grade classes. Students were randomly assigned to two conditions. The experimental group (N= 27, 16M, 11F) was guided by the proposed DGBL approach, that is, *Go Go Bugs*. The control group (N=19, 10M, 9F) used a multimedia learning environment.	Findings showed that students who used the proposed approach exhibited a significant improvement in their interest in science learning. The proposed online game had no significant impact on the learning gain of students.
Sung [52]	To assess the effects of a DGBL environment based on the repertory grid approach on the learning behavior of student in the unit of "Identifying the plants on the school campus,"	The sample consisting of 186 children (average age 12) from six sixth-grade classes. Three classes (N=83) were assigned to the experimental group and collaboratively played the proposed serious game embedded with the repertory grid mechanism. The control group (N=83) learned with a standard version of the proposed game that did not include the repertory grid approach.	Analysis of the experimental results showed that students who learned with the proposed approach exhibited more behavioral patterns of comparing, observing, seeking as well as reading the supplementary materials than those who learned with the standard version of the game.
Sung [54]	To examine whether different playing styles will affect students' learning motivation.	252 elementary students assigned to one of two groups: experimental group (N = 127) that used the DGBL application that matched the learners' playing style, and a control group (N = 125) that used a DGBL application that did not match the learners' learning styles.	The analysis of learning motivation and learning achievement scores revealed that students who learned with the serious games that matched their learning style significantly outperformed their counterparts in the control group who interacted with the game that did not match their learning styles.

TABLE 4. *(Continued.)* Knowledge acquisition/content understanding outcomes.

		standard version of the proposed game that did not include the repertory grid approach.	
Sung [54]	To examine whether different playing styles will affect students' learning motivation.	252 elementary students assigned to one of two groups: experimental group (N = 127) that used the DGBL application that matched the learners' playing style, and a control group (N = 125) that used a DGBL application that did not match the learners' learning styles.	The analysis of learning motivation and learning achievement scores revealed that students who learned with the serious games that matched their learning style significantly outperformed their counterparts in the control group who interacted with the game that did not match their learning styles.
Yen [51]	The impact of gender on learner motivation, participation and achievement are assessed via a mobile DGBL application designed to provide scaffolding learning in the subject of pond ecology.	The sample consisted of 123 (64M. 59F) (aged 9-10) fourth graders. The whole research sample participated in three learning activities: (a) a face-to-face classroom discussion, (b) outdoor observation, and (c) a collaborative gameplay of the proposed DGBL mobile application.	Results indicated that female students spoke significantly less than male students in the classroom discussions, and outdoor observation. However, in regards to the mobile DGBL application, there was no significant difference in terms of participation. Motivation ratings and learning outcomes revealed that male students significantly outscored female students in the mobile DGBL activity, but there was no significant difference between male and female students in the classroom discussion and the outdoor observation activity. For male students, the correlation analysis showed no significant relationship between male students' motivation and learning outcomes in the three learning activities. For female students, the correlation analysis demonstrated there was a positive correlation between motivation and learning outcomes in the classroom discussion and the outdoor learning activity. The proposed mobile DGBL application was not significantly correlated with learning outcomes of female students.

learning in elementary science education''. Our findings suggest that there is a promising potential for using serious games in the domain of primary science education. However, out of the 23 studies included in this review, only seven articles followed the RCT methodology, while the remaining 16 articles used the quasi-experimental approach. The frequent utilization of quasi-experimental studies is not unique to this article, similar observations have been reported by previous reviews [7], [8], [23].

Although traditional methods of teaching have received constant criticism, only 4 studies compared the effects of a serious game to a traditional method of teaching. This finding is similar to that of Hainey *et al.* [8], who also employed the multi-dimensional framework and found that the traditional method of teaching was not regularly implemented

In the current review, the majority (17 studies) focused on using serious games to foster students' content understanding and knowledge construction, an aspect in which the study resembles other previous systematic reviews in the domain of science education [23], [29].

Additionally, this current review attempted to answer the following questions ''Whether the multi-dimensional framework could be extended to classify the outcomes associated with DGBL in the area of primary science education''

Similar to Boyle*et al* [17], Hainey *et al.* [8], Novak [31], the present review employed the multi-dimensional framework proposed by Connolly *et al.* [7]. The utilization of the multi-dimensional framework was useful in providing detailed and specific information from individual papers regarding their topic of interest, research design, game genre, game type, and delivery platform. In addition, the framework highlighted whether the game was collaborative or not and whether a study utilized the traditional method of science teaching in the comparison group. Furthermore, Appendices A – B listed the authors and the year of the publication, the objectives of the study, the method used, and the main findings of the study.

Further, this study sought to investigate the following question: ''What are the barriers facing this domain of research?''. One of the main obstacles in utilizing gaming in education is parents' and teachers' attitudes. While some parents do acknowledge the learning opportunities afforded by this new method of learning, the majority of them lacked knowledge about video games and voiced their reluctance to euse them in education. Parents' attitude is influenced by the negative coverage of video games in the media [64]. Similarly, teachers shared parents' lack of video games experience while they did recognize the learning opportunities of video games in education. However, teachers did not believe that video games could improve their job performance, and stated their intention about the prospect of not utilizing video games in education [65].

Another barrier to adopt gaming in schools is accessibility. In order to harness the potential effects of gaming in science education or other subjects, schools need to acquire access to a functioning technology infrastructure (e.g., computers, high-end graphic cards, memory storage, and/or network connectivity). The financial costs of setting up such infrastructure will significantly limit schools' ability to integrate gaming in education [66], [67]. In addition, both researchers and educators aim to improve students' learning. Hence, granting access to schools will allow researchers to revise and enhance their game design based on teachers' assessment which in turn will benefit the students who are using these games to learn [68].

V. CONCLUSION

This study utilized the multi-dimensional framework proposed by [7] to classify the learning outcomes associated with DGBL in the field of science at the primary level. The goal of this review was to provide a synthesis of research on the effects of DGBL on primary science education. However, there are a number of limitations associated with the outcomes of the present study. Firstly, this literature review is limited to the research articles published between 2006 and 2017 in Web of Science, and Scopus repositories. Secondly, the rapid development of the research in this area hardly allow researchers to maintain an updated timeframe; this review did not include research studies from 2018 because the study commenced that year and the process of searching for articles and screening them is a time demanding task. Lastly, another factor that limits the finding of this study concerns the inclusion criteria, as studies that lacked the pairwise comparisons were excluded. As a consequence, the current literature review included only one aspect of DGBL research in primary science education, as qualitative and quantitative case studies were not considered for inclusion and analysis.

In addition, there are a few issues that warrant further research. Firstly, given their limited number and inconclusive results more RCT studies are required to investigate the effects of different learning dynamics (e.g., collaborative, and individual) on science learning. Secondly, future research should explore how DGBL applications might influence students' learning in areas other than content understanding and knowledge construction such as creativity, complex problem-solving abilities, and critical thinking skills. Thirdly, to provide more empirical evidence with regards to the effects of DGBL applications on students' science learning researchers are advised to include more comparisons to the traditional method of teaching. Lastly, the experimental intervention in nearly every article reviewed in this study lasted from a handful of sessions to a few weeks. Therefore, it would be an interesting albeit challenging to investigate the long-term effects of a serious game on students' science learning. The findings of this research could provide useful insights into serious game designers and practitioners in the domain of science education, particularly at the elementary level and assist them in their future research endeavors.

APPENDIX A

See Table 3.

APPENDIX B

See Table 4.

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