Article:

Kamarudin, M.Z. orcid.org/0000-0001-9670-9791, Noor, M.S.A.M. and Omar, R. (2024) 'How do plants grow?': teaching photosynthesis using digital inquiry-based science learning. Science Activities, 61 (3). pp. 118-131. ISSN: 0036-8121

https://doi.org/10.1080/00368121.2024.2315035

'How do plants grow?': Teaching photosynthesis using digital inquiry-based science learning

Muhammad Zulfadhli Kamarudin[a]*, Mohd Syafiq Aiman Mat Noor[b] and Romarzila Omar[a]

[a]*Faculty of Human Development, Sultan Idris Education University, Perak, Malaysia;*

[b]*School of Education, University of Leeds, Leeds, West Yorkshire, United Kingdom*

*corresponding author: g-15118668@moe-dl.edu.my

‘How do plants grow?’: Teaching photosynthesis using digital inquiry-based science learning

The use of digital technologies as teaching and learning materials supports and enhances science learning, encouraging students to develop valuable inquiry skills and knowledge. In response, this paper seeks to explore digital inquiry-based learning as a useful aid for teaching the elementary school science curriculum on plants in Malaysia. There is a strong rationale for this work, as (i) this curriculum has received less attention compared to the equivalent on animals, and (ii) students have developed misconceptions about plants, typically in the areas of plant nutrition and photosynthesis. Thus, the paper describes a 5E Instructional Model lesson plan, which uses various digital technologies to tackle different inquiry elements at each instructional model stage. The goals of the activities are to help students: (i) assess their pre-existing knowledge and engage with a new concept, (ii) create predictions and document their observations, (iii) display their conceptual understanding, (iv) gain a more profound and broader understanding through new experiences, and (v) examine their understanding and abilities with the aid of digital technology resources. The suggested activities are further discussed in relation to different types of digital technologies and evidence-based practice, thus encouraging other educators to integrate digital inquiry-based learning into their work.

Keywords: Digital technology, elementary science, inquiry-based learning, photosynthesis

Digital learning

In the 21st century, technology is playing an increasingly important role in our daily lives, exposing us to diverse sources of knowledge and alternative viewpoints, and encouraging us to reconsider our fundamental beliefs. Furthermore, technology is being utilized to transform education so that the education community can benefit more from it (Kumar Basak, Wotto, and Bélanger 2018). Emerging technologies are being used to promote teaching and learning and to ensure that students become scientifically literate citizens (Mat Noor 2021). When chosen carefully, emerging technologies can support learning experiences that are aligned with the requirements and aspirations of learners and the demands of the educational context (Díaz et al. 2019). When discussing 'emerging technologies' in teaching and learning, terms such as electronic learning and mobile learning are used interchangeably. However, 'digital learning' is the most widely used. It refers to any instructional approach that effectively employs technology to enhance students' learning experience and spans a broad range of tools and methods (Kumar Basak, Wotto, and Bélanger 2018). In experiencing essential digital learning, students are immersed in a learning environment that blends several technologies to support many roles, including learning activities, interaction, evaluation, and navigation (Sarkar, Mohapatra, and Sundarakrishnan 2017).

Inquiry-based activities refer to emulating the scientist's way of working to examine the natural world and propose interpretations based on the information gathered (Rönnebeck, Bernholt, and Ropohl 2016). Rocha Fernandes et al. (2019) highlighted different types of digital technology resources that can be used in digital inquiry-based learning: (i) simulations and simulations software, (ii) animations in an isolated system, (iii) internet, web, hypermedia, and multimedia resources, (iv) computer-assisted instruction, (v) computer games and serious games, (vi) multi-user virtual environments, (vii) specific resources, (viii) objects and mobile technologies, (ix) virtual laboratories, and (x) remote laboratories and data. The authors reflected on how using different technological tools can have contrasting effects on the teaching process and students' learning based on previous studies that have implemented digital inquiry-based learning. Thus, it is crucial for science teachers to choose suitable technological tools for digital learning that fit the learning objectives and the activities planned for students (Ianes and Venturoso 2021).

Previous studies have shown that integrating digital learning into an inquiry-based science lesson positively impacts elementary students' learning (Kamarudin, Mat Noor, and Omar 2022). Gerhátová et al. (2021) studied the impact of integrated e-learning and inquiry-based approaches on the quality of temperature education for elementary school students. In the paper, students who encountered a technology-integrated, inquiry-based approach in the classroom performed significantly better post-test than students who experienced a traditional inquiry-based approach. Meanwhile, Lin and Chan (2018) studied how technology-supported discourse and reflection can be used to expand students' scientific understanding. In scientific discourse, the students in the experimental group outperformed those in the control group with regards to comprehension of the inquiry process. In addition, the online debate via knowledge-building forum enticed students to engage in reflective discourse since it provided a more effective technique than traditional inquiry-based instruction. Lastly, So et al. (2019) investigated how elementary school students formed opinions regarding the experience of learning science online using diverse digital media. The paper reported that integrating multiple digital media facilitated students' self-learning by inspiring and motivating them to learn about science topics and enhance their conceptual knowledge.

Plants in the science curriculum

The initial stages of biology education begin in pre-school and elementary school, paving the way for the middle and high school development of higher-level concepts and skills (Tunnicliffe and Ueckert 2011). Humans, animals, and plants are typically included in the introductory biology curriculum in elementary school. However, plants seem to receive less emphasis in scientific curricula and biology textbooks relative to animals (Schussler et al. 2010). Therefore, students may be more interested in animals than plants and tend to overlook and disregard plants as living organisms (Patrick and Tunnicliffe 2011). Students may be afflicted with plant blindness, a prevalent condition in which people ignore the plants around them when investigating the natural environment (Comeau et al. 2019). Concerning the crucial issue of plant structures, plant blindness impacts students' perceptions and comprehension of plants and their life processes, thus contributing to their misconceptions about plants. Thus, these issues need to be addressed through a discussion on the positioning of plants within the science curriculum.

The teaching of distinct plant-related concepts has resulted in several misunderstandings. For instance, in Fokides et al.'s (2020) paper, comprehensive explanations were provided for the four basic categories of teaching about plant problems: (i) general difficulties, (ii) plant reproduction, (iii) plant nutrition, and (iv) photosynthesis, respiration, and transpiration. Students had difficulty grasping that plants were living beings and were categorized as plants only if they possessed distinguishing characteristics such as flowers. When comparing plant reproduction to animal and human reproduction, students had difficulties understanding the numerous types of plant reproduction. In plant nutrition, students understood that plants require 'food', in a similar way to humans, thus anthropomorphizing the process. This led to erroneous beliefs about photosynthesis, respiration, and transpiration. The students mistakenly believed that photosynthesis, respiration, and transpiration are substances rather than processes. As a result, students failed to establish the links between photosynthesis, respiration and transpiration as they progressed through secondary school.

Photosynthesis is a fundamental biological process essential for sustaining life on Earth. It is carried out by autotrophic organisms, primarily plants, algae, and certain bacteria. Through this process, these photosynthetic organisms harness sunlight as the primary energy source to convert carbon dioxide and water into glucose and oxygen. This transformation occurs within specialized cellular structures called chloroplasts, where pigments like chlorophyll absorb light energy from the sun, initiating the series of chemical reactions that drive photosynthesis (Khalid, Abdul Wahid, and Sudin 2020). The glucose produced serves as an organic compound that stores energy and is vital for the growth and development of the plant. At the same time, releasing oxygen into the atmosphere supports aerobic respiration and maintains the balance of atmospheric gases (Khalid, Abdul Wahid, and Sudin 2020). As such, photosynthesis plays a pivotal role in the Earth's carbon cycle, regulating atmospheric carbon dioxide levels and serving as the foundation of the food chain, as other organisms rely on the glucose synthesized during photosynthesis as a source of nourishment.

According to Fokides et al. (2020), the topic of photosynthesis is discussed more than other plant topics as it covers two categories of problems: plant nutrition and photosynthesis. This was supported by Özay and Öztas's (2003) paper, which showed that even though photosynthesis is a production process that green plants must undergo, the idea that the method provides nutrition for plants violates students' preconceived notions of nutrition as a solid or liquid item absorbed into the plant from the outside.

Moreover, O'Connell (2008) demonstrated that most photosynthesis activities in the classroom are not inquiry-based. As a result, students follow specific step-by-step directions provided by the teachers that fail to spark their curiosity about the photosynthesis process.

The practice of digital learning positively impacts students' learning and addresses their misconceptions about photosynthesis. In Kici's (2012) study, a courseware that emulated real-life scenarios enabled students to interact with and manipulate concepts, establishing a meaningful connection between abstract ideas and real-world applications to overcome misconceptions and learning challenges related to photosynthesis. Meanwhile, Martin, Silander, and Rutter (2019) concluded that digital instructional methods that facilitate visual analogy mapping could aid students in applying knowledge from educational gaming to understanding scientific concepts, specifically in the context of photosynthesis.

The teaching of photosynthesis

The researchers chose photosynthesis as the core topic of the lesson plan and corresponding teaching and learning activities developed for this paper. The activities were designed for upper elementary students (grades 4-5) in Malaysia, aged from 10-12 years old, and were trialed at Melaka, Malaysia from January to February 2023. Table 1 and Table 2 below show the recommended conceptual approaches and learning aims related to the topic of photosynthesis, as discussed in the Standards-Based Curriculum for Malaysian Primary Schools Science Year 4 (the syllabus that is relevant to the authors) and Next Generation Science Standards (National Research Council 2013).

Since 2011, the Ministry of Education Malaysia has implemented The Standards-Based Curriculum for Malaysian Primary Schools Science, with the goal of nurturing students’ curiosity and fostering creativity through immersive everyday experiences and investigative inquiry (Mat Noor 2022). The Standards-Based Curriculum for Malaysian Primary Schools Science Year 4 provides a comprehensive overview of the subtopics related to photosynthesis. These subtopics include understanding what photosynthesis is, exploring plants’ needs, examining the products of photosynthesis, and recognizing the importance of photosynthesis. These subtopics are aligned with five different learning standards, ensuring a well-rounded understanding of the concept. On the other hand, the Next Generation Science Standards focus on a specific topic within photosynthesis, namely the role of photosynthesis. However, the inclusion of Science and Engineering Practices and Disciplinary Core Ideas sets The Next Generation Science Standards apart. These additional components provide educators with brief information on how to effectively teach about photosynthesis and offer guidance on the breadth of the topic.

Materials list

- Vegetable or fruit seeds (e.g., chili seeds)
- Soil
- Polyethylene plant grow bag
- Garden trowel/ shovel
- Exploration worksheet

Digital technology applications and resources

- AhaSlides app (https://ahaslides.com) (Free app, subscription available)
- Arloon Plants app (http://www.arloon.com/) (Paid app, $2.99 one-off payment)
- Seesaw app (https://web.seesaw.me) (Free app, subscription available)

- Blooket app (https://www.blooket.com) (Free app, subscription available)
- Capcut app (https://www.capcut.com) (Free app, subscription available)
- iPad/mobile tablet (https://www.apple.com/education/k12/products/)

Out of the five digital technology applications utilized in this paper, only one required payment to be used. Arloon Plants was selected because it is the only app suitable for elementary students that provides essential details on plants' life processes, including photosynthesis, through simulations and augmented reality. The remaining four were free applications with paid subscriptions to access all the premium features. However, the essential features of the free apps were sufficient to carry out the steps outlined in this paper. The incorporation of mobile tablets for activities was not confined to specific brands, as digital technology applications were accessible on both the App Store (iPad) and Play Store (Android mobile tablets). Having explored the context of this paper and the materials used, it is now necessary to clarify what inquiry-based learning is and how it was utilized in this lesson plan.

Elements of Inquiry

In inquiry-based science, students examine a problem, look for alternative answers, make observations, pose questions, test hypotheses, and think creatively, so that they learn to reconcile their emerging understandings with prior knowledge and experiences (Gillies 2020). These are the critical elements of inquiry, and the activities planned here best fit the different phases of the 5E Instructional Model developed by Bybee et al. (2006). This model is comprised of five phases: engage, explore, explain, elaborate, and evaluate. The first phase seeks to engage students by setting them short tasks that stimulate curiosity and elicit prior knowledge to assess their pre-existing knowledge and to engage them with a new concept (Bybee et al. 2006). The second phase allows the students to create and explore predictions and hypotheses, attempt alternatives, discuss them with colleagues, and document their observations and thoughts (Bybee et al. 2006). The third phase allows students to display their conceptual understanding, procedural abilities, or behaviors based on their engagement and exploration experiences (Bybee et al. 2006). The fourth phase encourages students to gain a deeper understanding, additional knowledge, and necessary skills through new experiences (Bybee et al. 2006). In the fifth and final phase, students examine their understanding and abilities, which enables teachers to assess students' efforts to attain their academic goals (Bybee et al. 2006).

In the five-lesson sequence that follows, students elicited initial ideas through the formation of word clouds (engage phase), planned and collected data on the needs and products of photosynthesis (explore phase), presented and gave feedback on their findings (explain phase), expressed the importance of photosynthesis using drawings (elaborate phase), and answered multiple interactive quizzes (evaluate phase). The following sections explain how these five phases were applied in a photosynthesis lesson plan.

Engage phase

The objective of this phase was to elicit students' initial conception of photosynthesis. The teacher utilized chili plant seeds as they are familiar to students in Malaysia, a consequence of the prevalent climate conditions in the region. Alongside the seeds, the teacher introduced the necessary planting materials and encouraged students to discuss what aspects they would like to investigate. A series of questions were posed to explore students' preconceptions about how plants grow (Muhamad Dah et al. 2023). The questions were: (i) What will happen when you plant the seeds? (ii) How do you ensure that the seeds will grow into plants? (iii) Do plants require food to grow? and (iv) How do plants get food to grow? The students thought independently and brainstormed their answers in groups to record them in the word cloud using the AhaSlides app, as shown in Figure 1 below. The competitive element of the activity, wherein groups competed to be the first ones to provide answers to the questions, added an exciting dimension to the learning process. In this activity, the teacher indicated how the different size of each word answer represented its frequency and relevance to the questions asked about photosynthesis. This approach encouraged active participation and allowed the teacher to gauge the initial understanding and misconceptions prevailing among students. Using the solutions provided by the students, the teacher concluded the engagement phase by introducing the word photosynthesis and two concepts associated with it: the needs and products of photosynthesis.

Explore phase

The main activities in the explore phase were planning, conducting practical activities, and collecting data related to the needs and products of photosynthesis. The first step in this phase was to explore the plants and the process of photosynthesis using a mobile application. The app used was Arloon Plants, which combines interactive elements for students to explore plants using features like augmented reality and visual simulations. Figure 2 shows the Arloon Plants app interface, focusing on the visual simulations of photosynthesis.

As students were familiar with the growth of plants and photosynthesis, they needed to plan the investigation. In groups, students worked on the exploration worksheet. Students were expected to discuss and list the needs and products of photosynthesis while writing their step-by-step plan to plant the seeds. The purpose of this approach was to ensure proper planning and execution of the investigation, namely ensuring that the plants would stay alive and grow. Students could also source additional information by searching on websites or in science textbooks. Figure 3 shows an example of a worksheet completed as part of the preliminary explore phase activities, which examined students' primary conceptions of photosynthesis. The worksheet was completed before students started conducting the investigation.

Subsequently, each group received the necessary materials to investigate the needs and products of photosynthesis, including chili seeds, soil, polyethylene plant grow bags, and garden trowels. Polyethylene plastic grow bags were chosen based on their practicality and ability to provide a conducive environment to support plant growth. Polyethylene bags ensure optimal conditions, namely vent holes for plants to breathe and ample drainage for roots, thus resulting in better plant development compared to materials like plastic cups. The students needed to plant the seeds and ensure the plants stayed alive and grew. At the same time, they had to observe and make decisions based on the needs and products of photosynthesis from their experience of handling the plants in the investigation, as depicted in Figure 4. It is worth noting that safety precautions were emphasized, particularly when handling sharp plantation tools like garden trowels and shovels.

The students were allotted three weeks to complete the assigned task to facilitate a comprehensive investigation. Throughout this period, they were encouraged to refine the information on their worksheets, capture relevant photographs, and record videos for utilization in the subsequent phases of the lesson to facilitate further learning and documentation of the investigation process and results. Additionally, the teacher's involvement played a pivotal role in guiding the students' investigations. Notably, the teacher used perceptive questions, thereby ensuring the students' sustained commitment to and engagement with the activities.

Explain phase

In this phase, the Seesaw app was the primary medium for displaying students' work and gaining teacher and peer feedback. Using the app, students uploaded materials on their group's observation of their plants in relation to the needs and products of photosynthesis. Seesaw's differentiated instruction formats – text, voice and video – supported students that required specialized instructions, as seen in Figure 5. To complete their submission, students needed to explain and refer to the worksheet, as well as the photos and videos taken in the explore phase. For added flexibility and creativity, students were encouraged to utilize video editing applications such as the Capcut app to enhance the visual and auditory aspects of their presentations. As depicted in Figure 6, students integrated various media elements, such as images, videos, music, texts, and emojis, to elucidate their work in a meaningful way and to demonstrate their grasp of the subject matter.

After submission of their work on Seesaw, students referred to their friends' posts and gave feedback based on their friends' presentations, as seen in Figure 7. This peer interaction fostered a sense of community and collaboration and provided valuable insights that enhanced students' understanding. Concurrently, the teacher advised the students to take advantage of the social media comments section on the Seesaw app to boost classroom discourse and contribute to a more accurate diagnosis of their preconceptions surrounding natural phenomena. Additionally, the teacher offered constructive feedback, suggesting areas for improvement or providing encouragement for exemplary work.

Elaborate phase

The elaborate phase focussed on students applying the knowledge they had obtained from the previous phase in a new situation. In this phase, students were expected to reveal the importance of photosynthesis to all living things, not limited to plants themselves. By broadening the scope, students were encouraged to explore the far-reaching implications of photosynthesis in sustaining life on Earth. To facilitate this process, students engaged in creative activities using the drawing canvas feature of the Seesaw app, as depicted in Figure 8. Through dynamic discussions and creative expression in the form of drawings, students highlighted the diverse applications of photosynthesis in different life contexts.

Next, the students presented their work using the ‘record and reflect’ function on the Seesaw app. In this phase, the teacher expected students to apply the photosynthesis-related terms, definitions, and explanations presented in the preceding phase. The recorded presentations allowed the students to effectively communicate their understanding and demonstrate the depth of their knowledge on the topic.

Upon completing their presentations, the students participated in an interactive feedback session. They attentively listened to each other’s recorded presentations and provided constructive feedback to improve the content and delivery. Additionally, the Seesaw app’s versatile communication options, including text, audio recording, and emojis, enabled the students to express their input on the topic in a manner that suited their individual preferences and styles.

Evaluate phase

The evaluation process occurs in informal and formal situations, allowing students to review their knowledge and skills based on the activities conducted. Informal evaluation can take place at the start and throughout the 5E sequence, while formal evaluation occurs after the elaboration phase (Bybee et al., 2006).

In this study, students offered informal evaluation by managing their work presentations and giving peer feedback on the activities. This process enabled students to reflect on their performance, receive constructive input from their peers, and identify areas for improvement. By engaging in these ongoing feedback loops, students could continuously monitor their learning trajectory and make adjustments as needed to enhance their understanding and skills.

The students engaged in multiple interactive quizzes using the Blooket app, which features many interactive templates like fishing frenzy, for formal evaluation (see Figure 9). These quizzes are designed to gauge students' conceptual understanding in a structured manner. Notably, using Blooket allows for individual reflection without discussion or external reference, thus providing an authentic assessment of each student's comprehension and knowledge retention.

As the lesson concluded, the teacher comprehensively assessed the students' learning outcomes and evaluated whether the learning objectives had been met. Beyond mere academic performance, the teacher also examined evidence of changes in students' attitudes or actions, indicating a deeper level of learning and engagement with the subject matter.

Cross-curricular applications

The activities planned for the five-phase digital inquiry-based science learning sequence were tied into other related subjects of Music, Arts and Mathematics to support cross-curricular applications. In the Explore phase, the students chose suitable background music that complemented their video content using the Capcut app. The students practiced using digital tools and resources to generate melodic, rhythmic, and harmonic ideas for compositions and improvisations pertinent to their Photosynthesis video context (The National Standards for Music Education 2014). In the elaborate phase, the students used the digital visual arts to creatively present their work, exploring their interests in photosynthesis using their knowledge of accessible materials, tools, and technologies (National Core Arts Standards 2014). Meanwhile, in the Evaluate phase, while playing the Fishing Frenzy game mode in Blooket, students compared the weight of the fish captured by answering a series of questions. In this scenario, students compared two items that shared a quantitative attribute of weight to determine which had "more of" or "less of" the attribute (Common Core State Standards Initiative 2010).

Types of digital technologies

In the lesson plan for the photosynthesis activities, different types of digital media were integrated into the various phases of the 5E Instructional Model. The types of digital media used were: (i) simulations and simulations software, (ii) internet, web, hypermedia and multimedia resources, (iii) computer-assisted instruction, (iv) computer games and serious games, (v) specific resources, and (vi) objects and mobile technologies (Rocha Fernandes, Rodrigues, and Rosa Ferreira 2019). The classification of digital media used in the proposed photosynthesis activities is depicted in Table 3 below.

In general, the digital technologies used in the proposed photosynthesis activities were iPads – which were seen as both objects and mobile technologies – and several mobile applications that could be used on a range of devices. Each type of digital technology played a different role in supporting students' learning in digital inquiry-based learning. In the AhaSlides app, the internet and web resources ensure real-time student feedback while specific resources refer to discussion spaces that help students brainstorm ideas suggested by the teacher. The Arloon Plants app is rich in hypermedia and multimedia pictures and videos to elaborate on the investigation of plants, including structures, processes and ecosystems. The added features of augmented reality as simulations and simulation software guide students in observing their actions to manipulate the needs of photosynthesis before conducting the investigation. The mobile application offers computer-assisted instructions with an easy to navigate interface so that students can independently use the app with minimal guidance from the teacher.

Like the Arloon Plants app, Seesaw is a mobile application equipped with computer-assisted instruction. Seesaw has an interface and multimodal tools that are easy to manage and enable students to express their learning fully. With the internet, hypermedia and multimedia digital technology, students can publish their work on the Cloud and give feedback on each other's work to promote discourse and to develop a specific resources web forum. The Capcut app combines use of the internet and video as specific resources so that students can practice creating meaning and advancing evolving concepts in photosynthesis. In the case of the Blooket app, the different modes of interactive games encourage competition among peers, similar to types of computer games that use the internet. The use of digital technology is maximized by using an iPad as an object, as well as mobile technologies with flexible tools, which are available on the app store, to support students' digital inquiry-based learning.

Digital Technologies and the 5E Instructional Model

In relation to the first phase of the 5E Instructional Model – engage – using the AhaSlides app with a word cloud feature, the teacher and students posed questions to examine the students' knowledge and ability to integrate novel and challenging information into their cognitive schema. At the same time, the questions posed were structured as research questions that acted as driving questions for the inquiry investigations conducted in the next phase. Students practiced thinking skills by generating new information, relating different ideas, and synthesizing separate elements of plant growth to generate the initial ideas of photosynthesis.

Corresponding to the second phase of the 5E Instructional Model – explore – students obtained the stimulus of the Arloon Plants app to explore and make simulations on the needs and products of photosynthesis before they conducted the investigation. Based on experiences using the app and discussions with friends, students planned and hypothesized about the investigative procedures using the exploration worksheet to ensure they practiced the best strategies to promote their seeds' growth. The explore phase was focussed on the practice of science process skills like observing the plant's growth, making inferences on the state of the plant, and predicting the products of photosynthesis.

Next, in the explain phase, in groups, students reported on their inquiry investigations, explored the needs and products of photosynthesis using videos, and uploaded them through the private Cloud in the Seesaw app. At the same time, the teacher promoted students' discourses by asking questions, while students also offered feedback on each other's work using the comments function on the Seesaw app. This phase improved students' communication skills as they needed to represent their ideas through various forms of science communication and give feedback to their peers.

In the elaborate phase, students expressed their knowledge of a new situation by creating drawings that best described the importance of photosynthesis to all living things. Students were encouraged to conduct a more in-depth investigation using rigorous but attainable diagrammatic and graphical modes, to communicate information that provided more insights and expanded upon the notion of photosynthesis (Bybee 2014). This phase strengthened students' critical thinking strategies, notably their problem-solving abilities, as they needed to find the right solutions to problems and make decisions based on several alternative ideas (Ministry of Education Malaysia 2018).

With regards to the final phrase – evaluate – the students practiced discourse skills when giving peer feedback from the explain and elaborate phases. Meanwhile, by using a friendly games approach (the Blooket app), students entered a competitive stage where they independently reflected on the topic of photosynthesis based on their experiences of all four phases of the 5E Instructional Model.

Evidence-based practice

The activities planned for the students combined two strategies: hands-on science investigations and digital inquiry. In the hands-on activity, students conducted science investigations by manipulating the plants' growth to collect data on the needs and products of photosynthesis. Allen (2016) highlights that the best way to teach about plants' growth and nutrition (photosynthesis) is through an extended period of activity where students observe germinating seeds as they grow into adult plants. They suggest that photosynthesis activities help deal with misconceptions such as the notion that plants require soil for growth and that plants have similar physiological demands to animals (Allen 2016). The activities used chili seeds to observe the process of growth into an adult plant. Namely, students observed how sugar was produced as a product of photosynthesis. Thus, students could relate the parts of plants and plant nutrition when forming ideas about photosynthesis (Allen 2016).

Meanwhile, digital inquiry activities complement the elements of inquiry. Harlen and Qualter (2018) highlight a number of critical roles of digital technologies in science learning: capturing data, using models and simulations, and encouraging collaboration. When students captured data using photos and videos in the explore phase, they created permanent records and gained the ability to reveal unnoticeable evidence (Allen 2016; Harlen and Qualter 2018). Meanwhile, by using simulations in mobile applications, students could test their ideas as they were in a better position to understand what they saw on screen before physically testing them in real time (Harlen and Qualter 2018). Student collaboration was enhanced through the use of digital technologies, in particular when students used iPads in groups to collaborate on projects and gave feedback on each other's work in the engage, explore, explain and elaborate phases. Thus, this eliminated the challenges associated with early Information and Communication Technology (ICT) usage in which students often engage with the computer screen on their own, without any interaction or guidance (Harlen and Qualter 2018).

Conclusion

The photosynthesis activities described in this paper involved the application of digital inquiry-based learning. In the five-lesson sequence, students elicited initial ideas through the formation of word clouds (engage phase), planned and collected data on the needs and products of photosynthesis (explore phase), presented and gave feedback on their findings (explain phase), expressed the importance of photosynthesis using drawings (elaborate phase), and answered multiple interactive quizzes (evaluate phase). Different types of digital technologies were harnessed in the varying stages of the 5E Instructional Model to carry out the activities. The use of (i) simulations and simulations software, (ii) internet, web, hypermedia and multimedia resources, (iii) computer-assisted instruction, (iv) computer games and serious games, (v) specific resources, and (vi) objects and mobile technologies, ensured that students mastered various inquiry elements and skills in science learning. Students' science process skills, thinking skills, thinking strategies, communication skills, and discourse skills were targeted following the different requirements of the 5E Instructional Model. In this lesson plan, the combination of hands-on science investigations and digital inquiry was informed by existing evidence-based practice to complement and benefit students' learning about photosynthesis in the context of digital inquiry-based science learning. Hence, it is imperative to incorporate digital inquiry-based science learning into the elementary science curriculum to develop an effective and engaging teaching approach to the topic of photosynthesis.

Disclosure statement

No potential conflict of interest was reported by the authors.

Funding

This work was supported by Hadiah Latihan Persekutuan (HLP) (literally translated as 'Federal Training Prizes') from the Ministry of Education, Malaysia.

ORCID

Muhammad Zulfadhli Kamarudin https://orcid.org/0000-0001-9670-9791

Mohd Syafiq Aiman Mat Noor https://orcid.org/0000-0003-4123-7357

Romarzila Omar https://orcid.org/0000-0001-8591-0756

References

Allen, Michael. 2016. *The Best Way to Teach Primary Science Research into Practice*. Open University Press.

Bybee, Rodger, Joseph Taylor, April Gardner, Pamela Van Scotter, Janet Carlson Powell, Anne Westbrook, and Nancy Landes. 2006. "The BSCS 5E Instructional Models: Origin and Effectiveness." Colorado.

Bybee, Rodger W. 2014. "The BSCS 5E Instructional Model: Personal Reflections and Contemporary Implications." *Science and Children*, 15–18.

Comeau, Paula, Christina L.M. Hargiss, Jack E. Norland, Alison Wallace, and Anthony Bormann. 2019. "Analysis of Children's Drawings to Gain Insight into Plant Blindness." *Natural Sciences Education* 48 (1): 1–10. https://doi.org/10.4195/nse2019.05.0009.

Common Core State Standards Initiative. 2010. *Common Core State Standards for Mathematics*. Common Core State Standards Initiative.

Díaz, Paloma, Andri Ioannou, Kaushal Kumar Bhagat, and J. Michael Spector. 2019. *Learning in a Digital World: Perspective on Interactive Technologies for Formal* *and Informal Education*. Springer.

Fokides, Emmanuel, Penelope Atsikpasi, and Dorothea Karageorgou. 2020. “Tablets, Plants, and Primary School Students: A Study.” *Technology, Knowledge and Learning* 25 (3): 621–49. https://doi.org/10.1007/s10758-020-09445-7.

Gerhátová, Žaneta, Peter Perichta, Marián Drienovský, and Marián Palcut. 2021. “Temperature Measurement—Inquiry-Based Learning Activities for Third Graders.” *Education Sciences* 11 (9): 506. https://doi.org/10.3390/educsci11090506.

Gillies, Robyn M. 2020. *Inquiry-Based Science Education*. CRC Press. https://doi.org/10.1201/9780429299179.

Harlen, Wynne, and Anne Qualter. 2018. *The Teaching of Science in Primary Schools*. 7th ed. Routledge.

Ianes, Dario, and Leonardo Venturoso. 2021. “Learn by Distance: Advice for Choosing an Effective and Inclusive e- Learning Platform.” *Open Journal of IUL University* 2 (3): 172–84.

Kamarudin, Muhammad Zulfadhli, Mohd Syafiq Aiman Mat Noor, and Romarzila Omar. 2022. “A Scoping Review of the Effects of a Technology- Integrated, Inquiry-Based Approach on Primary Pupils’ Learning in Science.” *Research in Science & Technological Education*, 1–20. https://doi.org/10.1080/02635143.2022.2138847.

Khalid, Jariah, Rodiah Abdul Wahid, and Sudani Sudin. 2020. *Form 5 Biology Kurikulum Standard Sekolah Menengah (KSSM) Textbook*. Ministry of Education Malaysia.

Kici, Derya. 2012. “Using Technology In Science Education: A Courseware To Overcome Misconceptions And Learning Difficulties About Photosynthesis.”

International Journal of New Trensd in Arts, Sports & Science Education (IJTASE) 1 (2): 30–40.

Kumar Basak, Sujit, Marguerite Wotto, and Paul Bélanger. 2018. "E-Learning, M-Learning and D-Learning: Conceptual Definition and Comparative Analysis." *E-Learning and Digital Media* 15 (4): 191–216. https://doi.org/10.1177/2042753018785180.

Lin, Feng, and Carol K.K. Chan. 2018. "Promoting Elementary Students' Epistemology of Science through Computer-Supported Knowledge-Building Discourse and Epistemic Reflection." *International Journal of Science Education* 40 (6): 668–87. https://doi.org/10.1080/09500693.2018.1435923.

Martin, Wendy, Megan Silander, and Sarah Rutter. 2019. "Digital Games as Sources for Science Analogies: Learning about Energy through Play." *Computers and Education* 130 (March 2018): 1–12. https://doi.org/10.1016/j.compedu.2018.11.002.

Mat Noor, Mohd Syafiq Aiman. 2021. "Assessing Secondary Students' Scientific Literacy: A Comparative Study of Suburban Schools in England and Malaysia." *Science Education International* 32 (4): 343–52. https://doi.org/10.33828/sei.v32.i4.9.

Mat Noor, Mohd Syafiq Aiman. 2022. "An Insight into Primary Science Education in Malaysia." *ASE International* 16: 34–41.

Ministry of Education Malaysia. 2018. *Kurikulum Standard Sekolah Rendah Sains Tahun 4 Dokumen Standard Kurikulum Dan Pentaksiran (Edisi Bahasa Inggeris) [The Standards-Based Curriculum for Primary Schools Science Year 4 Curriculum and Assessment Standards Document (English Edition)]*. Curriculum Development Division, Ministry of Education Malaysia.

Muhamad Dah, Norsyazwani, and Mohd Syafiq Aiman Mat Noor. 2021. “Facilitating Pupils’ Questioning Skills in Open Inquiry Learning through an Investigable Question Formulation Technique (IQFT).” *Journal of Mathematics and Science Teacher* 1 (2): 1–11. https://doi.org/10.29333/mathsciteacher/11283.

Muhamad Dah, Norsyazwani, Mohd Syafiq Aiman Mat Noor, Muhammad Zulfadhli Kamarudin, and Mohd Mokhzani Ibrahim. 2023. “Facilitation of Student Questioning in the Malaysian Secondary Science Classroom Using the Investigable Questioning Formulation Technique (IQFT) Protocol.” *Asia-Pacific Science Education*, 1–35. https://doi.org/10.1163/23641177-bja10063.

National Core Arts Standards. 2014. *Visual Arts - Creating*. National Core Arts Standards.

National Research Council. 2013. *Next Generation Science Standards: For States, By States*. National Academies Press. https://doi.org/10.17226/18290.

O’Connell, Dan. 2008. “An Inquiry-Based Approach to Teaching Photosynthesis Cellular Respiration.” *American Biology Teacher* 70 (6): 350–56. https://doi.org/10.1662/0002-7685(2008)70[350:AIATTP]2.0.CO;2.

Özay, Esra, and Haydar Öztas. 2003. “Secondary Students’ Interpretations of Photosynthesis and Plant Nutrition.” *Journal of Biological Education* 37 (2): 68–70. https://doi.org/10.1080/00219266.2003.9655853.

Patrick, Patricia, and Sue Dale Tunnicliffe. 2011. “What Plants and Animals Do Early Childhood and Primary Students’ Name? Where Do They See Them?” *Journal of Science Education and Technology* 20 (5): 630–42. https://doi.org/10.1007/s10956-011-9290-7.

Rocha Fernandes, Geraldo W, Antonio M Rodrigues, and Carlos Alberto Rosa Ferreira. 2019. *Using ICT in Inquiry-Based Science Education*. Springer.

https://doi.org/10.1007/978-3-030-17895-6.

Rönnebeck, Silke, Sascha Bernholt, and Mathias Ropohl. 2016. “Searching for a Common Ground – A Literature Review of Empirical Research on Scientific Inquiry Activities.” *Studies in Science Education* 52 (2): 161–97. https://doi.org/10.1080/03057267.2016.1206351.

Sarkar, Subrata, Sanjay Mohapatra, and J. Sundarakrishnan. 2017. “Assessing Impact of Technology Based Digital Equalizer Programme on Improving Student Learning Outcomes.” *Education and Information Technologies* 22 (1): 195–213. https://doi.org/10.1007/s10639-015-9434-0.

Schussler, Elisabeth E., Melanie A. Link-Pérez, Kirk M. Weber, and Vanessa H. Dollo. 2010. “Exploring Plant and Animal Content in Elementary Science Textbooks.” *Journal of Biological Education* 44 (3): 123–28. https://doi.org/10.1080/00219266.2010.9656208.

So, Winnie Wing Mui, Yu Chen, and Zhi Hong Wan. 2019. “Multimedia E-Learning and Self-Regulated Science Learning: A Study of Primary School Learners’ Experiences and Perceptions.” *Journal of Science Education and Technology* 28 (5): 508–22. https://doi.org/10.1007/s10956-019-09782-y.

The National Standards for Music Education. 2014. *Music Standards (Music Technology)*. The National Standards for Music Education.

Tunnicliffe, Sue Dale, and Catherine Ueckert. 2011. “Early Biology: The Critical Years for Learning.” *Journal of Biological Education* 45 (4): 173–75. https://doi.org/10.1080/00219266.2010.548873.