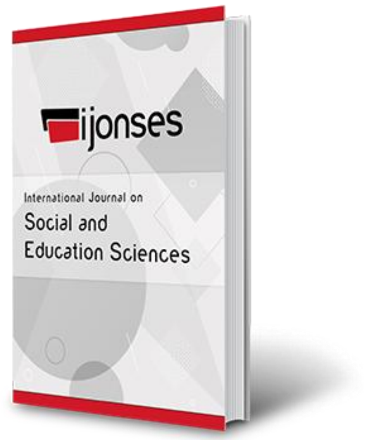

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Thaksaranyaporn Sittiya
Kalasin University, Thailand

Chulida Hemtasin
Kalasin University, Thailand

Wisarut Payoungkiattikun
Kalasin University, Thailand

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Designing and Developing Learning Management Processes to Promote Self-Directed Knowledge Construction

Thaksaranyaporn Sittiya, Chulida Hemtasin, Wisarut Payoungkiattikun

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Abstract

This study aims to: 1) Examine the experiences and needs essential for fostering self-directed knowledge construction among science teachers and lower secondary students; and 2) Develop a learning management process to enhance self-directed knowledge construction for lower secondary students. Targeting 35 students from a school in Kalasin province during the first semester of 2023, the research employs interviews, response assessments, and practical exercises. Following Richey & Klein's design-based research methodology, the project consists of two primary phases. The initial design phase analyzes user experiences and relevant research to construct a learning management framework. The subsequent development phase involves expert review to refine and ensure the framework's effectiveness. Expert evaluations have tailored the learning management process to the specific context of lower secondary education, promoting student engagement and knowledge creation through practical, real-world applications. Findings highlight the efficacy of constructivist approaches in learning management, demonstrating their ability to meet the evolving needs of students and educators by enabling independent knowledge generation. This study provides a robust framework for developing effective, self-directed learning environments, contributing significantly to the field of educational design.

Introduction

The Programme for International Student Assessment (PISA), conducted by the Organisation for Economic Co-operation and Development (OECD) in 2022, evaluates the competencies of 15-year-old students in applying knowledge and skills in real life, focusing on literacy in reading, mathematics, and science. These domains are pivotal for lifelong learning and future economic prosperity. However, the 2022 PISA results revealed a global decline in average scores across all areas, including Thailand (PISA Thailand, 2023). This downturn mirrors the widespread disruption caused by the COVID-19 pandemic, which significantly impacted educational systems worldwide, necessitating a swift transition to online learning formats. This has altering traditional teaching and learning dynamics (Altıparmak & Cebecioğlu, 2022; Taşkaya, 2021).

The shift to online learning, while demonstrating adaptability. However, it also highlighted significant challenges in effectively integrating practical and theoretical learning, underscoring the vital role of teacher clarity in enhancing education quality (Zhunusbekova et al., 2023). Nonetheless, the digital divide and the lack of hands-on guidance have led to educational setbacks characterized by losses in knowledge, attitudes, and practical skills. As a results, thereby impeding students' developmental trajectories have been impeded, diminishing their quality of life in a rapidly evolving world (Kölemen, 2023; Phonphanthorn et al., 2023).

Addressing these setbacks necessitates a re-evaluation of teaching competencies and methodologies. Emphasizing the need for transformational teaching approaches, educators are encouraged to adopt strategies that foster exploration, problem-solving, and critical thinking, moving away from traditional lecture-based methods (Kaeedi et al., 2023; Polyiem & Nuangchalerm, 2022). This paradigm shift aligns with constructivist theories, which advocate for a learner-centered approach where knowledge is constructed through experience and social interaction, contrasting with traditional transmission models of education (Szabó & Csépes, 2022; Tomljenović & Tatalović, 2020). Constructivism can be divided into cognitive constructivism, as described by Piaget, and social constructivism as described by Vygotsky, Both emphasizes the active role of learners in building knowledge through interaction and collaboration (Abderrahim & Colón, 2021; Jianing, 2022). This theory supports the view that effective learning involves constructing personal meaning and knowledge through engaged, experiential processes rather than passive reception (Czarnocha, 2020; Şanal & Erdem, 2022).

In light of these educational challenges and theoretical frameworks, this research aims to develop a learning management process that promotes self-directed knowledge creation. The process is designed to align with the United Nations' Sustainable Development Goals (SDGs), particularly the goal of ensuring inclusive and equitable quality education for all (Wolhuter, 2023). By examining the intersection of educational setbacks, the shift towards online learning, and the principles of constructivist learning, this study seeks to contribute to the discourse on educational quality and innovation in the context of global challenges and transformations.

Research Questions:

1. What are the experiences and necessary requirements to promote self-directed knowledge building among science teachers and lower secondary school students?
2. How can a learning management process be designed to promote self-directed knowledge building among lower secondary school students?

Research Objectives:

1. To identify the experiences and necessary requirements to promote self-directed knowledge building among lower secondary school teachers and students.
2. To design and develop a learning management process from these experiences to promote self-directed knowledge building among lower secondary school students in a large special school.

Method

Research Design

This study employs a Type I developmental research framework as outlined by Richey & Klein (2014), focusing on design and innovation across two primary phases: design and development.

Phase 1: Design Process

The initial phase centers on understanding user experiences and needs. This involves a comprehensive review of existing documents and research pertinent to the identified problem. The objective is to design a learning management process that facilitates self-directed knowledge construction among learners. The devised process undergoes expert review to ensure its relevance and effectiveness.

Outputs:

- Analysis of Science Learning Management Experiences: This output includes a detailed examination of existing science learning management practices, identifying strengths and areas for improvement.
- Analysis of Science Learning Experiences: This involves evaluating the learning experiences of students within science education, highlighting effective strategies and challenges encountered.
- Synthesis of Research on Science Learning Management: A comprehensive synthesis of existing research related to science learning management, focusing on strategies that promote autonomous knowledge creation.
- 5D User Experience Design: An innovative approach to designing learning experiences incorporating five dimensions (5D) to address users' roles, feelings, behaviors, and opinions.

Phase 2: Development Process

In the second phase, the learning management process designed in Phase 1 is submitted for expert verification to confirm its accuracy and suitability. Based on expert feedback, the process is refined and adapted to align with the specific context of lower secondary schools, enhancing the efficiency of the learning management process.

Outputs:

- The primary output of this phase is the design and development of a learning management process aimed at fostering self-directed knowledge creation among lower secondary school students.

Data Analysis

The research employs domain analysis to categorize words into groups based on specific relational characteristics inherent to each word. This analysis serves to illuminate the relationships within individual societies, dividing them into two main areas:

- Preliminary Analysis of Teachers' Learning Management Experience: Utilizing a 5D user experience framework, this analysis segregates data into roles, feelings, behaviors, and opinions.
- Preliminary Analysis of Students' Science Learning Experiences: Information is synthesized by dimension—role, feeling, behavior, and viewpoint—creating a full grid that stores the 5D user experience. It includes an emphasis on inquiries regarding past experiences in managed science learning.

The aim is to derive detailed design principles and patterns that cater to the needs and preferences of both teachers and students, reflecting the identified patterns or methods discovered throughout the learning process. The findings from this analysis will inform the redesign of the theoretical framework, documentation, and related research, culminating in the refinement of the learning management process. This process is then submitted to experts for verification of its accuracy and efficiency, with the goal of implementing improvements to enhance the efficacy of learning management.

Results and Discussion

This research delineates a comprehensive learning management process devised to foster self-knowledge construction among students, particularly within the context of specialized large schools. The process, grounded in constructivist theories propounded by Jean Piaget and Lev Vygotsky, emphasizes the critical role of connecting prior knowledge with new experiences and underscores the importance of social interactions in learning. This refined approach to learning management comprises several stages, each designed to engage students actively and promote critical thinking, problem-solving, and creative reasoning.

The research findings are reported according to the two objectives of the study, starting with the first objective to analyze the necessary requirements and experiences of teachers and students regarding the management of learning that promotes self-knowledge construction by learners (see Table 1 and 2).

Table 1. Analysis of Student User Requirements Results

Need’s and Requirement of Students	Dislikes
1. Interactive Learning Methods: Students show a strong preference for engaging in experiments, games, and practical activities rather than sitting through traditional lectures. 2. Modern Equipment: There's a clear demand for the integration of new and modern media equipment to facilitate learning. 3. Accessible Content: Students favor content that is easy to understand and encourages active learning. 4. Engaging Assessment Styles: A preference for game-style assessments that make the evaluation process more enjoyable. 5. Achievement in Science: Students express a desire to achieve good results in science subjects. 6. Real-world Application: There is a need for knowledge that students can apply in their daily lives, making learning more relevant and meaningful. 7. Opportunities for Self-experimentation: Students are interested in conducting experiments by themselves, fostering a hands-on learning experience. 8. Pursuing Dreams: Some students have aspirations of becoming	1. Lecture-focused Instruction: Students find lectures to be boring and challenging to understand, indicating a disengagement from this traditional method of teaching. 2. Complex and Difficult Content: There's a clear aversion to learning materials that are perceived as hard and complicated, suggesting a preference for more digestible and straightforward information.

Need's and Requirement of Students	Dislikes
scientists and seek educational experiences that support this dream.	
Summary: Students are looking for an engaging and stimulating educational experience that is both accessible and straightforward. They desire learning environments that are outfitted with the latest technology, content that has practical applications, and abundant opportunities for hands-on experimentation.	

Table 2. Analysis of Teacher User Requirements Results

Need's and requirement of teachers	Teacher concerns
1. Student Engagement: Teachers prioritize high levels of student involvement in the learning process. 2. Diverse Teaching Media: A need for a wide array of teaching materials to facilitate varied learning experiences. 3. Hands-on Learning: The desire for students to have opportunities for practical exercises and self-directed experimentation. 4. Holistic Integration: An emphasis on integrating academic content with other subjects, as well as games, activities, and real-life situations. 5. Applicable Knowledge: A focus on teaching content that has direct applications in students' daily lives. 6. Assessment Strategies: The necessity for measuring and evaluating student performance using specific criteria and indicators.	1. Homework Load: Teachers prefer to avoid assigning excessive amounts of homework to prevent student overload. 2. Complexity of Content: An avoidance of content that is challenging to memorize, aiming for more accessible learning material.
Summary: Teachers aim to facilitate science learning that actively involves students, utilizing a diverse array of media and placing a strong emphasis on practical application. Teachers seek to integrate learning with other subjects, games, activities, and real-life scenarios. The focus is on practical content that can be directly applied, with assessment based on specific criteria and indicators. Additionally, teachers value the ability to demonstrate the reality of science through hands-on experimentation.	

Table 3 presents a comparative analysis of constructivist theory alongside self-directed learning behaviors and teaching activities. Thongmaen and Pheungsophan (2019) detail how self-directed learning involves students independently managing their learning process, emphasizing the significance of goal setting, practical engagement, and the sharing of knowledge. This behavior is motivated by students' psychological interest and a learning environment fostered by educators. Prapasanobol and Nillapun (2021), and Anantasuk and Mangkon (2020), highlight constructivist theory's focus on creativity, the construction of knowledge through experience, and the critical role of interactive media. Chaijaroen (2008) discusses constructivism in terms of problem-solving and social interaction, drawing upon the foundational ideas of Piaget and Vygotsky to advocate for a socially collaborative learning and development process.

Table 3. Comparative Analysis of Constructivist Theory, Self-Directed Learning Behaviors, and Teaching Activities

Aspect	**Thongmaen and Pheungsophan (2019)**	**Prapasanobol and Nillapun (2021)**	**Anantasuk and Mangkon (2020)**	**Chaijaroen (2008)**
Self-directed learning behavior	Describes a process where students independently determine and conduct their learning through planning, practical practice, and review. Highlights the importance of goal setting and planning, hands-on work, and knowledge sharing and presentation.	N/A	N/A	N/A
Causes of self-directed learning behavior	Attributes self-directed learning to psychological interest in learning and determination, as well as to a socially conducive learning environment created by teachers.	N/A	N/A	N/A
Constructivist theory	N/A	Emphasizes creativity in learning through student enthusiasm and interest, advocating for integrated academic	Focuses on the learner as the creator of knowledge by linking new experiences with existing knowledge, underlining the	Discusses intellectual structure development through problem-solving and social interactions, highlighting Piaget's and

Aspect	**Thongmaen and Pheungsophan (2019)**	**Prapasanobol and Nillapun (2021)**	**Anantasuk and Mangkon (2020)**	**Chaijaroen (2008)**
		thinking and the provision of appropriate teaching materials by teachers.	importance of media and equipment in facilitating this process.	Vygotsky's principles on cognitive and social constructivism.
Constructivist teaching activities	N/A	Stresses learning outcomes that arise from practice, encouraging students to generate knowledge themselves. Advocates for learning management that allows students to actively engage in creating meaning from information or experiences.	N/A	Proposes that learning and development are socially collaborative, emphasizing the role of culture and social interaction in Vygotsky's Social Cognitive Const

Table 4 synthesizes user experience and theoretical research to illustrate the alignment between students' and teachers' needs with constructivist educational theories. Students prefer engaging, practical learning experiences over traditional lectures, emphasizing the value of experiments, innovative media, and real-life applicable content. Their learning is self-directed, driven by goal setting, planning, and active engagement, influenced by both their personal interest and the educational environment fostered by teachers.

Teachers, on the other hand, seek a learning management system that involves students actively, incorporates a variety of media, and applies practical knowledge. This approach is underpinned by constructivist theory, advocating for education that allows students to construct knowledge through their experiences and interactions. The theory promotes teaching methods that foster critical thinking, problem-solving, and active participation, emphasizing the importance of adapting teaching strategies to meet the diverse needs of learners and encourage self-directed knowledge construction.

Table 4. Analysis Results, User Experience and Requirements, Simulation, Theory, and Documentation

Category	**User Experience and Requirements**	**Relevant Theories and Research**
Students' Needs	Activities that emphasize practical experience over lectures, including experiments, and the use of innovative media and technologies. Content should be straightforward, applicable to daily life, and engaging to motivate learning. Preferences include fun evaluation methods and opportunities for self-conducted experiments with instructor guidance.	Self-creating Learning Behavior: Students engage in self-directed learning by setting goals, planning, acting, reviewing, and presenting work. Causes of Self-creating Learning Behavior: Divided into psychological (student interest) and social environmental aspects (teacher's role in creating an attractive learning environment).
Tachers' Needs	A science learning management system that actively involves students, utilizes a wide range of media, and emphasizes practical application, integration with other subjects, and real-life applicability. The content should be practical, with measurement and evaluation based on set criteria and indicators. Teachers also value empirical evidence of scientific concepts.	Constructivist Theory: Focuses on learning as a self-creation process, where students generate knowledge through experiences linked to existing knowledge. Constructivist Teaching Activities: Emphasize building knowledge and awareness, practical goals, diverse roles for students and teachers, and a variety of evaluation methods.

Constructivist Teaching Activities Detailed Analysis

Results: Focus on knowledge and awareness building, with practical teaching goals that encourage students to construct their own knowledge.

Student Roles: Act as information managers and meaning-makers.

Teacher Roles: Facilitators who prepare resources, create conducive learning environments, and shift from knowledge transmitters to learning assistants.

Evaluation: Utilizes goal-free or socially negotiated goals, emphasizing individual knowledge and meaning creation.

Teaching Activity Procedures: Include student preparation, review of previous knowledge, idea modification through experimentation, activity design for problem-solving, and skill training through varied contexts.

Principles of Constructivist Theory

Key Concepts: Knowledge is constructed through experiences involving problem-solving. Constructivism is underpinned by Jean Piaget's Cognitive Constructivism, focusing on integrating new and old experiences, and Lev Vygotsky's Social Cognitive Constructivism, highlighting the role of culture and social interaction in learning.

Social Cognitive Constructivism: Emphasizes collaborative learning, the Zone of Proximal Development in lesson planning, meaningful learning contexts, and the integration of school and real-world experiences.

A prototype learning management process aimed at fostering self-directed knowledge construction among lower secondary school students has been developed. This process integrates insights from user experiences, simulations, relevant theoretical frameworks, and a comprehensive review of existing literature and research findings (referenced in Table 5). Subsequently, the prototype underwent a rigorous evaluation by experts, allowing for further refinement and optimization of the learning management process based on the feedback received during the expert review phase (detailed in Table 6). This iterative approach ensures that the developed learning management system is both effective and aligned with the needs and experiences of the target learner group.

Table 5. Learning Management Process for Promoting Self-Directed Knowledge Construction

Activity Stage	Purpose	Method
1. Attention-Building	To capture student interest.	Utilize engaging cases or examples and pose thought-provoking questions to stimulate thinking and draw attention.
2. Original Knowledge Evaluation	To assess the extent of students' prior knowledge.	Present problems or scenarios for students to solve independently, encouraging them to document their solutions without fear of being wrong.
3. Adjustment	To evaluate and correct students' initial understandings.	Facilitate group discussions in a circle to enhance visibility and interaction, guiding students through questions that promote analysis and understanding without direct correction.
4. Challenge	To develop problem-solving skills.	Set up practical situations or problems post-adjustment for students to solve, using devices or simulations.
5. Planning	To encourage students to develop work plans.	Allow students to explore and select equipment, then plan and document their design and creative process.
6. Trial	To observe and assess learning progress and foster experiential learning.	Conduct experiments individually or in groups, emphasizing observation of results and comparative analysis to determine effectiveness.
7. Problem Analysis	To enable problem cause analysis and solution development.	Analyze experimental outcomes to identify and understand problem causes and solutions, encouraging peer exchange of insights and strategies.
8. Upgrade	To refine	After peer exchange and learning, encourage students to apply

Activity Stage	Purpose	Method
	understanding based on peer learning.	new solutions and share insights without direct assistance, aiming for successful outcomes.
9. Summary	To enhance learning efficiency through reflection.	Prompt students to document and discuss their challenges and solutions, fostering an exchange of learning experiences between peers and with teachers.

Table 6. Revised Learning Management Process Structure

Expert	Expert Feedback Adjustments
1	Integrated Constructivism principles by Jean Piaget and Lev Vygotsky, emphasizing the importance of linking old and new experiences and the role of social interaction in learning.
2	Tailored learning activities to the age and character of learners, ensuring the process is understandable, relevant, and capable of promoting self-knowledge. Emphasized appropriate measurement and evaluation tools.
3	Addressed the need to adjust evaluation criteria to match learning objectives and acknowledged potential constraints in learning time management.

The recommendations from experts led to the refinement of the learning management process, as shown in Table 7.

Table 7. Revised Learning Management Process Structure

Stage	Sub-Stages	Description
1. Engage and Assess	1.1 Attention-Building 1.2 Evaluation of Original Knowledge	Initiates the learning process by capturing students' attention through engaging activities. Assesses prior knowledge to tailor the learning experience.
2. Adjust and Challenge	2.1 Adjustment 2.2 Challenge	Facilitates the correction of misunderstandings and introduces challenges to stimulate problem-solving skills.
3. Plan and Experiment	3.1 Planning 3.2 Trial 3.3 Problem Analysis	Encourages students to plan their approach to learning tasks, followed by experimentation and analysis of problems encountered.
4. Refine and Evaluate	4.1 Upgrade 4.2 Summary	Focuses on refining understanding through feedback and summarizing key learning points to consolidate knowledge.
5. Personalize and Contextualize	-	Adapts learning activities to match the learners' age, personality, and current educational needs, ensuring relevance and promoting self-knowledge.

The development and refinement of a learning management process tailored to the specific context of the school and its students focus on enhancing accuracy and appropriateness. This process encompasses two main components: the facilitation of self-knowledge construction and the implementation of a learning management process designed to nurture this self-construction among learners.

Self-Knowledge Construction: This aspect is centered on the learners' ability to integrate their prior knowledge, derived from diverse experiences, with newly acquired insights. Such integration is facilitated through direct engagement in hands-on practice, experimentation, analytical problem-solving, and autonomous resolution of challenges. Through repetitive engagement in these activities, learners deepen their understanding, enhance their critical thinking abilities, and develop the capacity to distill complex information into cohesive personal knowledge. This iterative process significantly influences the learners' overall educational journey, promoting a profound and lasting impact on their approach to learning.

Learning Management Process to Promote Self-Knowledge Construction: This dimension addresses the pedagogical strategies that prioritize the learner's active role in knowledge construction. It emphasizes engaging learners in practical activities that present real-world problems or scenarios, thereby enabling learning through exploration, iterative trial and error, interaction with peers, and the exchange of information. Such a process culminates in the learners' ability to synthesize and internalize the knowledge gained, transforming it into a personal understanding of the subject matter. According to Thongman and Phengphothisat (2019), the educator's role transitions to that of a facilitator who cultivates an interactive and supportive learning environment, meticulously designed to resonate with the learners' developmental stage and interests. Educators employ dynamic teaching materials and methodologies, leveraging thought-provoking inquiries to guide learners through moments of uncertainty or challenge. Rather than offering direct solutions, educators encourage a reflective and critical approach to learning, fostering an atmosphere where learners are motivated to engage deeply with the content. This pedagogical approach facilitates a collaborative learning culture, where peer-to-peer support and the dynamic interaction between learners and teachers are central to the educational experience.

Figure 1. The Structure of the Learning Management Process for Promoting Self-Directed Knowledge Construction

Refined Learning Management Process Overview (see Figure 1)

Stage 1: Stimulating Cognitive Structure

The initial stage centers on capturing students' attention through the utilization of engaging scenarios, problems, or case studies. This approach is rooted in the understanding that effective problem positioning is crucial for learning enhancement. Activities designed for this stage, including games, experiments, and the use of diverse teaching media, are aimed at leveraging students' prior experiences and stimulating their interest. The objectives of this stage include sparking curiosity, activating prior knowledge, and fostering cognitive conflict to encourage deeper analysis and thought.

Stage 2: Knowledge Assessment

Following cognitive stimulation, this stage involves presenting learners with problems to solve independently, encouraging them to articulate their thought processes without fear of being judged on the correctness of their answers. This phase facilitates a collaborative learning exchange, wherein students share and discuss their solutions, guided by thought-provoking questions from the teacher. This method assesses and adjusts students' understanding, taking into account individual differences and fostering a community of learning where students are encouraged to think critically.

Stage 3: Creating New Knowledge

Building upon adjusted prior knowledge, this stage introduces new challenges to create cognitive conflict, urging students to explore hands-on activities for problem-solving. This approach emphasizes student communication and autonomy in learning outcomes, with teachers supporting as advisors rather than direct instructors. The process includes planning, experimentation, and analysis stages, where students are encouraged to critically evaluate their approaches and outcomes, fostering a cycle of continuous improvement and learning.

Enhancements and Objectives

Each stage of the learning management process is meticulously designed to support the self-construction of knowledge, with specific objectives aimed at developing students' critical thinking, problem-solving abilities, and creative reasoning. The process not only aligns with constructivist principles but also adapts to the learners' age and individual needs, ensuring the relevance and effectiveness of the educational experience.

Conclusion

The study aimed to meticulously analyze the experiences and pinpoint the essential requirements to cultivate the self-construction capabilities of both teachers teaching sciences and early high school students. By engaging in a thorough review of user experiences, documentation, and relevant scholarly works, the research unearthed valuable insights into the design and development of a learning management process that significantly promotes self-directed knowledge construction among learners. The research findings were distilled from structured interviews that included 17 questions covering roles, feelings, behaviors, and reviews. The results revealed a pronounced preference among students for practical activities over traditional lectures. This inclination towards hands-on learning experiences, coupled with a desire for modern and unique educational tools, underscored the necessity for content that is both easily comprehensible and applicable to real-life scenarios. The synthesis of this data, through the lens of domain analysis, underscored a dualistic approach focusing on both the psychological determinants and the socio-environmental facets that catalyze self-directed learning behaviors. This comprehensive analysis elucidated the vital role of an engaging and supportive learning atmosphere, facilitated by teachers, in encouraging students to actively participate in their learning journey, thereby stimulating a deeper understanding and enthusiasm for learning within and beyond the classroom walls.

In the development phase, the learning management process, having been rigorously reviewed by experts for its relevance and efficacy, underwent refinement to align more closely with the specific contexts of lower secondary schools. This phase not only validated the designed process but also enhanced its potential to effectively facilitate self-directed learning among students, thereby contributing to a more engaging and productive educational experience. Through the integration of practical activities, modern technological tools, and content that resonates with the daily experiences of students, this research contributes significantly to the field of educational design. It offers a robust framework for the development of learning environments that not only meet the evolving needs of students and teachers alike but also embrace the principles of constructivism and self-directed learning. The insights gleaned from this study pave the way for future endeavors aimed at optimizing the educational landscape, ensuring that it remains responsive to the needs of learners in an ever-changing world.

Future Research

While this study provides a structured framework for self-directed knowledge construction in lower secondary science education, further research is needed to refine and expand its applicability. One key area for future investigation is the long-term impact of this approach on academic performance, critical thinking, and problem-solving skills. Longitudinal studies tracking student progress across multiple academic years could provide deeper insights into the sustainability and effectiveness of self-directed learning. Another critical direction involves the integration of digital tools into self-directed learning environments. Technologies such as virtual labs, AI-assisted tutoring, and adaptive learning systems have the potential to enhance student engagement and knowledge retention. Research should explore how these tools can be effectively implemented to support constructivist-based learning while addressing challenges related to digital accessibility and equity.

Cross-cultural adaptation is also an important consideration. Investigating the feasibility of implementing self-directed learning frameworks in diverse socioeconomic and educational settings can provide valuable insights into best practices for scalability. Comparative studies across different regions can help identify context-specific adaptations that ensure the model's effectiveness in varying institutional environments. Furthermore, teacher training and professional development remain crucial for the successful implementation of self-directed learning. Future research should focus on designing comprehensive training programs that equip educators with the necessary instructional strategies, facilitation techniques, and assessment tools. Additionally, developing and validating alternative assessment frameworks, such as portfolio assessments, real-world problem-solving tasks, and self-reflection exercises, could provide more accurate measures of student learning beyond standardized tests.

Finally, research should examine the scalability and policy implications of integrating self-directed learning into national education systems. Understanding institutional barriers, resource constraints, and policy support mechanisms will be essential in ensuring the model's widespread adoption and long-term success. By addressing these areas, future research can further enhance self-directed learning models, ensuring their effectiveness in fostering scientific literacy, independent learning, and 21st-century skills in students worldwide.

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Author Information

Thaksaranyaporn Sittiya

https://orcid.org/0009-0007-5981-4083

Kalasin University

Thailand

Chulida Hemtasin

https://orcid.org/0000-0001-5147-1628

Kalasin University

Thailand

Contact e-mail: *chulida.he@ksu.ac.th*

Wisarut Payoungkiattikun

https://orcid.org/0009-0003-0459-6366

Kalasin University

Thailand