






IMPLEMENTATION OF CHEMISTRY LEARNING INNOVATION INTEGRATED WITH GENERIC SCIENCE SKILLS TO ENHANCE HOTS ABILITY

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Abstract

The integration of 21st-century learning and generic science skills (GSS) is critical in developing students' higher-order thinking skills (HOTS), especially in chemistry education. This quasi-experimental study aimed to analyze the effects of implementing four GSS-integrated digital learning models (PjBL-GSS, PBL-GSS, IBL-GSS, and DL-GSS) and students' initial abilities on their HOTS performance. A total of 397 students participated, grouped by initial ability levels and assigned to different learning models. Data were collected using validated instruments including scholastic tests and HOTS assessments, and analyzed using descriptive statistics and two-way ANOVA. The results showed significant effects of both initial abilities and learning models on HOTS, with IBL-GSS being the most effective, especially for high-ability students. Moreover, significant interactions were found between initial ability and the type of model used. The study suggests that selecting appropriate digital learning models based on students' prior knowledge is essential to foster optimal HOTS outcomes. Teachers are encouraged to align instructional design with both GSS indicators and students' learning readiness.

Keywords: Chemistry, Generic Science Skills, Hots Abilities



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INTRODUCTION

The trend of education policy in the 21st century is improving the quality of education to produce Human Resources (HR) who are able to compete in the era of globalization (Dung, 2021). Quality education is also one of the goals of the Sustainable Development Goals (SDGs), which emphasizes the importance of access to inclusive and quality education, Sustainable Development Goals (SDGs), especially in the goal of Quality education, which emphasizes the importance of access to inclusive and quality education, in this case is e-learning web-based education (Alenezi et al., 2023; Saini et al., 2023). Changes and developments in the world today are also the impact of the development of science and technology in the era of globalization which can be seen as adaptation problems that must be anticipated and resolved wisely and creatively (Alneyadi et al., 2023; Bandura, 2009). In the era of the industrial revolution 4.0, skills are needed that can lead humans to success in their lives (Alsuwaida, 2023; Purwanto et al., 2023). These skills are 4C skills including critical thinking, creativity, communication, and collaboration which are also higher-order thinking skills (HOTS) (Budiarto et al., 2024).

Improving the quality of human resources through education is focused on high-level thinking skills (HOTS), which are one of the abilities needed to prepare graduates who are able to compete and adapt to changing times (Dolmans et al., 2016; Bantilan et al., 2023; Nwune et al., 2023; Nwoji et al., 2025). However, the reality shows that the thinking skills of students in Indonesia are still very low, this can be seen from the results of the PISA 2022 report released in December 2023 and noted that the scores of 15-year-old Indonesian children were still below the threshold of 400, equivalent to level 2-3 (Anggraeni et al., 2022; Ayyildiz & Tarhan, 2018). The gap between expectations and reality in adapting to changes and developments in the world in the era of globalization is a problem that must be overcome, especially in the world of education (Andriyatno et al., 2023; Biswal & Behera, 2023). Therefore, it is necessary to develop education that can optimally increase the potential and abilities of students, so that they are able to adapt to the circumstances and changes that occur and are able to work collaboratively in solving life problems.

Education must be directed at forming students to be able to build their knowledge capacity by developing high-level thinking skills, such as critical thinking, creativity, decision making, and problem solving (Muslimin et al., 2024). High-level thinking skills are thinking skills that are able to form students not only to retain knowledge, but also at the level of transferring (Nadkarni et al., 2023). The application of HOTS for students is very urgent, considering the development of the era with various extraordinary challenges (Nuangchalerm & Prachagool, 2023). The development of the digital world that has the potential to create dependency, pseudo-maturity of students, and the challenges of globalization need to be answered by implementing HOTS in the world of education.

Science education has an important role in preparing quality human resources in facing the era of globalization (Nurgul & Akmaral, 2022). The potential of science education can be seen from the ability to communicate, think critically, solve problems, mastery of technology and the ability to adapt to change and the times (Öztürk et al., 2022; Ragab et al., 2024; Sigar et al., 2025). The process and learning of science can produce quality humans by demonstrating scientific awareness and high-level thinking skills that can produce human resources who are able to think critically, creatively, make decisions and solve problems (Sutiani et al., 2020). Chemistry is part of science, so students' high-level thinking skills can also be trained and developed through chemistry learning (Raj et al., 2022). Chemistry learning in general aims to strengthen knowledge about the study of matter and the energy that accompanies it and provide an understanding of chemical principles to answer various studies in natural phenomena and life problems, as well as develop an attitude of caring for the environment (Rajendran et al., 2023; Sam, 2024; Endra & Villafior, 2024). This means that the process of learning chemistry can improve conceptual skills, critical thinking skills, creativity, collaboration and communication to solve problems in everyday life (Ramdiah et al., 2019).

Learning that invites students to think through science in their lives is called generic science skills (GSS) learning (Sokha & Kinya, 2023). How to think critically and act in studying various science concepts and problem solving, both in theory and practice, is a generic competency that must be used in various scientific activities (Stanikzai, 2023). Generic competencies are derived from process skills by combining these skills with the components of nature studied in science that are found in the concept structure or the Principle of the Natural Study Triangle. Generic Science Skills (GSS) are skills that can be used to study various concepts and solve various science problems (Sutiani et al., 2021). To understand abstract concepts in general, high reasoning skills are needed and to achieve high reasoning skills, students are accustomed to learning methods that require the use of reasoning. Therefore, generic competencies are easier to understand and implement than process skills, and assessment techniques are easier. GSS is the basis for developing critical thinking skills, creativity, collaboration and communication which are 21st century skills which are also the era of globalization and internationalization (C. K. S. Singh & Marappan, 2020; Siregar et al., 2023).

One way to develop students' 21st century skills can be done by developing and implementing process-based learning through innovative learning models such as Project Based Learning (PjBL), Problem Based Learning (PBL), Inquiry Based Learning (IBL), and Discovery Learning (DL) integrated with GSS. Several previous studies have shown that the implementation of PjBL is effective in learning, able to improve creative thinking skills, improve communication skills, improve critical and creative thinking skills (Ananda et al., 2021), improve collaboration skills and student learning outcomes (Pratiwi et al., 2018), improve literacy skills, and can improve students' HOTS. Several studies also show that the PBL model can improve students' thinking skills (Ariani, 2020; Ratnawati et al., 2020; Aprilianingrum & Wardani, 2021; Julianti et al., 2025), improve understanding of science concepts, problem-solving

skills, and can improve student learning outcomes. Furthermore, several studies also show that the IBL model has an effect and can improve critical thinking skills, improve science process skills, improve HOTS abilities (Shanti et al., 2022; Muhibbuddin et al., 2023), improve student understanding (Singh et al., 2006), and can develop students' 21st century skills (Aji, 2019).

The development of students' 21st century skills can also be done through learning models. Basically, digital learning is a concept or learning method that utilizes digital technology as a learning medium for students. Digital learning is essentially learning that involves the use of digital technology tools innovatively during the teaching and learning process, and is often referred to as Technology Enhanced Learning (TEL) or e-Learning. Digital-based learning is a learning process that uses electronic media, namely by developing it into an internet and intranet network as a learning aid to improve the quality of learning. The benefits of digital learning in supporting the implementation of the learning process are to increase students' absorption in understanding the context of learning materials, encourage independent learning skills, increase active student participation, and improve the ability to display information with technological devices to develop skills in facing the 21st century, namely creative, critical thinking, collaborative and communicative. The digital learning model also emphasizes a collaborative work culture that prepares students to be accustomed to carrying out collaborative work and stimulates the ability to establish social relationships and communicate.

The application of digital-based learning models is one of the applications of 21st-century learning styles that has the potential to help improve students' academic performance in the form of learning outcomes in the cognitive domain (Elviana & Julianto, 2022). One application that can be used to create digital learning media or models is SAC (Smart Apps Creator), a software application that can be used to create multimedia features based on mobile, desktop, and websites. Research related to digital learning has been conducted, which states that digital learning media can improve students' cognitive abilities and creativity in learning (Suhartati, 2021; Puspitasari et al., 2022). In today's digital era, science and technology are developing rapidly, having an impact on today's world of education. On the other hand, the change in the educational paradigm that previously adopted teacher-centered learning to student-centered learning has brought very significant changes to the learning methods currently being developed, in order to form a creative, innovative and competitive generation so that the quality of graduates is in accordance with the demands of the world of work and technology by equipping students with 21st century skills who are able to think critically in solving problems, creatively and innovatively as well as communication and collaboration skills (Thornhill-Miller et al., 2023; Isyabire et al., 2025).

Based on the description above, it is necessary to innovated based high school chemistry learning integrated with GSS to improve students' HOTS abilities. This research is a multi-year study (three years). The research in the first year emphasized the initial analysis of teachers' abilities in understanding and integrating TPACK in learning. The results of the study showed that over all the ability of chemistry teachers in integrating TPACK (Technological Pedagogical Content Knowledge) in learning was included in the capable and fairly capable categories. The research in the second year led to the analysis of students' initial abilities & the development of teaching materials and Student Worksheets (SWs) based on GSS as well as the preparation of instruments (evaluation questions) to measure high-level thinking skills. The results of the second year of research showed that the initial student ability test instrument in the form of scholastic test items covering verbal reasoning and numerical reasoning had been successfully compiled for the topics of acid-base solutions, thermochemistry, reaction rates and chemical equilibrium and was adjusted to GSS to support the achievement of the learning outcome evaluation test on each topic. The development of Student Worksheets (SWs) and GSS-based Learning Materials as well as learning outcome evaluation instruments to measure HOTS were compiled using the R&D research method with the 4D model. Overall, the SWs and learning materials developed are included in the valid category for the material aspect and the very valid category for the media aspect, while the learning outcome instruments have met the eligibility requirements both in terms of content and construction. The third year of research leads to the implementation of various innovation-based learning models (PjBL, PBL, IBL, DL) integrated with GSS in chemistry learning on acid-base solutions, thermochemistry, and chemical equilibrium. This third year of research includes quasi-research including quasi-experimental research types, which aim to analyze the effectiveness and influence of the implementation of innovations in learning models integrated with GSS (PjBL-GSS; PBL-GSS; IBL-GSS; DL-GSS) and students' initial abilities on students' HOTS chemistry abilities. Although many studies have examined the effectiveness of PjBL, PBL, IBL, and DL models, there are still few that examine the comparison of their integration with GSS in a digital context in chemistry learning.

LITERATURE REVIEW

Chemistry Learning Innovation

Chemistry learning innovation must be carried out optimally in accordance with the nature of the scientific approach in order to develop 21st century skills in students (Kuang et al., 2022). Chemistry learning innovation is a new learning discovery in the interaction between educators and students to achieve learning goals optimally (Lai, 2021). Some learning innovations that have been successfully used in chemistry learning include learning innovations using laboratory and non-laboratory activities, learning innovations using media, and the most widely developed currently is information technology-based learning innovation. The learning innovations that are developed basically lead to the abilities that must be possessed in the 21st century (Lawson et al., 2021). Learning innovations need to be prepared by prospective educators so that they have pedagogical, professional, personality, and social competencies according to SKGP (Morze et al., 2018). In addition, prospective educators must also always be creative and innovative to produce various innovative works in their fields. Innovations or renewals/changes for prospective educators that must be prepared can be in the form of methods, models, materials, assessments, media, and innovations on how to learn.

Learning Models

A learning model is a plan or pattern that can be used to form a curriculum (long-term learning plan), design learning materials and guide learning in the classroom or others. Learning models are generally based on educational theory and certain learning theories, and have 4 (four) main elements, namely having learning stages (syntax), social systems, the existence of reaction principles and support systems (Munna et al., 2024). The chemistry learning models recommended for implementation are the PBL, PjBL, IBL, and DL models which are based on constructivism learning theory, namely a process of assimilating and linking experiences or lessons learned with existing understanding and is a process of completing new concepts and ideas with existing frameworks of thinking so that new constructions are obtained (Santos & Boyon, 2020; Saragih et al., 2023). Digital learning is essentially learning that involves the use of innovative digital technology tools during the teaching and learning process, and is often referred to as Technology Enhanced Learning (TEL) or e-Learning. Digital-based learning is a learning process that uses electronic media, namely by developing it into an internet and intranet network as a learning aid to improve the quality of learning (Sutiani et al., 2020). Digital learning requires teachers to have student leadership and personal development skills to develop students' potential and talents. Teachers must understand that each student's potential is different and must be developed (Tampa'i et al., 2023). Bring out and increase students' self-confidence in developing their potential and talents (Widyaningsih et al., 2021). Teachers must be critical of policies in the education sector and pay attention to various issues that are developing (Yaki, 2022). Teachers become advocates for students and help students who are in trouble, whether problems at home, in the environment, or academically at school (Yaseen et al., 2025). Teachers must be able to motivate, be good listeners, and encourage students in facing their problems (Anjaini & Kusasi, 2021). Another skill that must be possessed in digital learning is creating Game Based Learning to eliminate student boredom while learning (Pramasdyahsari et al., 2023). Learning combined with playing activities can stimulate students to think critically which is needed at the next level of education. The type of Game Based Learning that can be chosen must be related to the learning material and support students' thinking skills to understand the material. Games developed in digital learning must require students to make decisions correctly and quickly, solve problems, train creativity, and collaborate with classmates (Makuasa et al., 2024).

To implement the digital learning model, it is necessary to use the concept of TPACK (Technological Pedagogical Content Knowledge), namely the knowledge needed to integrate technology in learning that involves 7 domains of knowledge because there are new intersections or syntheses, including: 1) Content knowledge (CK), namely mastery of the field of study or learning material; 2) Pedagogical knowledge (PK), namely knowledge of the learning process and strategy; 3) Technological knowledge (TK), namely knowledge of how to use digital technology; 4) Pedagogical content knowledge (PCK), namely a combination of knowledge about the field of study or learning material with the learning process and strategy; 5) Technological content knowledge (TCK), namely knowledge of digital technology and knowledge of the field of study or learning material; 6) Technological pedagogical knowledge (TPK), namely knowledge of digital technology and knowledge of the process and learning strategy; and 7) Technological, pedagogical, content knowledge (TPCK), namely knowledge of digital

technology, knowledge of the learning process and strategy, knowledge of the field of study or learning material (Alenezi et al., 2023).

Generic Science Skills

Generic skills are known by different terms in different countries (Almulla, 2020; Chaipidech et al., 2021; Chiu & Li, 2023). These terms include: core skills, key skills, general skills, essential skills, skills for work, basic skills, essential skills, critical thinking skills, and transferable skills (Alneyadi et al., 2023). The initial development of generic competencies was developed in Australia in the mid-1980s. The education system helped the international competitiveness of the Australian labor market by recommending that education should prepare students to learn higher through teaching, among others, managing information, working in teams, and communicating effectively (Alsuwaida, 2023; Christiana & Anwar, 2021). The Mayer Committee Report was a major milestone in establishing generic skills in Australia (Desriyanti & Lazulva, 2016; Cotet et al., 2017). The committee made many important decisions that continued with a strong influence on policy regarding generic skills. The Mayer Committee (Australian Education Council, Mayer Committee, 1992) defined key competencies as essential competencies to participate actively in emerging patterns and organizations. These competencies focus on the capacity to apply integrated skills in work situations (El-sadi, 2015; Dong et al., 2020). Mayer developed seven key competencies that were considered important for preparing for workforce acceptance consisting of: 1) collecting, analyzing, and organizing information; 2) communicating ideas and information; 3) planning and organizing activities; 4) working with others in teams; 5) using mathematical ideas and techniques; 6) solving problems; and 7) using technology (Dool et al., 2021; Dung, 2021).

The research results of The Australia Chamber of Commerce Industry and Business Council of Australia (ACCI/BCA) identified that there are work skills needed, both for new workers and those who have been working for a long time (Găbureanu & Tripon, 2020; Gao et al., 2020). These skills are called employability skills which are referred to as generic skills capabilities or key competencies (Gopalan & Hashim, 2021). According to ACCI/BCA there are eight work skills needed, namely: communication skills; collaboration skills; problem-solving skills; initiative skills and courage to try; design and organization skills; self-management skills; learning skills and technology skills (Fauziyah et al., 2022). A key competency framework was identified based on feedback to achieve generic capabilities. The resulting framework was divided into five generic competency groups: 1) Thinking (e.g., critical and creative thinking); 2) Making meaning; 3) Participating and contributing; 4) Self-management; and 5) Getting along with others. The technical skills identified as important in this survey, from an industry perspective, indicated the key competencies required were: 1) Communication (e.g., writing, reading and speaking); 2) Collaboration (e.g., teamwork and getting along with others); 3) Computer literacy (e.g., accessing electronic information); 4) Creativity (e.g., lateral thinking); 5) Critical thinking (e.g., evaluation and synthesis) (Gupta & Mishra, 2021).

The skills developed by the Secretary's Commission on Achieving Necessary Skills (SCANS) encompass three basic skills required for effective employment: 1) Foundational skills (e.g., literacy, numeracy, communication); 2) Higher-order thinking skills (e.g., adapting to change, problem solving, creativity, decision making, learning how to learn); and 3) Interpersonal and team skills (e.g., responsibility, self-management, and integrity/honesty). SCANS skills have become the most widely used competency framework in the United States, having a significant impact on both industry and job readiness training programs (Han & Liu, 2024). Generic skills are skills that can support study in any discipline, and which are potentially transferable to a variety of contexts in education or the workplace (Bantilan et al., 2023; Olesen & Christensen, 2020). Not only are generic skills transferable, but they are essential in enabling students to apply their knowledge or discipline to a variety of contexts (Ayyildiz & Tarhan, 2018; Brata et al., 2020). Generic skills are basic skills that are useful for working in other fields (Awizar et al., 2013; Baysal, 2017). In natural science learning, generic skills are referred to as generic science skills (Antonio & Prudente, 2024; Catubig et al., 2024). In chemistry learning there are ten generic skills, namely direct observation, indirect observation, understanding of scale, symbolic language, logical frames, logical consistency, laws of cause and effect, modeling, logical inference and abstraction (Ambusaidi et al., 2018; Andriyatno et al., 2023). Generic chemistry skills are abilities that can be used to study higher chemistry or other sciences independently (Altun, 2018; Biswal & Behera, 2023).

RESEARCH METHOD

This research was conducted from July to December of the 2023-2024 academic year. The research location was the Chemistry Department, State University of Medan. The HOTS assessment grid includes indicators for analysis, evaluation, and creation, aligned with Bloom's taxonomy. Each question item is mapped to the corresponding GSS indicator (e.g., modeling, logical inference) and topic content (acids-bases, thermochemistry, equilibrium).

This study is a quasi-experimental study and the research design used is a 2×2 factorial design (Data 1). This study was conducted by implementing the innovation of several integrated digital learning models of GSS (PjBL-GSS; PBL-GSS; IBL-GSS; DL-GSS) as independent variables. While the moderator variable is the initial ability of students who are grouped into students with high and low initial abilities. The dependent variable in this study is students' HOTS abilities.

Table 1. Research design

Initial ability (B)	Innovation of digital learning models (A)			
	PjBL-GSS (A1)	PBL-GSS (A2)	IBL-GSS (A3)	DL-GSS (A4)
High (B1)	A1B1	A2B1	A3B1	A4B1
Low (B2)	A1B2	A2B2	A3B3	A4B4

The number of students who were samples in this study was 397 students who were divided into four groups that were given learning models: PjBL-GSS; PBL-GSS; IBL-GSS; and DL-GSS. The distribution of the research sample selected in this study is shown in Table 2.

Table 2. Research sample

No	Information	Group				Total
		PjBL-GSS	PBL-GSS	IBL-GSS	DL-GSS	
1	Class	3	3	3	3	12 class
2	Students	100	102	97	98	397 students

One of the procedures of this study can be seen from Figure 1 below. Figure 1 below shows the relationship between independent variables and moderator variables. The results of Figure 1 can be seen from data 1, data 2 and table 1.



Figure 1. Relationships between independent and moderator variables

The other procedures of this study can be seen from Figure 2 below. Figure 2 below shows the relationship between independent variables and dependent variables. The results of Figure 1 can be seen from table 2 and table 3.

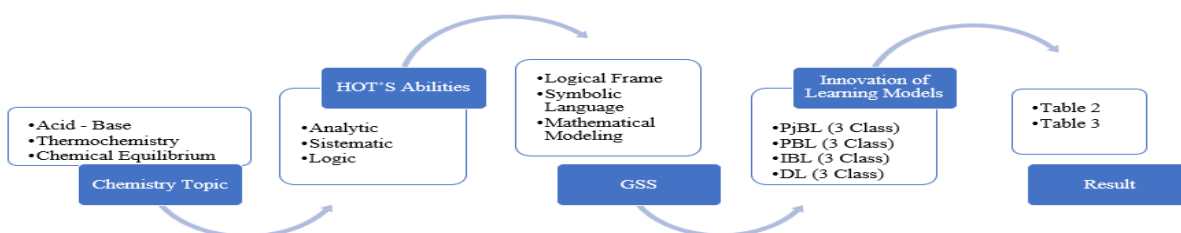


Figure 2. Relationships between independent and dependent variables

This research instrument is divided into 2 parts, namely evaluation of students' initial abilities (EIA) (consisting of scholastic and quizzes) and HOTS abilities. Evaluation of students' initial abilities (EIA) can be seen in Appendix 1 and HOTS abilities in Appendix 2. In appendix 1, we can see the three chemistry materials in the main topics and sub-topics, learning objectives, generic science skills and scholastic questions and quizzes. In appendix 2, we can see the three chemistry materials, namely acid-base material, thermochemistry and chemical equilibrium in the form of HOTS questions.

The data collection techniques and instruments in this study used test instruments consisting of scholastic tests in the form of verbal reasoning and numerical reasoning questions used to measure students' initial abilities; and tests of students' high-level thinking skills. The test instruments were compiled and developed in the form of multiple-choice tests on acid-base, thermochemistry, and chemical equilibrium materials and were adjusted to generic science skills (GSS). The tests that were compiled had met the eligibility requirements (validity) both in terms of content and construction and were declared reliable with a Cronbach's alpha value of 0.83 (initial ability test instrument) and 0.85 (HOTS test instrument). With a sample size of 397 students, this study achieved greater than 0.90 power to detect a medium effect size (Cohen's $f = 0.25$) at $\alpha = 0.05$. This ensures adequate sensitivity to capture meaningful differences between treatment groups.

The data analysis techniques used were descriptive analysis techniques and inferential techniques. Descriptive analysis techniques were used to describe data including average values (means) and standard deviations. Inferential statistical techniques were used to test the research hypothesis, using two-way analysis of variance (two-way ANOVA) techniques at the $\alpha = 0.05$ level with the help of the SPSS program. Statistical analysis was conducted using SPSS. A two-way ANOVA was employed to assess the main effects of learning models and initial abilities, as well as their interaction effects on HOTS. Post-hoc analysis (LSD) was used to identify significant pairwise differences between model groups.

RESULTS AND DISCUSSION

Initial Ability Analysis and Discussion

The evaluation of students' initial abilities (EIA) is intended to determine the extent of knowledge possessed by students as part of basic knowledge to construct new knowledge during learning. Students' initial abilities are very helpful in their involvement in the learning process to construct new knowledge and can optimize the role of subject teachers as facilitators and scaffolding providers during the learning process. Students' EIA is carried out by teachers continuously, as an indication of students' learning readiness before learning begins. Student involvement during the learning process will make it easier for students to develop their knowledge according to context, namely: 1) participating in solving real-world problems, 2) constructing new knowledge from their initial knowledge, 3) introducing new knowledge, 4) applying knowledge, and 5) new knowledge is integrated into real-world situations so that students can develop their thinking skills and reflect on the meaning of what students have done. The student's thinking framework shown by the EIA results is also used as a reference for choosing an appropriate learning model.

Table 3. Average EIA scores of students

Chemistry topic	Initial ability group	EIA scores			
		PjBL-GSS	PBL-GSS	IBL-GSS	DL-GSS
Acid Base	High	84.44±5.11	84.06±5.23	83.33±4.56	78.68±4.03
	Low	70.00±5.68	69.44±6.16	72.31±4.84	60.77±7.47
	Total	77.22±9.06	76.32±9.32	79.12±7.12	71.41±12.19
Thermochemistry	High	81.19±6.83	84.00±4.55	78.00±6.68	78.50±5.83
	Low	62.06±6.34	69.78±5.69	59.25±8.58	59.81±6.38
	Total	71.62±11.68	76.89±8.82	68.63±12.16	69.16±11.24
Chemical Equilibrium	High	80.93±3.56	82.40±4.17	80.71±8.11	78.52±5.40
	Low	67.82±5.78	67.94±5.64	63.64±2.80	60.53±7.73
	Total	73.97±8.21	74.72±8.83	73.00±10.51	71.22±11.26

EIA capability categories: >90 (Very competent), 80-89 (Competent), 70-79 (Quite competent) and <70 (less competent)

Table 3 shows that the EIA score for the Acid-base and chemical equilibrium material is in the competent category for students in the High Initial Ability (HIA) group who will be given PjBL-GSS

learning; PBL- GSS and IBL- GSS, but is included in the fairly competent category for students in the Low Initial Ability (LIA) group who will be given DL- GSS learning. Meanwhile, the EIA score for thermochemistry material is in the competent category for students in the High Initial Ability (HIA) group who will be given PjBL- GSS and PBL- GSS learning, but is included in the fairly competent category for students in the low initial ability (LIA) group who will be given IBL- GSS and DL- GSS learning. Overall, it can be stated that all students have basic knowledge to construct new knowledge during learning.

The EIA score for Acid-Base material is in the fairly competent category for KAT students who will be given PjBL-GSS and IBL- GSS learning, but is included in the less competent category for KAR students who will be given PBL- GSS and DL- GSS learning. Meanwhile, the EIA score for thermochemistry and chemical equilibrium material is in the less competent category for all HIA students who will be given PjBL- GSS, PBL- GSS, IBL- GSS and DL- GSS learning. This means that all LIA students lack the basic knowledge needed to construct new knowledge during learning. The student's EIA score is an indication of the student's learning readiness before learning begins. The initial abilities possessed by students are used by teachers as a reference for choosing approaches, strategies, methods and/or learning models that will be used in accordance with the GSS that will be developed during the learning process in developing students' HOTS abilities.

HOTS Analysis and Discussion

HOTS ability data was obtained after all students carried out GSS integrated learning on Acid Base, thermochemistry and chemical equilibrium materials. One of the objectives of implementing the GSS integrated digital learning model is to train students' reasoning skills as a basis for high-level thinking processes which include creative, critical thinking, decision-making and solving daily life problems. GSS helps students learn and show how to learn well by continuously training direct observation skills, indirect observation, awareness of scale, symbolic language, logical frameworks, logical inference, cause and effect, mathematical modeling and the ability to build concepts. GSS is not obtained suddenly but must be trained to continue to improve. GSS can be trained during the learning process using the right learning model.

Table 4. Average HOTS score with the GSS integrated learning model

Chemistry topic	HOTS scores			
	PjBL-GSS	PBL-GSS	IBL-GSS	DL-GSS
Acid base	82.52±6.55	80.15±8.12	83.41±7.14	78.68±59.63
Thermochemistry	84.34±6.68	80.47±7.28	80.78±10.01	81.34±5.93
Chemical equilibrium	80.38±6.42	85.19±3.82	85.52±8.38	81.66±6.51

HOTS categories: >90 (Very competent), 80-89 (Competent), 70-79 (Quite competent) and <70 (less competent)

Table 4, shows that the average HOTS value of students on acid-base material (83.41 ± 7.14) and chemical equilibrium (85.52 ± 8.38) after going through the learning process with the IBL-GSS model is higher than other learning models, while for thermochemistry material, students' HOTS abilities through the PjBL-GSS learning process (84.34 ± 6.68) are higher than other learning models. The inquiry learning model (IBL) is a learning model that teaches students to think through the process of formulating problems, proposing hypotheses, collecting information, and then testing the hypotheses proposed to draw a conclusion. IBL is a combination of science process skills (such as observing, inferring, classifying, predicting, measuring, asking, interpreting and analyzing data) with science content, scientific reasoning and critical thinking to develop science/knowledge. The character of chemical equilibrium material that emphasizes more on the integration of theory and practice with direct observation and mathematical modeling and the ability to build concepts makes the IBL-GSS model the right model for chemical equilibrium material. The integration of GSS in the IBL model presents a series of learning activities that emphasize the process of solving problems faced scientifically, so that students have the ability to think critically, analytically, systematically, and logically to find alternative solutions to problems.

Acid-base material is one of the materials that has several prerequisite materials that must be mastered first in order to understand the material, including chemical equilibrium, chemical reactions, stoichiometry, the nature of matter and solutions. The concept of acid-base material is also a prerequisite material for understanding buffer material, hydrolysis and acid-base titration. The character of acid-base

material which not only involves clearly observed concepts (concrete concepts) but also discusses invisible concepts, and concepts that involve symbols, makes the integration of GSS into the IBL model an appropriate model to use in acid-base material. The purpose of the IBL learning strategy is the ability of students to search and investigate systematically, critically, logically, analytically, so that students can formulate their own discoveries with confidence.

PjBL is a model that directs students to be active in learning, collaboration, raising real-life problems, training critical and creative thinking, improving understanding of the material being taught, and providing experience. The PjBL model is designed to be used on complex problems that students need to investigate and understand. The character of thermochemical material that focuses more on the context of energy changes that occur during chemical reactions and heat transfer that occurs in everyday life, makes the PjBL model integrated with GSS the right model to use for this material, because PjBL-GSS is a model that empowers students to combine theory and practice contextually to develop feasible solutions in solving problems. Through the PjBL model which always begins with raising a guiding question in a collaborative project that integrates aspects of GSS, namely indirect observation, awareness of scale and symbolic language, the learning model is more effective in improving in-depth investigation skills on a real-world topic. The emphasis of learning lies on student activities to produce products by applying research, analysis, creation, and presentation skills of learning products based on real experiences. HOTS ability analysis is not only carried out as a whole, but HOTS analysis is carried out based on students' initial abilities, which are grouped into HIA and LIA.

Table 5. Average HOTS score based on students' initial abilities

Chemistry topic	Initial ability group	HOTS scores			
		PjBL-GSS	PBL-GSS	IBL-GSS	DL-GSS
Acid base	High	87.50±4.83	85.35±5.89	89.00±4.93	84.74±5.13
	Low	78.55±6.74	74.94±6.62	79.00±5.29	77.00±8.46
	Total	82.53±6.54	80.15±8.13	83.41±7.14	78.68±9.63
Thermochemistry	High	89.92±6.47	84.63±4.75	90.64±4.56	87.33±4.05
	Low	80.53±3.32	75.82±6.83	75.62±7.97	77.75±3.40
	Total	84.35±6.68	80.47±7.28	80.78±10.01	81.34±5.93
Chemical equilibrium	High	85.80±3.30	87.47±2.88	93.45±3.04	86.67±2.38
	Low	77.47±5.98	83.18±3.45	79.78±5.85	77.24±5.74
	Total	81.38±6.42	85.19±3.82	85.52±8.38	81.66±6.51

EIA capability categories: >90 (Very competent), 80-89 (Competent), 70-79 (Quite competent) and <70 (less competent)

Table 5 shows that the HOTS ability of students in the HIA group for all materials in all classes is included in the competent and very competent categories. Students' HOTS for acid-base materials (89.00 ± 4.93), thermochemistry materials (90.64 ± 4.56) and chemical equilibrium materials (93.45 ± 3.04), the highest score in the IBL-GSS model. HOTS of students in the LIA group, for all materials in all classes is included in the fairly competent category, except for chemical equilibrium materials, in the PBL-GSS model (83.18 ± 3.45) is included in the competent category. The total average HOTS value of students for acid-base material is included in the fairly competent category with the highest score in the IBL-GSS model (79.00 ± 5.29), while for thermochemistry material, the HOTS value of students in the PBL-GSS model (75.82 ± 6.83), IBL-GSS (75.62 ± 7.97) and DL-GSS (77.75 ± 3.40) is included in the fairly competent category and in the PjBL-GSS model it is included in the competent category (80.53 ± 3.32).

Hypothesis Testing

Based on the HOTS value data of students after implementing learning with various innovations of integrated digital-based learning models GSS, a two-factor analysis of variance was carried out, which aimed to determine how the learning model and students' initial abilities influenced the overall HOTS value of chemistry in three materials, namely acids and bases, thermochemistry and chemical equilibrium.

Table 6. Analysis of the combination of initial abilities and the GSS integrated learning model on students' HOTS abilities

Source	Type III Sum of Squares	df	Mean square	F	Sig.
Initial ability	9683.837	1	9683.837	297.084	.000
Model-GSS	735.285	3	245.095	7.519	.000
Initial ability * model GSS	374.149	3	124.716	3.826	.010

Table 6 shows that there are two factors that affect students' HOTS abilities, namely the initial ability factor and the GSS learning model factor at a significance (α) of 0.05. The initial ability factor data shows that Sig. of $0.000 < 0.05$, which means that initial ability has a significant effect on students' HOTS abilities. The GSS integrated learning model data (Model-GSS) shows Sig. of $0.000 < 0.05$, which means that the GSS integrated learning model has a significant effect on students' HOTS. The interaction data of initial ability and the GSS integrated model (Initial Ability*Model-GSS) obtained a sig. value of $0.010 < 0.05$, which means that there is an interaction between initial ability and the GSS integrated learning model on students' HOTS abilities. This means that different initial abilities (high and low) with different GSS integrated learning models produce different HOTS averages or have a significant effect on students' HOTS.

Table 7. Multiple Comparison Test of GSS Integrated Learning Model on HOTS Ability

	(I) Model	(J) Model	Mean Difference (I-J)	Std. Error	Sig.
LSD	PjBL-GSS	PBL-GSS	.90	.803	.265
		IBL-GSS	-.48	.814	.558
		DL-GSS	2.22*	.812	.007
	PBL-GSS	IBL-GSS	-1.37	.810	.091
		DL-GSS	1.32	.808	.102
	IBL-GS	DL-GSS	2.70*	.818	.001

Table 7 shows that there are two pairs of GSS integrated learning model treatments that have an effect on students' HOTS, namely between DL-GSS and PjBL-GSS and between DL-GSS and IBL-GSS. This means that the average HOTS chemistry score for students with the DL-GSS model is significantly different from the average HOTS score for students with the PjBL-GSS and IBL-GSS learning models.

The next stage is to test the hypothesis for the learning model with the categories of high initial ability and low initial ability on students' HOTS.

Table 8. Factor Analysis of GSS Integrated Learning Model on HOTS for HIA and LIA Groups

Group initial ability	Source	Sum of squares	df	Mean square	F	Sig.
HIA	Between Groups	724.619	3	241.540	11.012	.000
	Within Groups	3860.581	176	21.935		
	Total	4585.200	179			
LIA	Between Groups	311.064	3	103.688	2.504	.060
	Within Groups	8819.378	213	41.406		
	Total	9130.442	216			

Table 8, the test results for the HIA group show that there is a significant difference in HOTS of HIA group students who are given different learning models (Sig. $0.000 < 0.05$). While for the LIA group, there is no significant difference in HOTS of students between the LIA group who are given different learning models (Sig. $0.060 > 0.05$)

The test results for the HIA group showed that there was a significant difference in HOTS of students in the HIA group who were given different learning models, so further testing was needed to determine which model had a significant effect on HOTS in the HIA group.

Table 9. Multiple comparison test of GSS-based learning model on students' HOTS in the HIA group

	(I) Model	(J) Model	Mean Difference (I-J)	Std. Error	Sig.
LSD	PjBL-GSS	PBL-GSS	1.930*	.964	.047
		IBL-GSS	-3.312*	1.030	.002
		DL-GSS	1.593	.988	.109
	PBL-GSS	IBL-GSS	-5.243*	.996	.000
		DL-GSS	-.338	.952	.723
	IBL-GS	DL-GSS	4.905*	1.019	.000

Table 9 shows that there are significant differences between the IBL-GSS model and the PjBL-GSS model (sig. 0.002); PBL-GSS (sig. 0.000); and with the DL-GSS model (sig. 0.000); and there are significant differences between the PjBL-GSS model and PBL-GSS (sig. 0.047). Meanwhile, the DL-GSS model has no significant differences with the PjBL-GSS (sig. 0.109) or with the PBL-GSS model (sig. 0.723).

This study is a multi-year study (three years) and includes the third year of research that aims to compare the effectiveness of various digital-based learning models integrated with generic science skills (GSS) and analyze their interaction with students' initial abilities in improving HOTS in chemistry learning and analyze the effect of the implementation of the GSS integrated digital-based learning model innovation (PjBL-GSS; PBL-GSS; IBL-GSS; DL-GSS) and students' initial abilities on students' HOTS chemistry abilities. The findings of this study indicate that students' initial abilities have a significant effect on students' HOTS abilities, which means that students' learning readiness and initial knowledge before starting learning have a significant effect on students' HOTS abilities obtained by students. Students' initial abilities are also grouped into high initial abilities (HIA) and low initial abilities (LIA). The results of the study also show that there is a significant effect of the implementation of the GSS integrated digital learning model innovation on students' HOTS abilities and there is an interaction between initial abilities and the GSS integrated digital learning model on students' HOTS abilities.

The research findings and further comparative tests of the GSS model with students' HOTS statistically show that there are two pairs of GSS integrated learning model treatments that affect students' HOTS, namely between DL-GSS and PjBL-GSS and between DL-GSS and IBL-GSS. This means that the average HOTS chemistry score for students with the DL-GSS model is significantly different from the average HOTS score for students with the PjBL-GSS and IBL-GSS learning models, while for the PBL-GSS model it is not significantly different from other GSS models. Further hypothesis testing for the GSS model with the HIA and LIA categories on students' HOTS shows that for the LIA group there is no significant difference between the HOTS of students who are given different GSS models, while for the HIA group there is a significant difference between the HOTS of students who are given different GSS models. Significant differences occur between the IBL-GSS model and the PjBL-GSS model (sig. 0.002); PBL-GSS (sig. 0.000); and with the DL-GSS model (sig. 0.000); and between the PjBL-GSS model and PBL-GSS. Overall, it also shows that the implementation of the IBL-GSS model has a higher and more significant influence on students' HOTS abilities, followed by the PBL-GSS, PjBL-GSS, and DL-GSS models.

However, the innovation of the GSS integrated digital learning model that was tested was still limited to the material of acids and bases, chemical equilibrium and thermochemistry and was only implemented in 12 schools in North Sumatra and each school was only taken one class. Therefore, further research is needed and wider schools throughout North Sumatra, so that the effectiveness of the implementation of the GSS integrated model can be generalized more widely. The GSS integrated learning model, both PjBL-GSS, PBL-GSS, IBL-GSS and DL-GSS, is the result of the development of the PjBL, PBL, IBL or DL models which are integrated into the GSS learning model. This implies that for teachers who are interested in implementing the GSS learning model, they should first study the PjBL, PBL, IBL, DL models and various indicators in GSS. In addition, students are expected to have studied the initial material independently, because achieving optimal learning outcomes and HOTS will be very possible if they already have initial knowledge related to the material to be studied. Furthermore, this study also suggests the need for further research that examines the relationship between initial abilities in the form of scholastic tests and quizzes with the innovation of the GSS integrated digital learning model and other abilities and learning outcomes so that various variables that influence abilities and learning outcomes can be measured comprehensively. The integration of digital learning models with generic

science skills significantly influences students' HOTS in chemistry, with IBL-GSS emerging as the most effective for high-ability students. The study reinforces the need for differentiated instruction based on initial abilities. Why IBL-GSS excels—because it supports the scientific process and active engagement.

For optimal HOTS development, chemistry educators should select learning models based not only on pedagogical goals but also on students' readiness levels and the nature of the topic. The present study, which focuses on enhancing students' Higher Order Thinking Skills (HOTS) in stoichiometry through a Moodle-based Inquiry-Based Learning (IBL) model integrated with STEM and Artificial Intelligence (AI), demonstrates notable distinctions and advancements when compared with prior works by Antonio & Prudente (2024), Muhibbuddin et al. (2023), and Ananda et al. (2021).

Antonio & Prudente (2024) implemented a STEM-based intervention to improve critical thinking in chemistry learning. However, their approach relied heavily on offline project-based implementation without the incorporation of digital platforms or AI tools. In contrast, the present study emphasizes the role of a digital learning environment (Moodle) enhanced with adaptive AI-based features (e.g., feedback automation, real-time analytics), offering a more scalable and data-driven pedagogical model that aligns with modern learning contexts. Muhibbuddin et al. (2023) explored the effect of inquiry learning on students' conceptual understanding in chemistry. While the study successfully demonstrated improvements in student engagement and learning outcomes, it did not integrate interdisciplinary STEM contexts nor utilize a digital or AI-assisted medium. The current study addresses these gaps by embedding inquiry within STEM problem-solving tasks and leveraging Moodle's AI plugins to support individualized learning pathways and improve assessment precision. Ananda et al. (2021) focused on HOTS development through ICT-based learning but limited their intervention to general digital content delivery. The novelty of the current research lies in its structured integration of IBL-STEM pedagogy within a smart learning ecosystem that adapts to student needs through AI. Moreover, the use of pretest-posttest data alongside student perception analysis provides a more comprehensive evaluation framework for measuring both cognitive gains and learner experience.

Thus, compared to the three previous studies, this research contributes a unique combination of (1) structured IBL-STEM pedagogy, (2) AI-supported Moodle implementation, and (3) targeted intervention in one of the most challenging chemistry topics—stoichiometry. This integrated approach not only addresses the limitations of past studies but also offers practical implications for scalable and future-ready chemistry instruction. In this study, the scope of generalization is still limited to certain areas and materials. Limitations on local context and three chemistry topics (acids-bases, thermochemistry, equilibrium). Further studies are needed to test the integration of GSS in other chemistry topics and with full experimental designs.

CONCLUSION

This study demonstrates that the integration of digital-based learning models with Generic Science Skills (GSS) significantly enhances students' Higher Order Thinking Skills (HOTS) in chemistry learning. Both students' initial abilities and the choice of learning model influence HOTS achievement, with Inquiry-Based Learning integrated with GSS (IBL-GSS) emerging as the most effective, particularly for students with high initial ability levels. The findings emphasize that students' readiness and prior knowledge play a crucial role in shaping learning outcomes, while the alignment of learning models with the nature of the material is equally important. The research also highlights meaningful interactions between initial ability and the selected learning model, suggesting the need for differentiated instructional strategies. Teachers are encouraged to design chemistry learning that not only incorporates GSS indicators but also considers students' initial competencies to optimize HOTS development. Although the study was limited to three chemistry topics (acid-base, thermochemistry, and chemical equilibrium) and a restricted number of schools, the results provide strong evidence of the potential of GSS-integrated models to prepare students for the demands of 21st-century skills. Future research should expand the scope to other chemistry topics and broader school contexts, as well as explore the integration of digital innovations such as AI-driven platforms to further strengthen adaptive and personalized learning. Overall, the study reaffirms the strategic role of GSS-integrated digital learning models in cultivating critical thinking, problem-solving, creativity, and scientific reasoning, thereby equipping students to meet the challenges of the global era.

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AUTHOR CONTRIBUTIONS

Ani Sutiani and Zainuddin Muchtar designed the study, conducted the data collection, and wrote the original manuscript with support and guidance from other authors. Ratu Evina Dibyantini, Marudut Sinaga, and Freddy Tua Musa Panggabean contributed to the planning, data collection, discussion of the results, and the final manuscript. All authors read and approved the manuscript. All authors have read and approved the published version of the research, analysis, and manuscript.

CONFLICTS OF INTEREST

The author(s) declare no conflict of interest.

USE OF ARTIFICIAL INTELLIGENCE (AI)-ASSISTED TECHNOLOGY

The authors declare that no artificial intelligence (AI) tools were used in the generation, analysis, or writing of this manuscript. All aspects of the research, including data collection, interpretation, and manuscript preparation, were carried out entirely by the authors without the assistance of AI-based technologies.

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