PROBLEM BASED LEARNING IN HIGH SCHOOL SCIENCE

NY Performance Standards Consortium

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The NY Performance Standards Consortium embraces and supports a *problem-based* approach to teaching and learning as the core of the science curricula in its member schools. Since the ultimate goal of problem-based learning is to educate students to be self-directed, independent, life-long learners (Hung, et al., 2008), the Consortium regards each of its components as integral to the pedagogy of its science curriculum.

INTRODUCTION

Problem-based learning was originally developed in the 1950s to enable medical students to apply knowledge learned to solve problems in real life medical situations (Awan, R. et al., (2017); Hung,, W. et al., 2008; Lonergan, R. et al., 2022). K-12 problem-based learning implementation occurred in the 1990s (Hung., et al., 2008).

Problem-based learning has been defined in several ways:

1. "An instructional method that initiates students' learning by creating a need to solve an authentic problem" (Hung, et al., 2008).
2. "A method of inquiry where students solve difficulties, oddities, qualms, and problems in the context of real life" (Awan, R. et al., 2008).
3. "An instructional (and curricular) learner-centered approach that empowers learners to conduct research, integrate theory and practice, and apply knowledge and skills to develop a viable solution to a defined problem" (Savery, J.R. 2006).

The unifying characteristic common to these definitions is that students have the responsibility for their own learning. Other problem-based learning characteristics relevant to Consortium high school pedagogy are (Hung, et al., 2008; Savery, J.R. 2006):

1. The problems that students are required to solve must be ill-structured and allow for free inquiry.
2. Collaboration with group members is essential.
3. Information that students collect through their research must be reanalyzed and applied back to the problem.
4. A closing analysis of what students have learned from their research is essential. This includes student discussion as well as self and peer assessment.
5. Student assessments must be both knowledge-based and process-based.
6. The pedagogical base must be a problem-based curriculum and not one that is

teacher-centered.

Sadeh, I. and Zion, M. (2009) have further clarified the first problem-based learning characteristic. There are three levels at which students can solve problems. The lowest level (structured inquiry) is teacher-directed where teachers provide the question to be solved as well as the prescribed procedure. At the intermediate level (guided inquiry) the students may choose a teacher-supplied question but devise their own research design. At the highest level (open inquiry) it is the students' responsibility to formulate the question, design the procedure, and find a solution. One critical difference between the guided and open levels is the role of the teacher. In guided inquiry the teacher is both facilitator and source of information. In open inquiry the teacher is only the group supporter and facilitator. Researching information and engaging in higher order thinking necessary to solve the problem is therefore the students' responsibility (Savery, J.R., 2006).

The Consortium regards each of the above six elements as integral pedagogical components of its science curricula. In addition to demonstrating positive long-term effects on their self-directed, life-long learning skills and attitudes, the literature cites numerous studies that provide strong evidence that student-centered problem-based learning significantly improves students' ability to develop critical higher order thinking and problem-solving skills compared with students in traditional teacher-centered classes (reviewed in Garicke, N., et al., 2022; Hung, et al., 2008; Karan, E., and Brown, L., 2022). Studies have shown that inquiry-based high school science students regardless of race (Wilson, C.D., et al., 2009) or who are low achievers with long histories of failure (Yerrick, R.K., 2000), reach significantly higher levels of achievement in knowledge, reasoning, and argumentation. Since teacher-centered classes typically emphasize coverage over depth, the typical means of evaluating student achievement is the standardized test. In a controlled investigation Stanger-Hall (2017) concluded that multiple choice standardized testing hindered critical thinking in introductory science courses. In lieu of traditional evaluation methods, case studies of secondary school problem-based teaching and learning have documented the powerful impact that performance-based assessments have made on students' intellectual skills (Darling-Hammond, L., Ancess, J., and Falk, B.,1995). Therefore performance-based assessment is the prime tool implemented to evaluate Consortium student achievement.

This review will present primary research evidence that supports problem-based Consortium teaching and learning in the following skill areas:

I. Formulating Questions

II. Designing Experiments

   A. FORMULATING HYPOTHESES

   B. TESTING HYPOTHESES

DISCUSSION OF PBL RESEARCH EVIDENCE

I. FORMULATING QUESTIONS

If students are to take responsibility for their own learning, ultimately internalize the scientific method, and think like scientists they need to be able to generate thoughtful questions. (reviewed in Chin,C. and Osborne, J., (2008). Different categories of questions have been proposed as a means of evaluating their levels of thinking (Bloom, B.S. et al.,1956), the possible answers to the highest level requiring scientific research (Dillon, J.T., 1984; Dori, Y.J. and Herscovitz, O., 2002; Shepardson, D.P. and Pizzini, E.L., 1991).

High school science curricula that include inquiry-based or problem-solving student centered science courses significantly improve students' ability to generate high level research questions compared with traditional teacher-centered courses in biology (Bielik, T. and Yarden, A., 2016; Brill, G. and Yarden, A., 2003; Chin, C.and Chia., L.G., 2004; Dori, Y.T. and Herscovitz, O., 1999), chemistry (Hofstein, A., et al., 2004; Hofstein, et al., 2005), and physics (Roth, W.M., 1994).

In addition to the above scientific investigations, the literature also cites inquiry-based classroom strategies that stimulate student-generated high level questions compared with traditional teacher-centered practices. These include teacher inquiry-based questioning designed to elicit what students think (Chin, C. 2007; Chin, C. and Osborne, J., 2008; Seok Oh, P., 2010), teacher-facilitated student discussions including the crucial role of periods of silence (Fox, B.J., 2004; van Zee, et al., 2001), observations of inanimate objects (Hynes-Berry, M. and Berry, G., 2014) and living animals (Fox, B.J., 2004), and interviews with guest speakers (Fox, B.J., 2004; Ostorga, A.N. and Farruggio, P., 2013).

As discussed above in the Introduction, a pivotal role of the problem-based teacher is facilitator of group discussions. Studies have shown that the quality of teacher questioning has a strong impact on the level of student discussions (reviewed in Zhang, M. et al., 2010). Types of questions likely to stimulate discussion are: (1) teacher-generated that do not have predetermined answers. (2) teacher-generated that incorporate student contributions to the discussion. (3) student-generated (Nystrand, et al., 2003). Various professional development (PD) strategies have successfully trained teachers to be able to construct questions that encourage student thinking and express their own ideas during reflective discussions (van Zee, E. et al., 2001; Zhang, M., et al., 2010). In controlled investigations (reviewed in Chin, C. and Osborne, J., 2008), students can be taught how to ask researchable questions when teachers model researchable questions as well as teach students their characteristics (Fox, B.J., 2004). The Consortium's science PD programs—moderation studies, conferences, mentoring, workshops, and intra- and inter-school classroom visitations—all contribute to developing science teachers' ability to generate problem-based appropriate questions.

II. DESIGNING EXPERIMENTS

A. FORMULATING HYPOTHESES

An hypothesis can be defined as a "testable explanation of an empirical relationship among variables in a given problem situation" (Quinn, M.E. and George, J.D., 1975). The role that hypotheses formation plays in guiding the process of inquiry learning (reviewed in Kuang, X., Eysink, T., and de Jong, T., 2023) is so fundamental that inquiry learning has been described as an hypothesis-generating,

hypothesis-testing, and hypothesis-revising process (Zimmerman, C., 2007). There are two possible factors that are capable of enabling students to formulate relevant and useful hypotheses (reviewed in Kuang, X, et al., 2023). The first is acquiring background or domain information so that students become familiar with the pertinent variables involved (variables defined as the factors that can change the data collected in the experiment) and their interrelationships . Based on the literature cited there appears to be considerable evidence supporting this prerequisite. The second possible factor is exploring (physically or abstractly) in lieu of or in conjunction with knowledge acquisition, a position that appears to be open to considerable debate and in need of further study.

In the Consortium's science curricula problem-based learning is the pedagogical vehicle for the teaching and learning of knowledge acquisition. There are various possible sources of knowledge: primary and secondary readings, interviews with experts, field trips (e.g., science research facilities, botanical and zoological gardens, museums, green roofs, nature walks, etc.), classroom science demonstrations, and science videos. The ultimate goal is to provide methodologies whereby students are given the freedom to critically analyze each of these sources in order to develop their thinking skills to the best of their abilities. Consequently they will be better equipped to identify, isolate, and understand the interrelationships of variables, skills necessary for thoughtful hypothesis generation.

The role that teacher inquiry-based questioning plays to expand students' thinking has been discussed above in Section I-Formulating Questions (Chin, C. 2007; Chin, C. and Osborne, J., 2008). Another strategy used in the Consortium especially in neuroscience courses is the teaching and learning of concept mapping. Joseph Novak developed concept mapping at Cornell University in 1972 to shift traditional teaching practices that stressed memorization toward more meaningful learning (Brinkerhoff, J.L. and Booth, G.M., 2013). A concept map is a diagram that represents relationships among concepts with the more general and exclusive concepts depicted above connected in hierarchical fashion by lines or arrows to the more specific and more inclusive concepts below.

Research has shown that compared with traditional teaching methods concept mapping significantly improves student knowledge acquisition (reviewed in Danmole, B.T. and Femi-Adeoye, K.O., 2004) in ninth grade or basic science (Fraser, K. and Edwards, J., 1985; Ogonnaya, U., et al., 2016), biology (Barenholz, H. and Tamir, P. 1992; Danmole, B.T. and

Femi-Adeoye, K.O., 2004; Okoye, N.S. and Okechukwu, R.N. 2010), chemistry (Fatokun, K. and Eniayeju, P., 2014), and physics (Wambugu, P.W., et al., 2013).

The literature also cites several investigations demonstrating that concept mapping has a positive effect on students' critical thinking. The bulk of this research has been carried out in nursing education. (reviewed in Garwood, J.K., et al., 2018; Yue, M., et al., 2017). At the high school level concept mapping can improve critical thinking skills in biology (Choudhary, F. and Bano, R., 2022) and physics (Muhali, M. and Sukaisih, R., 2023). Thus in addition to its role in knowledge acquisition, concept mapping is also a problem-based strategy that can enable students to develop their thinking skills needed to generate thoughtful hypotheses.

B. TESTING HYPOTHESES

Hypotheses testing consists of two broad categories—planning the procedure or experimental research design and physically performing the experiment in a laboratory setting. As discussed above in the Introduction, there are several possible gradations of student- and teacher-centered instructional approaches for hypotheses testing from total teacher-centered (structured inquiry) to total student-centered with the teacher acting only as group supporter and facilitator (open inquiry). Gericke, N., et al., (2022) have extensively reviewed the investigations researching the effectiveness of secondary school laboratory work cited in the literature between 1996 and 2019. They concluded that the research consistently provided evidence that student-centered approaches were more beneficial for students' academic achievement than teacher-centered. They also concluded that based on their research the degree of teacher-support (i.e., guided or open) needs further investigation.

Gericke, N. et al., (2022) cite the research of Dobber, et al., (2017) who examined 186 studies of K-12 Inquiry instruction. Their analyses found that inquiry-based strategies are channeled into three different directions or "regulations:" (1) the metacognitive which includes supporting inquiry discussions and improving thinking skills, (2) the conceptual which includes acquiring knowledge, and (3) the social which includes heterogeneous grouping and collaboration. These findings have important pedagogical implications for inquiry-based hypotheses testing strategies.

A pedagogical strategy that the Consortium implements to enable students to plan their research designs is a modified form of the Science Writing Heurisitic (SWH). The SWH is an inquiry learning-to-write approach that was developed in 1999 (Stephenson, N.S. and Sadler-McKnight, N.P., 2016). The SWH provides a scaffolding to enable students to think through their planning. It consists of two parts or frameworks: teacher-designed activities and a specific sequence of student questions (Kinger, S., et al., 2012).

Some of the teacher directed activities in the SWH include: student informal writing, brainstorming, posing questions, sharing and comparing, writing group notes, and individual reflection and writing. The first two student questions are (1) What are my questions? and (2) What did I (or will) do? These are the same activities that the Consortium implemented during one of its summer Professional Development programs in a workshop where teachers became students working in small groups to plan a procedure that would investigate a contemporary scientific question (Fox, B.J., et al., 2004). Like students (Chang, P., et al., 2022; Keys, C.W., et al.,1999; Kinger , S., et al., 2012) by being engaged in the Science Writing Heuristic process, the teachers expanded their critical thinking skills by raising questions not only about knowledge (i.e., the conceptual regulation) but also about issues concerning the process of science (i.e, the metacognitive regulation). It should also be noted that in this testing hypothesis inquiry workshop teachers (i.e., students) were working collaboratively in small groups (i.e., the social regulation).

Two crucial metacognitive components of hypothesis testing planning are (1) identification, isolation, and interrelationships of variables (referred to in the literature as CVS—Control-of-Variables strategy) and (2) collection, recording, interpretation, and analysis of data. Research has shown that students are able to think through these two aspects through the complete or modified Science Writing Heuristic approach (e.g., Gericke, N., et al., 2022; Kinger, S. et al., 2012). The literature frequently alludes to the use of modeling as another means of implementing a Control-of-Variables Strategy (e.g., Gericke, N., et al., 2022). Modeling as used here is the metacognitive method of applying known concepts to explain a new and unfamiliar phenomenon. During one of its summer Professional Development programs the Consortium ran a workshop where teachers were required to use modeling to explain why pennies were floating in a liquid (Fox, B.J., et al., 2004). Through the modified Science Writing Heuristic approach described above, teachers—acting as students—were able to use a Control-of-Variables strategy to think through their hypotheses testings. Another way Consortium science teachers employ modeling as a vehicle for using a Control-of-Variables strategy in the classroom is through demonstrations and videos where students are required to make predictions using supporting evidence. Models as a diagrammatic or physical prototype is also an integral component of the Consortium's Engineering and Design PBAT. Students are able to design experiments successfully when they are given the means to think through the manipulation of variables, either through modified versions of the Science Writing Approach as discussed above and/ or modeling (Arnold, J. C.,et al, 2014; Garcia-Mila, M., et al., 2011; Gericke, N., et al., 2022). They not only are able to understand cause and effect relationships, but are also better equipped to detect sources of error in their results.

The second element of hypothesis testing concerns the collection, recording, interpretation, and analysis of data. Roth, W.M. (1994) found that students were very capable analyzing data in an open inquiry science course environment. Gericke, N., et al. (2022) cite several studies that demonstrate the impact that student argumentative discourse (i.e., discussions) made on their ability to think through data processing (Andersson, J. and Engage,M., 2017; Katchevich, D., et al., 2013; Kind, P.M.,et al., 2011; Kipnis, M. and Hofstein, A., 2008). As discussed above Consortium science inquiry of teaching and learning heavily emphasizes small and full group student and teacher-facilitated discussions through a modified SWH approach. To assist in helping students analyze data, one SWH framework scaffolding strategy alluded to above that expands students' thinking is having them write their reflections to "What can I claim (from the data)?" and "How do I know?" (What is my evidence?). As mentioned above in the Introduction, it is crucial that students feel comfortable to engage in critical thinking particularly when analyzing data, a skill that many students find challenging. Therefore in the words of Gericke,, N., et al., (2022) the prime role of the inquiry teacher is “to *establish a learning environment* that stimulates students’ construction of explanations” (italics mine). This is especially pertinent when students are processing data. It is not a coincidence that the title of the first chapter’s case study in the Consortium’s inquiry science publication is: Establishing an Atmosphere. (Fox., B.J., 2004).

After students have analyzed their data they usually begin to write their lab reports and prepare for a presentation in the form of a round table discussion, exhibition, and/or an outside evaluation. It is worth noting that the last phase of experimentation — presentation preparation — is one of the final teacher-designated activities of the SWH framework (Kinger, S., et al., 2012). It has been recommended (Gericke, N., et al., 2022; Pedaste, M., et al., 2015) that the writing/communication/reflection phases of inquiry occur periodically *during* the hypothesis-testing process instead of after its completion in order to increase the development of students’ higher order thinking (i.e, their metacognition). This could be a pedagogical strategy more Consortium science teachers might consider to implement.

CONCLUSION: The Significance of the Structural Elements of Problem-Based Learning

One of the crucial functions of problem-based learning is to provide the structural framework for redirecting science education. Thus, in the Consortium problem-based pedagogy focuses on the teaching and learning (1) *of* science (i.e., its concepts, models, and theories), (2) *about* science (i.e., its process), and (3) *of doing* science (i.e., testing hypotheses) (Gericke, N., et al., 2022; Hodson, D. 2014). In addition, research has been carried out on the affective (i,e., feelings and attitudes) aspects of problem-based learning. Controlled studies have shown that secondary school students in problem-based environments have significantly higher positive attitudes towards learning science than students in traditional classes in biology (Manishimwe, H., et al., 2022), chemistry (Juntunen, M. and Aksela, M., 2013; Acar Sesen, N.A. and Tarhan, L., 2013), and physics (Bezen, S. and Bayrdak, C., 2020). Problem-based learning students also have a significantly higher level of self-confidence in learning science (Hung, W., et al., 2008; Karan, E. and Brown, L. 2022) regardless of content area (Pečiuliauskienė, P. 2020). Lastly, problem-based learning has a significant effect on students’ attitude toward science and scientists as measured by their career aspirations (Haynes, M., et al., 2023; Kanag, J. and Keinonen, T., 2017).

The structural elements of problem-based learning are also the core of the socio-scientific inquiry-based learning approach (SSIBL) (Amos, R and Levinson, R., 2019). Inquiry-based learning, in conjunction with citizenship education and socio-scientific issues, is the driving force that enables responsible citizens to take action to ameliorate potentially hazardous conditions that threaten our society e.g., policies dealing with climate change or the covid-19 pandemic. Thus problem-based learning and teaching can provide the foundation for intelligent responsible citizenship.

And lastly, the structure of problem-based learning aligns with these core ideas of the Next

Generation Science Standards (https://www.nextgenscience.org):

> A high-quality science education means that students will develop an *in-depth understanding of content and develop key skills—communication, collaboration, inquiry, problem solving, and flexibility*—that will serve them throughout their educational and professional lives (italics mine).

These core ideas of the Next Generation of Science Standards have profound implications for the training of our next generation of science teachers.

REFERENCES CITED

INTRODUCTION

Awan, R., Hussain, H. and Anwar, N. (2017). Effects of Problem based Learning on Students' Critical Thinking Skills, Attitudes toward Learning and Achievement. *Journal o*f *Educational Research, 20,* 28-41.

Darling-Hammond, L, Ancess, J, and Falk, B (1994). *Authentic Assessment in Action.* New York, NY: Teachers College Press.

Gericke, N., Högström, P., & Wallin, J. (2022). A systematic review of research on laboratory work in secondary school. *Studies in science education*, 1-41.

Hung, W., Jonassen, D. H., & Liu, R. (2008). Problem-based learning. In *Handbook of research on educational communications and technology* (pp. 485-506). Routledge.

Karan, E, and Brown, L. (2022). Enhancing Students' Problem-solving Skills through Project-based Learning. *Journal of Problem Based Learning in Higher Education, 10(1),* 74-87.

Lonergan, R., Cumming, T.M., and O'Neill, S.C. (2022). Exploring the efficacy of problem-based learning in diverse secondary school classrooms: Characteristics and goals of problem-based learning. *International Journal of Education Research,112,* 101945.

Sadeh, I. and Zion, M. (2009), The development of dynamic inquiry performances within an open inquiry setting: A comparison to guided inquiry setting. *J. Res. Sci. Teach., 46*: 1137-1160.

Savery, J. R. (2015). Overview of problem-based learning: Definitions and distinctions. *Essential readings in problem-based learning: Exploring and extending the legacy of Howard S.Barrows, 9(2),* 5-15.

Stanger-Hall, K.F. (2012). Multiple-Choice Exams: An Obstacle for Higher-Level Thinking in Introductory Science Classes. *CBE—Life Sciences Education 11(3),* 294-306.

Wilson, C. D., Taylor, J. A., Kowalski, S. M., & Carlson, J. (2010). The relative effects and equity of inquiry‐based and commonplace science teaching on students' knowledge, reasoning, and argumentation. *Journal of Research in Science Teaching: The Official Journal of the National Association for Research in Science Teaching*, *47*(3), 276-301.

Yerrick, R. K. (2000). Lower track science students' argumentation and open inquiry instruction. *Journal of Research in Science Teaching: The Official Journal of the National Association for Research in Science Teaching*, *37*(8), 807-838.

I. FORMULATING QUESTIONS

Bielik, T. and A.Yarden. (2016). Promoting the asking of research questions in a high-school biotechnology inquiry-oriented program. *IJ STEM Ed 3*, 15.

Brill, G., & Yarden, A. (2003). Learning biology through research papers: A stimulus for question-asking by high-school students. *Cell Biology Education*, *2*(4), 266-274.

Bloom, B.S., Engelhart, M.B., Furst, E.J., Hill, W.H., and Krathwohl, D.R. (1956). Taxonomy of educational objectives: The classification of educational goals. In: *Handbook I: Cognitive Domain*, New York: Longmans Green.

Chin, C. (2007). Teacher questioning in science classrooms: approaches that stimulate productive thinking. *Journal of Research in Science Teaching, 44*(6), 815–843.

Chin, C. and Chia, Li-Gek. (2004). Problem-based learning: Using students' questions to drive knowledge construction. *Science Education, 88:707-727.*

Chin, C., & Osborne, J. (2008). Students' questions: a potential resource for teaching and learning science. *Studies in Science Education, 44*(1), 1–39.

Dillon, J.T. (1984). The classification of research questions. *Rev. Educ. Res. 54(3),* 327–361.

Dori, Y. J., & Herscovitz, O. (1999). Question-posing capability as an alternative evaluation method: analysis of an environmental case study. *Journal of Research in Science Teaching, 36*(4), 411–430.

Fox, B.J., (2004). Establishing an atmosphere. In A. Cook (Ed.), *Inquiry teaching in the Sciences* (pp. 49-59). New York, NY: Teachers College Press.

Hofstein, A., Shore, R. & Kipnis, M. (2004) RESEARCH REPORT: Providing high school chemistry students with opportunities to develop learning skills in an inquiry-type laboratory: a case study, *International Journal of Science Education, 26(1)*, 47-62.

Hofstein, A., Navon, O., Kipnis, M., & Mamlok‐Naaman, R. (2005). Developing students' ability to ask more and better questions resulting from inquiry‐type chemistry laboratories. *Journal of research in science teaching*, *42*(7), 791-806.

Hynes-Berry, M. and Berry, G. (2014). "Reading and Object": Developing Effective Scientific Inquiry Using Student Questions. *European Journal of Science and Mathematics, 2(2),* 87-97.

Nystrand, M., Wu, L. L., Gamoran, A., Zeiser, S., & Long, D. A. (2003). Questions in time: Investigating the structure and dynamics of unfolding classroom discourse. *Discourse Processes, 35*(2), 135-198.

Ostorga, A.N. and Farruggio, P. (2013). The use of a virtual guest speaker as a catalyst for deep learning. *Procedia—Social and Behavioral Sciences, 93,* 244-2151.

Shepardson, D.P., and Pizzini, E.L. (1991). Questioning levels of junior high school science textbooks and their implications for learning textual information. *Sci. Educ., 75(6)*, 673–682.

Van Zee, E.H., Iwasyk, M., Kurose, A., Simpson, D., & Wild, J. Student and teacher questioning during conversations about science. *Journal of Research in Science Teaching, 38(2),* 159-190.

Zhang, M., Lundeberg, M., McConnell, J., Koehler, M. and Eberhardt, J., (2010). *Interdisciplinary Journal of Problem-Based Learning, 4(1),* 57-82.

II <u>DESIGNING EXPERIMENTS</u>

A. FORMULATING HYPOTHESES

Barenholz, H., & Tamir, P. (1992). A comprehensive use of concept mapping in design instruction and assessment. *Research in Science & Technological Education*, *10*(*1),* 37-52.

Brinkerhoff, J., & Booth, G. M. (2013). The effect of concept mapping on student achievement in an introductory non-majors biology class. *European International Journal of Science and Technology, 2(8), 43-72.*

Choudhary, F., & Bano, R. (2022). Concept maps as an effective formative assessment tool in biology at secondary level. *Journal of Education and Educational Development*, *9*(*1),* 157-175.

Danmole, B. T., & Femi-Adeoye, K. O. (2004). Effect of concept mapping technique on senior secondary school students' achievement and retention of ecology concepts.

Journal of the Science Teacher Association of Nigeria, *39(1),* 31-37.

Fatokun, K. V. F., & Eniayeju, P.A. (2014) The effect of concept mapping-guided discovery integrated teaching approach on Chemistry students achievement and retention. *Educational Research and Reviews 9(22),* 1218-1223.

Fraser, K., & Edwards, J. (1985). The effects of training in concept mapping on student achievement in traditional classroom tests. *Research in Science Education, 15,* 158-165.

Garwood, J. K., Ahmed, A. H., & McComb, S. A. (2018). The effect of concept maps on undergraduate nursing students' critical thinking. *Nursing education perspectives*, *39(4),* 208-214.

Kuang, X., Eysink, T. H. S., & de Jong, T. (2023). Presenting domain information or self-exploration to foster hypothesis generation in simulation-based inquiry learning. *Journal of Research in Science Teaching*, 1– 33 [Electronic version]. Retrieved June 3. from **https://doi.org/10.1.002/tea.21865**.

Muhali, M., & Sukaisih, R. (2023). Guided Discovery Learning Model Using Concept Map Strategy to Improve Students Metacognition and Critical Thinking Skills. *Jurnal Penelitian Pendidikan IPA*, *9*(*1*), 554-563. Retrieved June 9, 2023 from *https://doi.org/10.29303/jppipa.v9i1.3868.*

Ogonnaya, U. P., Okafor, G., Abonyi, O. S., & Ugama, J. O. (2016). Effects of Concept Mapping Instruction Approach on Students' Achievement in Basic Science. *Journal of Education and Practice*, *7(8),* 79-84.

Okoye, N. S., & Okechukwu, R. N. (2010). The effect of concept mapping and problem solving teaching strategies on achievement in biology among Nigerian secondary school students. *Education*, *131*(2), 288-295.

Quinn, A. E., & George, K. D. (1975). Teaching hypothesis formation. *Science Education*, **59**(3), 289– 296.

Seok Oh, Phil. (2010) How can Teachers Help Students Formulate Scientific Hypotheses? Some Strategies Found in Abductive Inquiry Activities of Earth Science, *International Journal of Science Education*, *32*(4), 541-560.

Soika, K., & Reiska, P. (2014). Using Concept Mapping for Assessment in Science Education. *Journal of Baltic Science Education, 5,* 662-673.

Wambugu, P. W., Changeiywo, J. M., & Ndiritu, F. G. (2013). Effects of experiential cooperative concept mapping instructional approach on secondary school students' achievement and motivation in physics in Nyeri County, Kenya, *Asian Journal of Social Sciences & Humanities, 2,* 279-296.

Yue, M., Zhang, M., Zhang, C., & Jin, C. (2017). The effectiveness of concept mapping on development of critical thinking in nursing education: A systematic review and meta-analysis. *Nurse education today*, *52*, 87-94.

Zimmerman, C. (2007). The development of scientific thinking skills in elementary and middle school. *Developmental Review*, **27**(2), 172– 223.

B. TESTING HYPOTHESES

Andersson, J., & Enghag, M. (2017). The relation between students' communicative moves during laboratory work in physics and outcomes of their actions. *International Journal of Science Education*, 39(2), 158–180.

Arnold, J. C., Kremer, K., & Mayer, J. (2014). Understanding students' experiments — What kind of support do they need in inquiry tasks? *International Journal of Science Education*, 36(16), 2719–2749.

Chang, P., Lee, S., & Wen M. (2022.) Developing an inquiry-based laboratory curriculum to engage students in planning investigations and argumentation. *International Journal of Science Education*, 44:18, 2659-2684.

Dobber, M., Zwart, R., Marijn Tanis, M. & van Oers,B. (2017). Literature review: The role of the teacher in inquiry-based education. *Educational Research Review, 22,* 194-214.

Fox, B.J., Grosso, T., & Tashlik, P. (2004). Research and Research Design. In A. Cook (Ed.), *Inquiry teaching in the Sciences* (pp. 27-30). New York, NY: Teachers College Press.

Garcia-Mila, M., Andersen, C., & Rojo, N. E. (2011). Elementary students' laboratory record keeping during scientific inquiry. *International Journal of Science Education*, 33(7), 915–942.

Gericke, N., Högström, P., & Wallin, J. (2022). A systematic review of research on laboratory work in secondary school. *Studies in science education*, 1-41.

Keys, C. W., Hand, B., Prain, V., & Collins, S. (1999). Using the science writing heuristic as a tool for learning from laboratory investigations in secondary science. *Journal of research in science Teaching*, *36*(10), 1065-1084.

Katchevich, D., Hofstein, A., & Mamlok-Naaman, R. (2013). Argumentation in the chemistry laboratory: Inquiry and confirmatory experiments. *Research in Science Education*, 43(1), 317–345.

Kind, P. M., Kind, V., Hofstein, A., & Wilson, J. (2011). Peer argumentation in the school science laboratory–Exploring effects of task features. *International Journal of Science Education*, 33(18), 2527–2558.

Kinger, S, Geban, O, & Gunel, M. (2012). How does the science writing heuristic approach affect students' performance of different achievement levels? A case for high school chemistry. *Chem. Educ. R*es. Pract., 13, 428-436.

Kipnis, M., & Hofstein, A. (2008). The inquiry laboratory as a source for development of metacognitive skills. *International Journal of Science and Mathematics Education*, 6(3), 601–627.

Pedaste, M., Mäeots, M., Siiman, L. A., De Jong, T., Van Riesen, S. A., Kamp, E. T., ... & Tsourlidaki, E. (2015). Phases of inquiry-based learning: Definitions and the inquiry cycle. *Educational research review*, *14*, 47-61

Stephenson, N. S., & Sadler-McKnight, N. P. (2016). Developing critical thinking skills using the science writing heuristic in the chemistry laboratory. *Chemistry Education Research and Practice*, *17*(1), 72-79.

<u>CONCLUSION</u>

Acar Sesen, B., & Tarhan, L. (2013). Inquiry-based laboratory activities in electrochemistry: High school students' achievements and attitudes. *Research in Science Education*, *43*, 413-435.

Amos, R., & Levinson, R. (2019). Socio-scientific inquiry-based learning: An approach for engaging with the 2030 Sustainable Development Goals through school science. *International Journal of Development Education and Global Learning*, *11*(1), 29-49.

Bezen, S., & Bayrak, C. (2020). Teaching Mechanical Waves by Inquiry-Based Learning. *Journal of Baltic Science Education*, *19*(6), 875-892.

Gericke, N., Högström, P., & Wallin, J. (2022). A systematic review of research on laboratory work in secondary school. *Studies in science education*, 1-41.

Haynes, M., Brown, A., Nichols, K., & Parveen Musofer, R. (2023). Measurement of student attitudes to science and association with inquiry-based learning in regional schools. *International Journal of Science Education*, 1-20.

Hodson, D. (2014). Learning science, learning about science, doing science: Different goals demand different learning methods. *International Journal of Science Education*, 36(15), 2534–2553.

Hung, W., Jonassen, D. H., & Liu, R. (2008). Problem-based learning. In *Handbook of research on educational communications and technology* (pp. 485-506). Routledge.

Juntunen, M., & Aksela, M. (2013). Life-cycle analysis and inquiry-based learning in chemistry teaching. *Science Education International*, *24*(2), 150-166.

Kang, J. & Kenianen, T. (2017). The effect of inquiry-based learning experiences on adolescents' science-related career aspiration in the Finnish context. *International Journal of Science Education, 39(12),* 1669-1689.

Karan, E, and Brown, L. (2022). Enhancing Students' Problem-solving Skills through Project-based Learning. *Journal of Problem Based Learning in Higher Education, 10(1),* 74-87.

Manishimwe, H., Shivoga, W. A., & Nsengimana, V. (2022). Effect of inquiry-based learning on students' attitude toward biology at upper secondary school in Rwanda. *Journal of Baltic Science Education,* 21(5), 862-874.