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Data-authentic modeling in IoT-enabled aquaponics PjBL-STEAM: Enhancing function graph literacy and mathematical critical thinking

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Abstract

Authentic sustainability contexts remain insufficiently integrated into mathematics instruction, limiting opportunities for students to connect empirical data, mathematical representations, and evidence-based reasoning. This study addresses this gap by positioning aquaponics as a sustainability-oriented context within Project-Based Learning integrated with STEAM (PjBL-STEAM), offering a novel learning environment for developing function graph literacy and mathematical critical thinking. The study examined the effectiveness of Aquaponics-Based PjBL-STEAM and explored the learning processes characterizing students' engagement with these competencies. A mixed-methods embedded experimental design involved 126 Grade 10 students from Sekolah Adiwiyata Latansa Mashiro 1 Cipanas, Indonesia, assigned to Aquaponics-Based PjBL-STEAM ($n = 43$), STEAM with a scientific approach (n = 42), or direct instruction ($n = 41$). The Aquaponics-Based PjBL-STEAM group demonstrated the largest gains in function graph literacy, from $M = 47.26$ ($SD = 8.31$) to $M = 83.51$ ($SD = 6.74$; $N - Gain = 0.69$), and mathematical critical thinking, from $M = 44.71$ ($SD = 7.86$) to $M = 81.62$ ($SD = 6.95$; $N - Gain = 0.67$). ANCOVA indicated significant instructional-condition effects on function graph literacy, $F(2,122) = 18.74, p < .001$, partial $\eta^2 = .235$, and critical thinking, $F(2,122) = 21.63, p < .001$, partial $\eta^2 = .262$. Qualitative analysis identified data-driven mathematical reasoning, construction of functional relationships, coordination of multiple representations, and evidence-based graph interpretation. These processes illuminate students' connections between empirical data, mathematical models, and graphs, complementing the quantitative findings without establishing causal mechanisms. Overall, the intervention was associated with stronger

development of both competencies, highlighting the potential of sustainability-oriented project-based STEAM for mathematics learning.

Keywords: Aquaponics; Function graph literacy; Mathematical critical thinking; PjBL-STEAM

Introduction

Mathematics education in the twenty-first century is no longer confined to procedural computation (Suh et al., 2021) but increasingly emphasizes students' ability to interpret data and construct mathematical reasoning grounded in real-world contexts (Kohen & Nitzan-Tamar, 2022; Santos-Trigo et al., 2021). This shift encompasses the modelling of real-life phenomena through mathematical representations and decision-making processes rooted in contextual problem solving, which constitute the core of STEM education and mathematical modelling practices (Hartmann et al., 2021; Kohen & Orenstein, 2021). Contemporary mathematics instruction also highlights authentic problem solving and contextual reasoning as essential foundations for developing data literacy and addressing real-world challenges in the era of digital transformation (Verschaffel et al., 2020; Chiu, 2021).

Within this framework, function graph literacy emerges as a critical competence, defined as the ability to understand (Jungjohann et al., 2022), interpret (Rolfes, 2021), analyze (Kop et al., 2021), and represent relationships between variables through function graphs across diverse real-life contexts (Venneker et al., 2025). This competence has become increasingly important in response to the growing demand for data literacy, complex problem-solving skills (González-Pérez & Ramírez-Montoya, 2022), and decision-making based on information visualization (Chiu, 2021) in the era of Society 5.0 and digital transformation in education (OECD, 2021; UNESCO, 2023). Nevertheless, international reports consistently indicate that students' graph comprehension remains underdeveloped (Rosenblum et al., 2021). Students frequently struggle to relate changes in variables to functional relationships and to interpret graphical representations in a meaningful way (Chang et al., 2024), particularly when dealing with authentic, data-rich problems that require critical and multidimensional interpretation of graphs (Jungjohann et al., 2022).

The persistent weakness in function graph literacy is closely associated with mathematics instruction that remains highly abstract and representational (Mayer, 2021), predominantly procedural in nature, and limited in interactive engagement (Clinton-Lisell et al., 2023). Moreover, such instruction is often insufficiently connected to students lived experiences and real-world contexts (Venneker et al., 2025). Function graph content is typically presented through equation manipulation and mechanistic practice, rather than through exploratory learning grounded in real phenomena (Antonini & Lisarelli, 2021). As a result, students' conceptual understanding of covariational relationships remains underdeveloped (Qetrani & Achtaich, 2022; Borji et al., 2021), and they encounter significant difficulties in integrating algebraic, tabular, graphical, and empirical representations simultaneously (Venneker et al., 2025; Clinton-Lisell et al., 2023). These limitations further contribute to weak mathematical

critical thinking, particularly in evaluating patterns (Darmayanti et al., 2022; Kocak et al., 2021), interpreting causal relationships (González-Pérez & Ramírez-Montoya, 2022), and constructing and testing evidence-based arguments (Rapanta et al., 2021). Such competencies are widely recognized as essential twenty-first-century skills that underpin effective problem solving, informed decision-making, and evidence-based reasoning in mathematics education (Kocak et al., 2021; González-Pérez & Ramírez-Montoya, 2022; Khoiri et al., 2021).

This study proposes an innovative pedagogical framework that aligns with the demands of globalization by leveraging technology to foster creativity, critical thinking, and problem-solving through interdisciplinary learning. One prominent implementation of this framework is Science, Technology, Engineering, Arts, and Mathematics (STEAM) education, which emphasizes interdisciplinary, collaborative, and experiential learning, enabling students to apply knowledge and skills in authentic, real-world contexts. Within science education, students engage with natural phenomena through scientific inquiry and science process skills to develop understanding and address problems using critical thinking skills (CTS). CTS is widely recognized as an essential 21st-century competency for enhancing human resource quality and responding to global challenges in the Society 5.0 era. However, graduates' limited readiness for the workforce is still associated with weak critical thinking abilities (OECD, 2021), which is often attributed to the absence of instructional designs explicitly targeting these skills and the continued dominance of rote-based learning approaches.

The development of CTS is consistent with contemporary curriculum demands that emphasize transferable skills applicable to real-life and professional contexts, while also supporting the transformation of educational quality toward sustainability-oriented learning through STEAM approaches. A growing body of research indicates that STEM/STEAM-based instruction is effective in enhancing CTS, scientific literacy, and learning achievement, although further empirical investigation is still needed to fully understand its potential in 21st-century learning contexts. CTS is defined as the ability to evaluate both relevant and irrelevant information in order to make appropriate decisions and take justified actions. CTS comprises five dimensions: elementary clarification (posing questions and analyzing arguments), basic support (evaluating source credibility and observational evidence), inference (drawing and evaluating conclusions), advanced clarification (defining terms and identifying assumptions), and strategy and tactics (deciding on actions and interacting effectively with others).

Environmental crises represent complex, multifaceted problems that require comprehensive identification and solution-oriented thinking, making CTS a key competence in understanding and addressing such issues. Nevertheless, the development of CTS in education remains limited due to insufficient instructional designs that systematically engage students in scientific processes through the exploration of real-world phenomena. As a result, students often struggle to understand scientific concepts, principles, theories, and laws needed to solve problems systematically in authentic contexts. This condition contributes to students' low capacity to address complex problems and to meaningfully contribute to their surrounding environment. Such issues highlight a persistent gap between the goals of contemporary mathematics education and classroom practices, particularly in relation to 21st-century skills

development, contextual problem-solving, and data-based representational learning (González-Pérez & Ramírez-Montoya, 2022; OECD, 2021). Mathematics instruction also continues to be dominated by teacher-centered approaches that position students as passive recipients of information, thereby limiting opportunities for active knowledge construction (Chiu, 2021; Hattie, 2023). In addition, students are rarely provided with learning experiences that are investigative, contextual, collaborative, and project-based in authentic settings, all of which are essential for cultivating 21st-century competencies (González-Pérez & Ramírez-Montoya, 2022; Kocak et al., 2021).

In the topic of function graphs, students are commonly trained to plot graphs from given equations without fully understanding the relationship between symbolic and visual representations (Venneker et al., 2025). Instruction also tends to remain procedure-oriented, limiting students' ability to interpret variable changes and functional relationships in real-world contexts (Wannagat et al., 2022). As a result, graphs are often perceived as abstract mathematical objects rather than as tools for modeling empirical phenomena (Kim & Li, 2021). This condition constrains contextual understanding, weakens the interpretation of visual mathematical representations, and hampers the development of critical reasoning based on covariational relationships (Clinton-Lisell et al., 2023; Wannagat et al., 2022; Venneker et al., 2025). In contrast, graph literacy constitutes a foundational component of data literacy in contemporary STEM education (OECD, 2021), while mathematical critical thinking plays a central role in scientific reasoning and real-world problem solving through inquiry-based and data-driven learning (Kocak et al., 2021; González-Pérez & Ramírez-Montoya, 2022).

A substantial body of research has demonstrated that Project-Based Learning (PjBL) and STEAM integration effectively enhance student engagement (Chiu, 2021; Yulianto & Juniawan, 2025), problem-solving ability (Rahimi & Kim, 2021), creativity (González-Pérez & Ramírez-Montoya, 2022), and mathematical critical thinking (Kocak et al., 2021; Darmayanti et al., 2022). STEAM implementation is theoretically grounded in constructivist learning theory and, in certain instructional designs, incorporates behaviorist principles to support cognitive, affective, and skill development aligned with curriculum objectives. More broadly, STEAM fosters instructional innovation in addressing global challenges by promoting constructivist thinking, complex environmental problem solving, and the enhancement of human capital quality. From a constructivist perspective, STEAM cultivates integrative and transdisciplinary thinking that connects theory and practice to generate context-based solutions across disciplines and perspectives.

Empirical studies further indicate that STEAM exerts a positive influence on critical thinking, creativity, and problem-solving skills required for 21st-century competencies (OECD, 2021). It also prepares learners for future workforce demands by developing skills aligned with the needs of modern industry and society. However, its implementation requires carefully designed, technology-enhanced instruction that adheres to scientific principles and ethical considerations. The rapid advancement of science and technology in the 21st century further underscores the importance of integrating digital technologies to improve human resource quality, particularly among pre-service and in-service educators.

As an extension of STEM, STEAM incorporates the Arts component, which strengthens logical, objective, analytical, and intuitive thinking processes. It supports constructivist learning through active student engagement in knowledge construction and promotes transdisciplinary learning to address complex problems through the integration of aesthetics, science, and engineering perspectives. Effective implementation of STEAM further requires TPACK competence, encompassing technological, pedagogical, and content knowledge as well as their integration to ensure meaningful instructional practice. Through authentic investigation (Kokotsaki et al., 2021), collaboration (Chen & Yang, 2021), data exploration (Capraro et al., 2016), and contextual problem solving, PjBL promotes more meaningful and participatory learning experiences (Guo et al., 2020). Meanwhile, STEAM integration fosters interdisciplinary learning (Perignat & Katz-Buonincontro, 2019), connecting mathematics with science, technology, engineering, and creative design in real-world contexts (González-Pérez & Ramírez-Montoya, 2022). The combination of PjBL and STEAM has also been shown to enhance higher-order thinking skills, collaborative inquiry, and real-world problem-solving abilities through exploratory, project-based activities (Chiu, 2021; Rahimi & Kim, 2021; González-Pérez & Ramírez-Montoya, 2022).

Sustainability-oriented education has received increasing scholarly attention due to its capacity to connect academic concepts with environmental issues, data-informed decision-making, and real-world contexts (Zguir et al., 2021; Kopnina, 2020). Within this paradigm, aquaponics represents a particularly promising context for mathematics learning, as it provides an authentic, data-driven learning environment in which students can observe plant growth, monitor water quality, and analyze interrelated variables in real time (Junge et al., 2019). Aquaponics is a symbiotic food production system that integrates aquaculture and hydroponics within a closed-loop, sustainable ecosystem (Yep & Zheng, 2019). This system generates rich and dynamic empirical data, including plant and fish growth patterns (Wang et al., 2023), as well as continuously measurable water parameters such as pH, temperature, and nutrient concentration (Mori et al., 2021). Such multidimensional datasets create meaningful opportunities for contextual mathematical modeling, functional relationship analysis, and graph-based representation grounded in empirical observation (Tarigan et al., 2021). Through engagement with aquaponics systems, students can collect and analyze real-world data, construct contextual mathematical models, and interpret functional changes through graphical representations (Rahimi & Kim, 2021). Moreover, aquaponics-based learning environments support authentic data-driven inquiry that strengthens conceptual understanding through contextualization, visualization, and multimodal representation, in alignment with inquiry-based learning principles (Kim & Li, 2021; Mayer, 2021).

Despite its potential, prior research on aquaponics-based learning has predominantly focused on science, biology, and environmental education, while its integration into mathematics instruction particularly for function graph learning remains limited (Suh et al., 2021; Junge et al., 2019). Existing studies indicate that aquaponics can enhance student engagement (Yulianto & Juniawan, 2025), environmental awareness (Greenfeld et al., 2022), and experiential learning through direct observation and experimentation (Kalvakaalva et al.,

2023). However, these studies have not explicitly addressed the development of function graph literacy through the analysis of variable relationships derived from authentic data sources (Rolfes et al., 2022; Sproesser et al., 2022; Ruf et al., 2024). Furthermore, the integration of aquaponics with a PjBL-STEAM framework in mathematics education remains underexplored, particularly in relation to the simultaneous development of mathematical critical thinking and contextual mathematical modeling skills despite evidence that PjBL-STEAM approaches effectively foster critical thinking through contextual, interdisciplinary learning experiences (Widiyono & Ghufron, 2024).

The broader literature on PjBL indicates that research in mathematics education has largely emphasized learning outcomes and problem-solving skills, often without strong integration of sustainability contexts or authentic real-world projects (Chang et al., 2024; Hwang et al., 2017; Yulianto & Juniawan, 2025). Similarly, STEAM education studies frequently position mathematics as a supporting discipline rather than as a central tool for data analysis and mathematical modeling (Just & Siller, 2022; Diego-Mantecón et al., 2021; Roehrig et al., 2021), resulting in a limited emphasis on the epistemic role of mathematics within STEAM-based project learning (Marín-Marín et al., 2021; Bautista, 2021). Research on graph literacy, on the other hand, has primarily concentrated on data visualization interpretation and statistical literacy (Radermacher, 2021; Jungjohann, Gebhardt, & Scheer, 2022), while statistical literacy studies tend to focus on formal statistical reasoning rather than function-based graph interpretation within authentic contexts (Çakıroğlu & Güler, 2021; Phadke, Beckman, & Morgan, 2022). In addition, mathematical critical thinking has often been investigated independently of graph literacy and sustainability-based learning, despite their strong interdependence in reasoning, interpretation, and context-based decision-making processes (van Dijke-Droogers et al., 2021; Ruf et al., 2024).

However, the unresolved issue is not simply whether these approaches can be combined, but how an authentic, sensor-mediated sustainability context can function as a mathematical knowledge-generating environment. Existing studies have rarely examined how continuously generated aquaponics data can be systematically transformed into mathematical objects such as variable relationships, functional models, tables, and graphs and subsequently used as evidence for mathematical reasoning and critical evaluation. Consequently, three interrelated gaps remain. First, aquaponics has predominantly been positioned as a context for science, environmental, and experiential learning rather than as a source of authentic mathematical data for function-based modeling. Second, PjBL-STEAM research has largely emphasized engagement, creativity, problem solving, and interdisciplinary learning, with comparatively limited attention to the epistemic role of mathematics in transforming empirical data into functional relationships and graphical representations. Third, previous research has rarely explained the learning mechanisms through which data-authentic project experiences connect graph construction and interpretation with mathematical critical thinking. Thus, what remains theoretically and empirically underexplored is the mechanism by which students move from observing and measuring a dynamic real-world system to constructing functional relationships,

coordinating multiple mathematical representations, and evaluating graphical evidence to formulate justified mathematical conclusions.

The role of IoT in this framework is therefore not conceived merely as a technological enhancement, but as a mechanism for establishing a data-authentic learning environment. IoT-enabled sensors allow students to access continuously generated measurements of aquaponics variables, such as water temperature, pH, and other system parameters, thereby introducing temporal variability, measurement uncertainty, and inter-variable dependencies into mathematical inquiry. These characteristics transform the learning task from interpreting predetermined textbook data into constructing and interrogating mathematical representations from empirical evidence. In this sense, IoT provides the empirical data stream, aquaponics provides the authentic sustainability system, PjBL structures the inquiry process, STEAM establishes interdisciplinary integration, and mathematics provides the epistemic tools for modeling, representing, and evaluating the observed relationships. The scientific contribution of the proposed framework therefore lies not in the juxtaposition of these components, but in their functional alignment within a data-to-model-to-evidence learning cycle.

Accordingly, a clear research gap remains in the development of an integrated instructional model that combines PjBL (Belland et al., 2017), STEAM education (DeJarnette, 2018), aquaponics as a sustainable STEM context (Lennard & Goddek, 2019), graph literacy (Ruamba et al., 2025), and mathematical critical thinking (Villa et al., 2026) within a coherent, authentic, and PjBL ecosystem. Such integration is essential to reposition mathematics not merely as a computational tool, but as a core epistemic instrument for interpreting real-world systems and supporting data-informed reasoning in sustainability-oriented education. The observed gap underscores the need for instructional innovation that meaningfully connects mathematical representations with students lived empirical experiences through authentic data exploration and contextual problem solving (Allanta & Puspita, 2021; Sari et al., 2024). Such approaches have been shown to enhance critical thinking, mathematical literacy, and data analytical skills (Sofiani & Abdullah, 2025). In this regard, the integration of aquaponics into function graph learning within a PjBL-STEAM framework offers a promising pedagogical solution. It provides an interdisciplinary learning environment in which students construct mathematical concepts through direct observation, measurement, data analysis, and graphical interpretation (Hehakaya et al., 2022).

This approach aligns closely with the core characteristics of PjBL-STEAM, which emphasize contextualized, collaborative, and authentic PjBL experiences (Allanta & Puspita, 2021; Diana et al., 2021). Consequently, it has the potential to foster higher-order mathematical thinking and critical reasoning. Through this learning design, students are guided not only to interpret function graphs as symbolic representations but also to understand them as dynamic depictions of variable change within real-world systems (Sasaki & Sawada, 2026). This perspective strengthens the connection between mathematics and real-world phenomena (Hehakaya et al., 2022; Sari et al., 2024; Sofiani & Abdullah, 2025s) while simultaneously developing function graph literacy and mathematical critical thinking through inquiry,

reflection, argumentation, and evidence-based evaluation of empirical data (Widiyono & Ghufron, 2024).

Furthermore, the integration of aquaponics within a PjBL-STEAM framework supports the development of 21st-century skills through interdisciplinary learning that promotes collaboration, creativity, scientific communication, and evidence-based decision-making (Wilson et al., 2021; Marlina & Andiani, 2026; Tallapragada et al., 2021; Manikutty et al., 2022). Contextual PjBL enables students to engage in authentic, data-driven inquiry that bridges classroom learning with scientific practices and real-world problem solving (Bell, 2010; Helle et al., 2021; Blumenfeld et al., 2021). Through aquaponics activities, students identify growth patterns, construct functional models, make predictions, evaluate variable interactions, and represent their findings through meaningful function graphs (Hehakaya et al., 2022; Sofiani & Abdullah, 2025). Prior studies have demonstrated that STEAM-based PjBL enhances critical thinking, mathematical modeling, and contextual data representation through hands-on inquiry and experimentation, particularly when students engage in project-based inquiry that requires authentic data analysis, pattern interpretation, and functional visualization (Yulianto & Juniawan, 2025). Accordingly, mathematics is repositioned not as an abstract and isolated discipline, but as a cognitive tool for understanding and addressing sustainability-oriented contextual problems (Garcia-Piqueras & Ruiz-Gallardo, 2021; Kleshnina et al., 2025). This shift has been shown to enhance students' mathematical modeling abilities, problem-solving skills, and functional literacy in real-world contexts.

The novelty of this study is therefore conceptual, pedagogical, and empirical. Conceptually, it reconceptualizes aquaponics from a sustainability context into a data-authentic mathematical modeling environment in which empirical measurements become the basis for constructing and interpreting functional relationships. Pedagogically, it proposes a data-to-model-to-evidence learning cycle that aligns IoT-generated data, PjBL inquiry, STEAM integration, and mathematical representation rather than treating them as independent instructional components. Empirically, the study identifies four interrelated learning mechanisms data-driven mathematical reasoning, construction of functional relationships, coordination of multiple representations, and evidence-based graph interpretation that explain how students' engagement with authentic aquaponics data can simultaneously strengthen function graph literacy and mathematical critical thinking. Thus, the contribution of the study extends beyond demonstrating the effectiveness of PjBL-STEAM; it provides evidence for how a data-authentic, IoT-mediated learning environment can transform empirical observations into mathematical models, graphical representations, and evidence-based reasoning. This study develops function graph literacy through authentic observational data derived from aquaponics systems, thereby supporting data-driven learning and scientific inquiry in applied mathematics (Mufida et al., 2022). In addition, mathematical critical thinking is reinforced through contextual mathematical modeling and inquiry-based project learning, both of which have been shown to enhance students' critical reasoning abilities in STEAM–PjBL contexts (Diana et al., 2021). Unlike previous studies that treat PjBL, STEAM, and sustainability as separate constructs, this study integrates all three into a unified, interdisciplinary, contextual, and data-

authentic learning framework (Hehakaya et al., 2022). Accordingly, this research aims to examine the effectiveness of aquaponics-based PjBL-STEAM in enhancing students' function graph literacy and mathematical critical thinking. In line with this objective, the following research questions are posed: (1) How effective is aquaponics-based PjBL-STEAM in improving students' function graph literacy and mathematical critical thinking? (2) How does aquaponics-based PjBL-STEAM facilitate the development of function graph literacy, contextual mathematical modeling, graphical interpretation, and mathematical critical thinking?

Methods

Research Design

This study employed a mixed-methods approach using an embedded experimental design, in which the quantitative strand served as the primary source of evidence for evaluating the effectiveness of the intervention, while the qualitative strand was used to explain the learning mechanisms underlying students' development of function graph literacy and mathematical critical thinking (see Figure 1). A quasi-experimental pretest–posttest control group design was implemented in intact classrooms, with an initial equivalence test conducted to maintain comparative validity across groups. The independent variable consisted of three instructional conditions: Aquaponics-Based PjBL-STEAM, STEAM with a scientific approach, and direct instruction. The dependent variables were function graph literacy and mathematical critical thinking. All classes were taught by the same teacher, with instructional materials, learning duration, and learning resources carefully controlled to minimize teacher-related effects. Consequently, the primary differences among groups were concentrated in the pedagogical structure, particularly in terms of the level of inquiry, scaffolding processes, and student autonomy.

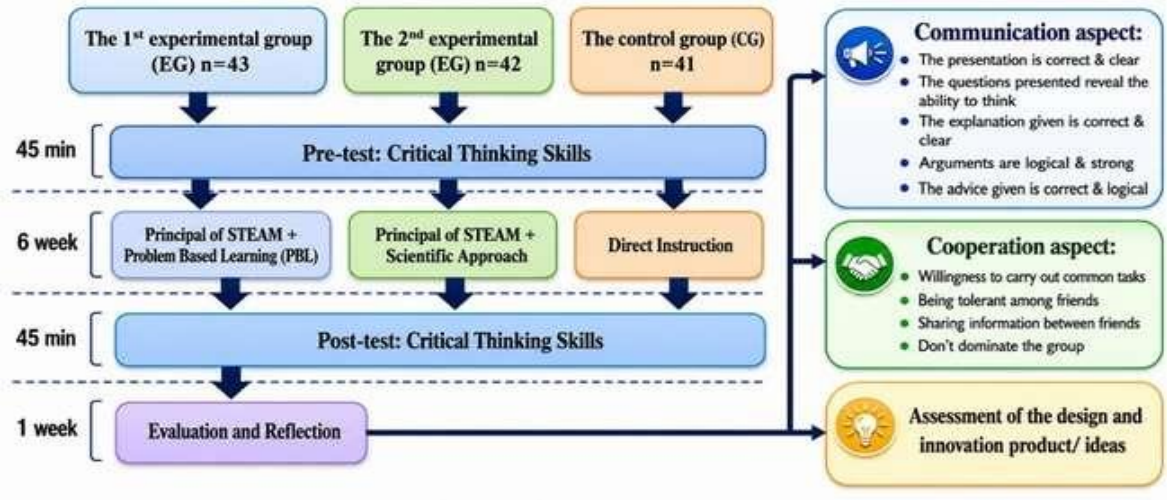


Figure 1. Experimental Procedure

The intervention was designed as a project-based instructional ecosystem centered on aquaponics activities that continuously generated authentic data through iterative cycles of investigation, mathematical modelling, representation, and reflective analysis. Qualitative data were collected longitudinally across the three instructional conditions to capture both common and condition-specific learning processes. Structured classroom observations were conducted during each instructional session to document students' engagement, inquiry processes, teacher scaffolding, collaboration, use of representations, and mathematical reasoning. Project artefacts and mathematical modelling tasks were collected from participating students to examine how students generated, interpreted, transformed, and justified function representations. Weekly reflective journals were collected from focal students to capture changes in their perceptions, strategies, difficulties, and reflections on the learning process. At the end of the intervention, semi-structured interviews were conducted with purposively selected students and the instructional teacher. Student interviewees were selected from each instructional group based on their pretest–posttest change profiles, ensuring representation of relatively high, moderate, and low levels of improvement. This sampling procedure was used to connect students' quantitative learning trajectories with qualitative evidence concerning the instructional experiences and learning mechanisms associated with those trajectories. The same qualitative evidence was examined across the three instructional conditions to identify both convergent and divergent patterns. Particular attention was given to differences in the degree of inquiry, teacher scaffolding, student autonomy, collaborative mathematical reasoning, engagement with authentic data, and the use of multiple representations. These dimensions were selected because they corresponded directly to the hypothesized mechanisms through which Aquaponics-Based PjBL-STEAM, STEAM with a scientific approach, and direct instruction were expected to influence function graph literacy and mathematical critical thinking.

To establish an explicit quantitative–qualitative linkage, the qualitative strand was purposively structured to explain the differences observed in the quantitative outcomes across the three instructional conditions. Qualitative evidence was collected from all three groups through classroom observations and selected project or learning artefacts, while reflective journals and semi-structured interviews were used to obtain more detailed accounts of students' learning experiences. Following the preliminary quantitative analysis, focal cases were purposively identified based on their patterns of change from pretest to posttest, with attention to students representing relatively high, moderate, and low levels of improvement within each instructional condition. This case-selection strategy enabled the qualitative analysis to examine why students exposed to different instructional structures demonstrated different levels of development in function graph literacy and mathematical critical thinking. Thus, the qualitative strand was not treated as a parallel description of classroom activities but as an explanatory component specifically designed to illuminate the mechanisms underlying the quantitative group differences.

STEAM education represents a comprehensive interdisciplinary approach that has evolved through several developmental stages: (1) the STS stage (*enlightenment*), (2) the STSE stage (*exploration*), (3) the STEM stage (*prosperity*), and (4) the STEAM stage (*sublimation*).

The characteristics of STEAM learning emphasize comprehensive, contextual, and applied learning experiences, while simultaneously fostering collaboration, communication, critical reasoning, and reflective thinking throughout the learning process.

In Experimental Group 1, STEAM instruction was fully integrated with PjBL, emphasizing contextual problem solving, interdisciplinary integration, and student-centered learning, with the teacher acting primarily as a facilitator. The learning problems were derived from real-world phenomena that required students to connect newly acquired experiences with their prior knowledge. PjBL was implemented to support the construction of knowledge, attitudes, and skills through experiential learning situated within authentic everyday contexts. The instructional process followed five stages: (1) problem orientation, (2) learning planning, (3) individual and group investigation, (4) product development and presentation, and (5) analysis and evaluation of the problem-solving process. In Experimental Group 2, STEAM instruction was integrated with the scientific approach, which emphasizes the sequential processes of observing, questioning, collecting information, associating, and communicating. Students observed natural phenomena in their surrounding environment and subsequently formulated critical questions addressing rationality, evaluative criteria, practical application, and scientific intellectualism. They then gathered and analyzed information to deepen their conceptual understanding of the observed phenomena and communicated the results of their analyses as part of the evaluation and reflection process.

Meanwhile, the control group received instruction through a direct instruction approach characterized by teacher-centered learning. The instruction was supported by multimedia resources to facilitate students' conceptual understanding (see Figure 2). Although direct instruction primarily relies on explicit teacher explanation, students were still engaged through limited exploratory activities and guided discussions. However, the effectiveness of this approach largely depends on students' working memory capacity. Consequently, the success of direct instruction in fostering critical thinking skills (CTS) is strongly influenced by the appropriateness of the instructional strategies employed.

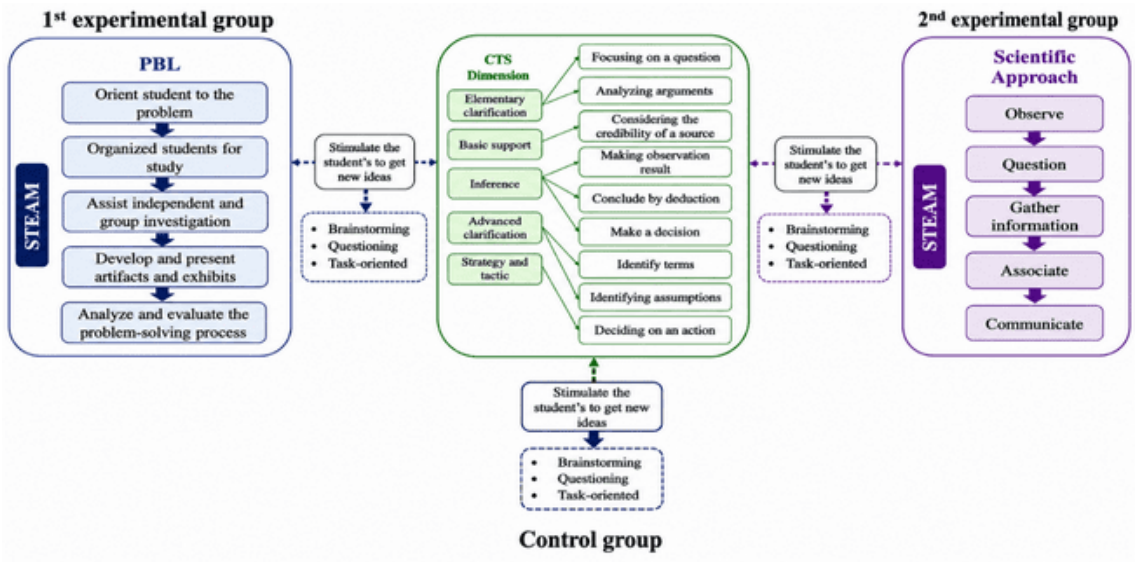


Figure 2. Teaching Environment

The Aquaponics-Based PjBL-STEAM intervention was implemented over eight instructional sessions (90 minutes each) across a six-week period. Students worked collaboratively in groups of four to five using an aquaponics system that integrated fish cultivation with vegetable production. Throughout the project, students collected authentic longitudinal data, including plant height, fish growth, water temperature, pH levels, and nutrient concentrations. The instructional design followed the core phases of PjBL. In the orientation phase, students explored sustainability issues and examined the principles of aquaponic systems. During the planning phase, they formulated investigational questions, identified relevant variables, and designed data-collection procedures. In the investigation phase, students conducted periodic observations and measurements using the aquaponics system. The data analysis phase required students to organize data into tables and function graphs, analyze relationships among variables, and construct contextualized mathematical models. In the product development phase, students developed graphical interpretations and predictive models based on empirical findings. Subsequently, students presented their project outcomes to peers and teachers, followed by a reflection phase in which they evaluated the validity of their models and drew conclusions grounded in empirical evidence.

The STEAM integration was embedded systematically throughout the intervention. Science components involved observing biological and environmental processes within the aquaponics ecosystem. Technology integration focused on data recording, digital visualization, and data management. Engineering elements emerged through the design, maintenance, and regulation of the aquaponics system. Arts components were reflected in the preparation of visual reports and project presentations, while Mathematics was emphasized through function graph construction, mathematical modelling, data interpretation, and quantitative reasoning. Collectively, these activities were designed to foster students' function graph literacy and mathematical critical thinking through engagement with authentic data analysis and contextual problem solving.

Research Population and Sample

This study involved 126 tenth-grade students (aged 15–16 years) enrolled at SMA Adiwiyata Latansa 1 Cipanas, Indonesia, during the 2026/2027 academic year. The accessible population comprised four intact classes taught by the same teacher and exposed to the same curriculum, instructional schedule, and learning duration. The sample was selected using cluster random sampling, in which three classes were assigned through computer-generated randomization to Experimental Group 1 (n = 43), Experimental Group 2 (n = 42), and the Control Group (n = 41). Preliminary analysis based on pretest scores and students' previous semester mathematics achievement indicated no statistically significant differences in prior ability across the groups ($p > .05$). Over a six-week intervention period, Experimental Group 1 participated in Aquaponics-Based PjBL integrated with STEAM (Aquaponics-Based PjBL-STEAM), Experimental Group 2 received STEAM instruction implemented through a scientific approach, while the Control Group was taught using direct instruction (see Table 1). All participants

completed pretests and posttests designed to assess function graph literacy and mathematical critical thinking.

Table 1. Overview of Research Procedures and Instructional Interventions

Stage	Duration	Experimental 1	Experimental 2	Control
Pretest	45 minutes	Function Graph Literacy & Mathematical Critical Thinking		
Intervention	6 weeks	Aquaponics-Based PjBL-STEAM	STEAM + Scientific Approach	Direct Instruction
Posttest	45 minutes	Function Graph Literacy & Mathematical Critical Thinking		
Evaluation	1 week	Yes	Yes	Yes

An a priori power analysis conducted using $G*Power$ 3.1 ($\alpha = .05, power = .80, effect\ size\ f = .25$) indicated a minimum required sample of 111 participants. Therefore, the final sample size ($N = 126$) was considered sufficient to achieve adequate statistical power. The study was conducted after obtaining approval from the school administration, parents or guardians, and all participating students.

Before the intervention, baseline equivalence analyses were performed to ensure comparability among the three groups in terms of function graph literacy and mathematical critical thinking (see Table 2). Shapiro–Wilk tests demonstrated that all pretest scores were normally distributed ($p > .05$), while Levene's tests confirmed homogeneity of variance across groups ($p > .05$). Furthermore, one-way ANOVA revealed no significant differences in function graph literacy, $F(2,123) = 0.37, p = .689, \eta^2 = .006$, or mathematical critical thinking, $F(2,123) = 0.24, p = .788, \eta^2 = .004$. The extremely small effect sizes ($\eta^2 < .01$) indicate that initial differences among groups were negligible, confirming that the three groups possessed comparable baseline characteristics for evaluating the effectiveness of the instructional interventions (see Table 2).

Table 2. Baseline Equivalence Across Groups

Variable	Group	n	Mean ± SD	95% CI	Cohen's d
Function Graph Literacy	Experimental 1	43	41,72 ± 8,63	39,06–44,38	0,09
	Experimental 2	42	40,95 ± 8,11	38,42–43,48	0,16
	Control	41	40,28 ± 8,94	37,47–43,09	0,08
Test Statistics	SW = 0,214; Levene = 0,647; F (2,123) = 0,37; p = 0,689; η^2 = 0,006				
MCT	Experimental 1	43	39,84 ± 7,56	37,51–42,17	0,06
	Experimental 2	42	40,31 ± 7,81	37,88–42,74	0,09
	Control	41	39,15 ± 7,69	36,74–41,56	0,15
Test Statistics	SW = 0,173; Levene = 0,589; F (2,123) = 0,24; p = 0,788; η^2 = 0,004				

Note. *SW* = Shapiro–Wilk test. All pretest scores were normally distributed ($p > 0.05$) and met the assumption of homogeneity of variance (Levene's $p > 0.05$). The ANOVA results indicated no statistically significant differences in baseline ability across the three groups for either variable ($p > 0.05$). Moreover, the effect sizes were negligible ($\eta^2 < 0.01$), confirming the initial equivalence of the groups prior to the intervention.

Research Instruments

The study employed two principal instruments: the *Mathematical Critical Thinking Test* and the *Function Graph Literacy Test*, both designed as contextual open-ended assessments grounded in authentic aquaponics data. The *Mathematical Critical Thinking Test* comprised 13 items developed according to Ennis's critical thinking indicators, including interpretation, analysis, evaluation, inference, and mathematical argumentation. Meanwhile, the *Function Graph Literacy Test* consisted of 10 items assessing students' abilities to read and interpret graphs, analyze covariational relationships, transform representations across tables, graphs, and equations, examine relationships among variables, and solve contextual problems involving functional graphs.

Each item was constructed based on a detailed test blueprint and contextualized using authentic aquaponics data, such as plant growth rates, pH fluctuations, water temperature, and nutrient dynamics. This contextualization enabled the assessment of students' representational competence and mathematical reasoning within meaningful real-world situations. All responses were evaluated using a four-level analytic rubric (0–4) incorporating descriptors for interpretive accuracy, quality of mathematical relationships, representational consistency, and the strength of argumentative justification. Content validity was established through expert review by three specialists in mathematics education and STEAM pedagogy. The experts evaluated the alignment between indicators and constructs, contextual appropriateness, conceptual clarity, and representational accuracy of the instruments. Revisions were subsequently made based on their recommendations prior to empirical testing with 28 students who possessed characteristics comparable to those of the research participants.

Empirical validity analysis using Pearson item–total correlations indicated that all items were valid, with correlation coefficients ranging from 0.565 to 0.930. Internal consistency reliability analysis yielded a Cronbach's alpha coefficient of 0.933, indicating excellent reliability. Given the open-ended nature of the instruments, scoring was conducted independently by two raters using a standardized scoring rubric. Inter-rater consistency was then examined using the Intraclass Correlation Coefficient (ICC), which demonstrated a high level of agreement between raters. To strengthen data triangulation within the embedded mixed-methods design, several supporting instruments were also employed, including observation sheets, project performance rubrics, reflective journals, and peer-assessment forms. These instruments were used to capture students' engagement, collaboration, mathematical modelling processes, data communication, and argumentative reasoning throughout the implementation of the aquaponics-based PjBL-STEAM intervention (see Figure 3).

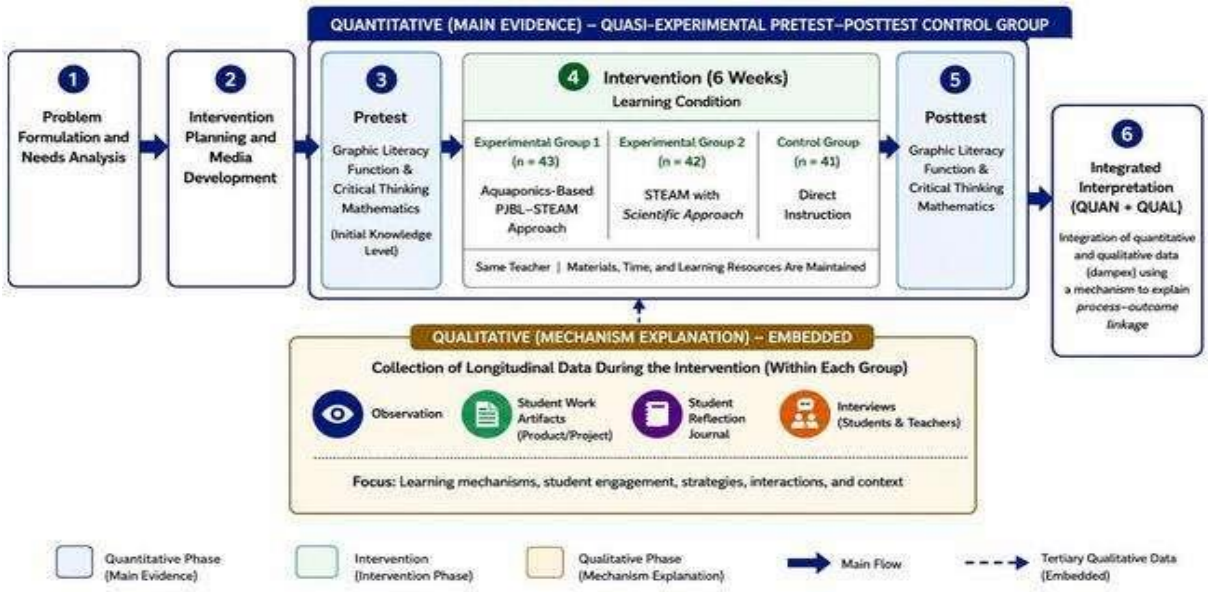


Figure 3. Embedded Experimental Design Framework

Data Collection Techniques

Quantitative data were collected through pretests and posttests administered using the *Function Graph Literacy Test* and the *Mathematical Critical Thinking Test*. Both instruments consisted of contextual open-ended problems assessed using a four-level analytic rubric. The pretest was administered prior to the intervention to establish the equivalence of students' initial abilities, whereas the posttest was conducted after eight instructional sessions. To enhance scoring reliability and minimize subjectivity, all responses were independently evaluated by two raters who used the same scoring guidelines. Qualitative data were collected concurrently throughout the instructional implementation through structured classroom observations conducted during each session, documentation of students' project artifacts and mathematical modelling tasks, weekly reflective journals, and semi-structured interviews with both students and teachers at the end of the intervention. The use of these multiple data sources was intended to provide a more comprehensive understanding of the development of students' function graph literacy and mathematical critical thinking, while also strengthening the trustworthiness of the findings through data triangulation.

Data Analysis Procedures

Quantitative data were analyzed using both descriptive and inferential statistics. Prior to the main analysis, the assumptions underlying parametric testing were examined through the Shapiro–Wilk test for normality, Levene's test for homogeneity of variance, and the homogeneity of regression slopes test. Students' learning improvement was evaluated using normalized gain (N-Gain) scores. To determine the effectiveness of the interventions across groups, Analysis of Covariance (ANCOVA) was employed with pretest scores treated as covariates. This procedure was intended to increase the precision of treatment effect estimation

while controlling for differences in students' initial abilities. The magnitude of the intervention effects was interpreted using partial eta squared and Cohen's *d* effect sizes.

Qualitative data were analyzed through thematic analysis following the procedures proposed by Braun and Clarke, including open coding, axial coding, and theme generation. The resulting themes were subsequently aligned with the indicators of function graph literacy and mathematical critical thinking. To enhance the trustworthiness of the findings, several strategies were employed, including source, method, and time triangulation, member checking, maintenance of an audit trail, and inter-rater agreement among coders. Integration of the quantitative and qualitative strands followed an explanatory, case-linked procedure. First, quantitative analyses were used to identify the magnitude and direction of differences in posttest performance and learning gains across the three instructional conditions. Second, students were classified according to their individual pretest–posttest change profiles, and purposive qualitative cases were selected from each instructional condition to represent contrasting levels of improvement. Third, the qualitative data associated with these cases were coded and thematically analyzed to identify learning processes and instructional mechanisms that could account for the observed quantitative patterns.

The qualitative themes were then compared across the three instructional conditions to determine whether specific features of the interventions were consistently associated with higher or lower levels of improvement. To facilitate integration, a joint display was constructed in which quantitative outcomes were mapped against qualitative themes for each instructional condition and focal case. Quantitative indicators included pretest–posttest change, N-Gain, and adjusted posttest performance, whereas qualitative indicators included students' engagement with authentic data, inquiry and problem-solving processes, use and coordination of mathematical representations, teacher scaffolding, collaborative reasoning, and reflective evaluation. Convergence between quantitative and qualitative evidence was interpreted as corroboration of the proposed learning mechanisms, whereas divergence was examined to identify contextual or process-related explanations for unexpected quantitative patterns. This integration enabled the qualitative findings to function as an explanatory layer for the quantitative results rather than as an independent descriptive component. Accordingly, the mixed-methods integration provided an empirically grounded explanation of not only whether the three instructional conditions differed in their effects, but also how and why differences in inquiry, scaffolding, autonomy, authentic data engagement, representation use, and mathematical reasoning contributed to the observed development of students' function graph literacy and mathematical critical thinking.

Results

Implementation of the Aquaponics-Based PjBL-STEAM Learning Environment

The Aquaponics-Based PjBL-STEAM learning environment was supported by an aquaponics system integrated with Internet of Things (IoT) technology to generate authentic real-time data throughout the investigation process (see Figure 4).

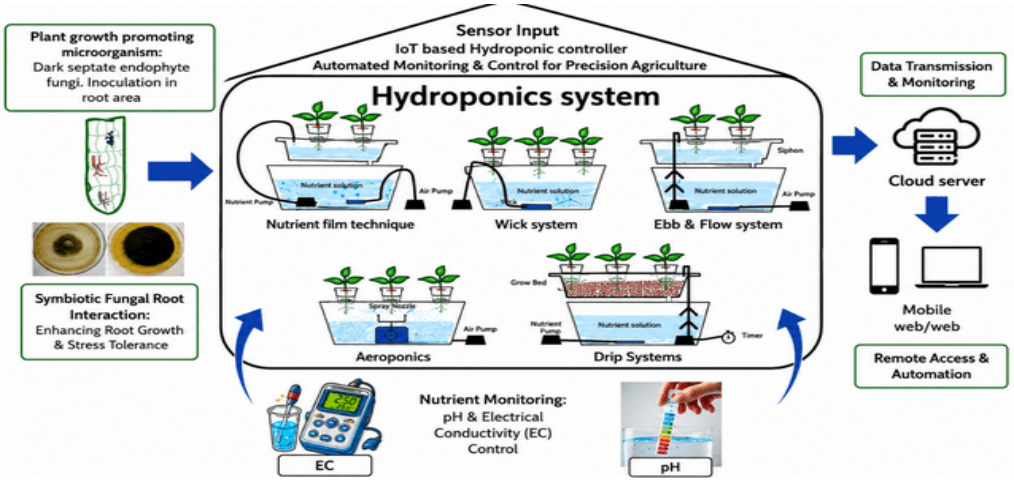


Figure 4. Integration of the IoT-based aquaponics system

The system consisted of interconnected fish cultivation and plant-growing units equipped with multiple sensors to monitor water temperature, light intensity, water flow, pH levels, and nutrient concentration. In addition, the system incorporated several automated actuators, including water pumps, air pumps, ventilation fans, and LED grow lights to regulate environmental conditions and support plant growth (see Figure 5).

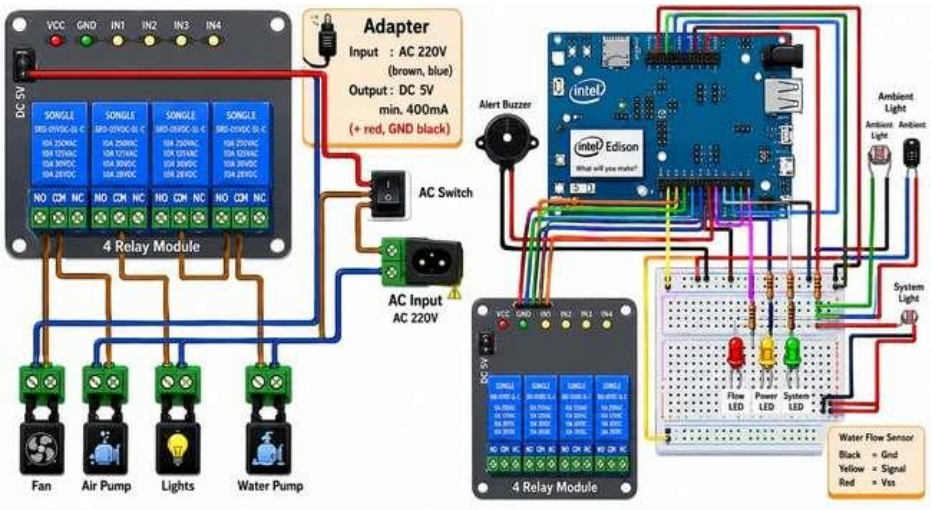


Figure 5. IoT-Based Aquaponics Learning Environment Implemented in the Aquaponics-Based PjBL-STEAM Intervention.

The system was operated through a web-based interface that enabled real-time environmental monitoring and device control. Throughout the intervention, data on plant growth, fish growth, water temperature, pH, light intensity, water flow rate, and nutrient concentration were continuously collected and stored in a digital database (see Figure 6).

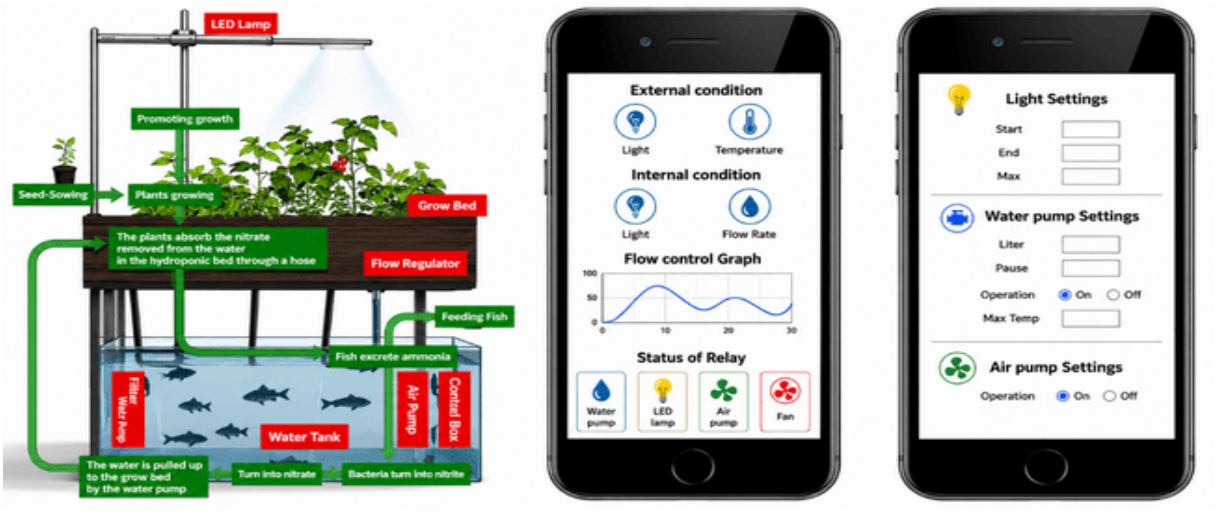


Figure 6. System Overview and Remote-Control User Interface

System logs indicated that all sensors functioned reliably, with a data acquisition success rate of 97.8%, generating approximately 120–150 data points per group over the six-week observation period. These data served as the basis for students to construct tables, generate function graphs, identify patterns of change, make predictions, and develop contextualized mathematical models (see Figure 7).



Figure 7. Program Operation Results

Overall, the implementation of the Aquaponics-Based PjBL-STEAM model created an authentic investigative learning environment that integrated empirical observation, data analysis, mathematical modelling, and evidence-based reflection. This learning environment

not only facilitated the development of students' function graph literacy and mathematical critical thinking but also strengthened essential twenty-first-century competencies, including collaboration, scientific communication, data-driven decision-making, and contextual problem-solving skills.

Effectiveness of Aquaponics-Based PjBL-STEAM on Function Graph Literacy and Mathematical Critical Thinking

The descriptive results indicate that students in the Aquaponics-Based PjBL-STEAM group demonstrated the largest pretest-to-posttest improvements in both function graph literacy and mathematical critical thinking (see Table 3). For function graph literacy, the mean score increased from 47.26 ($SD = 8.31$) to 83.51 ($SD = 6.74$), corresponding to a mean gain of 36.25 points and an N-gain of 0.69. For mathematical critical thinking, the mean score increased from 44.71 ($SD = 7.86$) to 81.62 ($SD = 6.95$), corresponding to a mean gain of 36.91 points and an N-gain of 0.67. By comparison, the STEAM-scientific approach group showed mean gains of 26.59 and 26.28 points, with N-gain scores of 0.50 and 0.48 for function graph literacy and mathematical critical thinking, respectively, whereas the direct instruction group showed smaller gains of 15.47 and 14.64 points, with N-gain scores of 0.29 and 0.26. These N-gain values should be interpreted as descriptive indicators of within-group learning improvement rather than as evidence of statistically significant differences between instructional conditions. Based on Hake's classification used in this study, the overall N-gain values for Exp. 1 fall within the moderate category, whereas several individual indicators reach the high category.

More importantly, the inferential analyses provide stronger evidence that the observed differences were associated with the type of instructional intervention. After controlling for pretest scores, ANCOVA revealed a significant effect of instructional condition on function graph literacy, $F(2,122) = 18.74, p < .001$, partial $\eta^2 = .235$, and on mathematical critical thinking, $F(2,122) = 21.63, p < .001$, partial $\eta^2 = .262$. Both effect sizes exceed the conventional threshold for a large effect, indicating that instructional condition accounted for a substantial proportion of the adjusted variance in the two outcomes. Bonferroni-adjusted post-hoc comparisons further showed that the Aquaponics-Based PjBL-STEAM group significantly outperformed both the STEAM-scientific approach group and the direct instruction group on both function graph literacy and mathematical critical thinking ($p < .001$ for all comparisons). Thus, the superior performance of Exp. 1 should not be interpreted solely from its larger N-gain values; rather, the effectiveness of the Aquaponics-Based PjBL-STEAM intervention is primarily supported by the statistically significant between-group differences after adjustment for baseline performance.

Table 3. Descriptive Statistics and ANCOVA Results for Function Graph Literacy and MCT

Variable	Group	n	Pre → Post (M ± SD)	Improvement (Δ; N-Gain)	Category	Mean (95% CI)
Function Graph Literacy	Exp 1	43	47.26 ± 8.31 → 83.51 ± 6.74	+36.25; 0.69	Low	83.18 (81.12–85.24)
	Exp 2	42	46.88 ± 8.04 → 73.47 ± 7.52	+26.59; 0.50	Moderate	73.65 (71.42–75.88)
	Control	41	46.35 ± 8.27 → 61.82 ± 8.15	+15.47; 0.29	Low	62.06 (59.67–64.45)
Mathematical Critical Thinking	Exp 1	43	44.71 ± 7.86 → 81.62 ± 6.95	+36.91; 0.67	High	81.27 (79.18–83.36)
	Exp 2	42	45.10 ± 8.12 → 71.38 ± 7.43	+26.28; 0.48	Moderate	71.59 (69.31–73.87)
	C	41	44.93 ± 8.03 → 59.57 ± 8.27	+14.64; 0.26	Low	59.71 (57.22–62.20)

Note. Exp 1 = Aquaponics-Based PjBL-STEAM; Exp 2 = STEAM with scientific approach; C = direct instruction

The Aquaponics-Based PjBL-STEAM group consistently demonstrated the highest improvement across both dependent variables. Specifically, function graph literacy increased by 36.25 points with a high N-gain score of 0.69, while mathematical critical thinking increased by 36.91 points with an N-gain of 0.67. In contrast, the direct instruction group exhibited only modest gains, with increases of 15.47 points in function graph literacy and 14.64 points in mathematical critical thinking, both classified within the low N-gain category. These differences indicate that passive exposure to mathematical procedures alone was insufficient to support deeper conceptual understanding, graphical interpretation, and evidence-based reasoning. To further examine these differences, Table 4 presents the differential improvement across each dimension of function graph literacy and mathematical critical thinking, showing that the Aquaponics-Based PjBL-STEAM group consistently achieved the highest gains across all indicators.

Table 4. Differential Improvement Across Function Graph Literacy and MCT Dimensions

Variable	Dimension / Indicator	N-Gain			Category
		Exp 1	Exp 2	C	
Function Graph Literacy	Reading graph information	0.72	0.55	0.31	High
	Graph interpretation	0.71	0.53	0.30	High
	Representation transformation	0.74	0.52	0.27	High
	Analysis of variable relationships	0.68	0.49	0.28	Moderate–High

	Contextual graph-based problem solving	0.63	0.44	0.24	Moderate–High
Mathematical Critical Thinking	Interpretation	0.69	0.51	0.29	High
	Analysis	0.71	0.50	0.27	High
	Evaluation	0.65	0.46	0.25	Moderate–High
	Inference	0.68	0.47	0.24	Moderate–High
	Mathematical argumentation	0.63	0.44	0.22	Moderate–High

Note. Exp 1 = Aquaponics-Based PjBL-STEAM; Exp 2 = STEAM with scientific approach; C = direct instruction. N-Gain categories were interpreted based on Hake's classification: low (<0.30), moderate (0.30–0.69), and high (≥0.70).

The adjusted mean differences further demonstrate the consistency of this treatment effect across the specific dimensions of function graph literacy and mathematical critical thinking (see Table 5). For function graph literacy, Exp. 1 obtained higher adjusted means than Exp. 2 and the control group across reading graph information (84.12 vs. 75.08 and 63.51), graph interpretation (85.37 vs. 73.84 and 60.92), representation transformation (87.41 vs. 74.21 and 58.63), analysis of variable relationships (82.96 vs. 72.53 and 59.84), and contextual graph-based problem solving (86.25 vs. 72.11 and 57.96). A comparable pattern was observed for mathematical critical thinking, with Exp. 1 achieving higher adjusted means for interpretation (80.94), analysis (82.37), evaluation (81.85), inference (84.26), and mathematical argumentation (83.74). All indicator-level ANCOVA effects were statistically significant, with partial η^2 ranging from .204 to .361, while the corresponding Cohen's *d* values ranged from 0.81 to 2.03, indicating moderate-to-very-large, standardized differences between instructional conditions.

Taken together, these findings establish a clear distinction between descriptive improvement and treatment effectiveness. The N-gain results describe the magnitude of students' improvement within each group, whereas the ANCOVA and Bonferroni analyses provide inferential evidence that the observed superiority of the Aquaponics-Based PjBL-STEAM group was statistically attributable to differences in instructional condition after controlling for initial achievement. The convergence of statistically significant overall and indicator-level effects, together with substantial effect sizes, therefore, provides stronger evidence for the effectiveness of the Aquaponics-Based PjBL-STEAM intervention than the N-gain classifications alone.

The highest improvement was observed in representation transformation (N-Gain = 0.74), suggesting that repeated engagement with tables, graphs, and equations strengthened students' multi-representational fluency. This finding supports prior studies emphasizing that coordinated transitions across mathematical representations facilitate deeper functional understanding and covariational reasoning (Rolfes et al. 2022; Sproesser et al. 2022; Ruf et al. 2024; Ruamba et al. 2025). In contrast, mathematical argumentation demonstrated the lowest relative improvement despite remaining within the moderate-to-high category. This result suggests that constructing evidence-based mathematical justification requires more sustained

scaffolding and dialogic interaction than other dimensions of critical thinking (Rapanta et al. 2021; Kocak et al. 2021; Marlina & Andiani, 2026).

The first mechanism, authentic data engagement, was reflected in students' sustained use of real-time aquaponics data to examine changes in water temperature, pH, light intensity, water flow, nutrient concentration, and biological growth. Unlike students in the comparison groups, Exp. 1 students repeatedly interpreted continuously generated data and used these data to construct mathematical representations. This process was particularly consistent with the improvement in reading graph information ($N-gain = 0.72$) and analysis of variable relationships ($N-gain = 0.68$). The qualitative evidence therefore suggests that students' repeated encounters with authentic, changing data provided a concrete basis for interpreting variation and relationships among variables, which was subsequently reflected in their quantitative performance. The second mechanism, iterative coordination of multiple representations, emerged as students repeatedly moved between raw data, tables, graphs, equations, and contextual explanations. This mechanism provides a plausible process-level explanation for why representation transformation showed the highest N-gain (0.74) among the function graph literacy dimensions and also achieved the largest adjusted mean difference in the indicator-level ANCOVA analysis. The qualitative evidence indicated that students did not merely reproduce graphical procedures; rather, they progressively coordinated different representations to explain the same aquaponics phenomenon. Such repeated representational transitions likely strengthened their ability to recognize functional relationships across representations.

The third mechanism, collaborative evidence-based reasoning, was evident in students' group discussions, comparison of interpretations, and justification of conclusions using collected aquaponics data. These interactions were particularly relevant to the development of mathematical critical thinking because students were required to explain why a particular interpretation was supported by the observed data, evaluate alternative explanations, and negotiate conclusions with peers. This mechanism is consistent with the relatively strong gains in analysis ($N-gain = 0.71$), interpretation (0.69), and inference (0.68). However, the comparatively lower gain in mathematical argumentation (0.63) suggests that collaborative reasoning alone did not automatically produce fully developed mathematical justification and that explicit scaffolding for argument construction remained necessary. The fourth mechanism, contextualized mathematical modelling and reflection, connected students' mathematical representations to decisions concerning the aquaponics system. Students were required to interpret patterns, predict changes, and use mathematical relationships to explain or respond to authentic system conditions. This mechanism was particularly aligned with the improvement in contextual graph-based problem solving ($N-gain = 0.63$) and mathematical argumentation (0.63), as students needed to connect quantitative evidence with contextual explanations and justify the implications of their mathematical models. Taken together, these qualitative processes indicate that the intervention operated not simply by increasing students' exposure to mathematical content, but by creating repeated opportunities to observe, represent, interpret, test, explain, and reflect on mathematical relationships within an authentic system.

Taken together, the qualitative and quantitative findings show a coherent pattern of mechanism–outcome alignment. The strongest quantitative gains occurred in dimensions that were most directly supported by repeated opportunities for authentic data interpretation and representational coordination, particularly representation transformation, graph interpretation, and analysis of variable relationships. Conversely, mathematical argumentation showed a comparatively smaller gain, consistent with qualitative evidence indicating that students required more sustained scaffolding to transform collaborative reasoning into formally structured mathematical justification. This convergence strengthens the interpretation that the superior performance of Exp. 1 was not attributable solely to exposure to STEAM activities, but to the specific learning mechanisms embedded in the Aquaponics-Based PjBL-STEAM environment. In this sense, the qualitative findings function as explanatory evidence for the quantitative differences rather than as supplementary descriptions of students' learning experiences.

The ANCOVA results further confirmed that the type of instructional intervention significantly affected both outcome variables after controlling for pretest scores. Significant effects were found for function graph literacy, $F(2,122) = 18.74, p < .001$, partial $\eta^2 = .235$, and mathematical critical thinking, $F(2,122) = 21.63, p < .001$, partial $\eta^2 = .262$. The effect sizes indicate a strong practical impact of the intervention. Furthermore, Bonferroni post-hoc analyses revealed that the Aquaponics-Based PjBL-STEAM group significantly outperformed both comparison groups on both variables ($p < .001$). These findings demonstrate that embedding sustainability-oriented aquaponics projects within a PjBL-STEAM framework contributed substantially to the development of students' graph literacy and mathematical critical thinking abilities (see Table 5).

Table 5. Indicator-Level ANCOVA Results for Function Graph Literacy and MCT

Variable	Indicator	Mean			F(2,122); (η^2)	Cohen's d
		Exp. 1	Exp. 2	C		
FGL	Reading graph information	84.12	75.08	63.51	15.63 (0.204)	0.81–1.37
	Graph interpretation	85.37	73.84	60.92	22.74 (0.271)	0.95–1.62
	Representation transformation	87.41	74.21	58.63	29.11 (0.323)	1.08–1.84
	Analysis of variable relationships	82.96	72.53	59.84	24.68 (0.288)	0.99–1.71
	Contextual graph-based problem solving	86.25	72.11	57.96	31.42 (0.340)	1.14–1.93
MCT	Interpretation	80.94	71.63	60.11	18.47 (0.232)	0.86–1.49
	Analysis	82.37	71.02	58.74	23.15 (0.276)	0.97–1.68
	Evaluation	81.85	70.48	57.82	24.91 (0.291)	1.01–1.74

Variable	Indicator	Mean			F(2,122); (η^2)	Cohen's d
		Exp. 1	Exp. 2	C		
	Inference	84.26	70.91	56.93	32.76 (0.349)	1.17–1.96
	Mathematical argumentation	83.74	69.88	55.47	34.12 (0.361)	1.21–2.03

Note: Exp 1 = Aquaponics-Based PjBL-STEAM; E2 = STEAM with scientific approach; C = direct instruction. ***p < .001; **p < .01. E1>E2***; E1>C***; E2>C***

Qualitative Mechanisms Underlying the Quantitative Differences. The qualitative findings provide convergent evidence for how the Aquaponics-Based PjBL-STEAM intervention generated the higher gains observed in function graph literacy and mathematical critical thinking. Rather than treating the qualitative themes as independent descriptions of students' experiences, the analysis was used to trace the learning processes through which the intervention translated authentic aquaponics experiences into measurable mathematical outcomes. Across classroom observations, student work, learning logs, and interview data, four interconnected mechanisms were identified: (1) authentic data engagement, (2) iterative coordination of multiple representations, (3) collaborative evidence-based reasoning, and (4) contextualized mathematical modelling and reflection. These mechanisms were substantially more visible in Exp. 1 than in Exp. 2 and the control group, providing a process-level explanation for the observed differences in post-intervention performance. Students in Exp. 1 repeatedly used real-time aquaponics data to identify changes across variables, construct graphs, and compare alternative representations. This process was particularly evident during activities requiring students to transform sensor-generated data into graphical and algebraic representations. The prominence of this process corresponds with the highest N-gain observed for representation transformation (0.74) and the significantly higher adjusted mean for Exp. 1 (87.41) than Exp. 2 (74.21) and the control group (58.63). Thus, the qualitative evidence provides a process-level explanation for the quantitative advantage of Exp. 1 in representational transformation.

Discussions

Development of Function Graph Literacy and Mathematical Critical Thinking through Aquaponics-Based PjBL-STEAM

The qualitative findings indicate that students' function graph literacy developed through sustained engagement in data collection, interpretation, and mathematical modelling within the aquaponics project, rather than through mere exposure to graphical representations. At the initial stage of the intervention, most students demonstrated predominantly procedural understanding, interpreting graphs as static visual objects rather than dynamic representations of quantitative relationships between variables (Antonini & Lisarelli, 2021; Qetrani & Achtaich, 2022). Only 11 of 43 students (25.6%) were able to articulate the mathematical relationship between observation time and plant growth, whereas the majority limited their

responses to superficial descriptions of graphical patterns without linking them to quantitative variation. This pattern reflects weak functional reasoning and underdeveloped covariational understanding (Rolfes et al., 2022; Sproesser et al., 2022). Such difficulties are consistent with prior studies showing that students tend to rely on surface-level interpretations of graphs when instruction is dominated by isolated symbolic procedures rather than contextualized, data-driven modelling activities (Borji et al., 2021; Ruf et al., 2024). Research on graph literacy further confirms that students often struggle to interpret variation, trends, and inter-variable relationships due to limited opportunities for iterative representation transformation and evidence-based reasoning (Chang et al., 2024; Jungjohann et al., 2022; Rosenblum et al., 2021).

Within the aquaponics learning environment, students were continuously engaged in interpreting fluctuations in pH, temperature, plant growth, and fish development. This sustained exposure required them to repeatedly analyze patterns, compare variables, and construct mathematical explanations grounded in empirical evidence. Such processes strengthened their conceptual understanding and supported the development of contextual mathematical modelling skills (Kohen & Orenstein, 2021; Kohen & Nitzan-Tamar, 2022; Suh et al., 2021). These findings align with prior research demonstrating that project-based STEM and STEAM learning fosters deeper conceptual understanding through authentic inquiry, multidimensional data interpretation, and evidence-based collaborative reasoning (Chen & Yang, 2021; Diego-Mantecon et al., 2021; Roehrig et al., 2021). The gradual shift from descriptive graph reading to analytical interpretation reflects the emergence of data-driven mathematical reasoning, in which graphs function not merely as visual artefacts but as tools for identifying trends, predicting change, and explaining relationships between variables (Chang et al., 2024; Ruamba et al., 2025; Ruf et al., 2024). Accordingly, the development of graph literacy in this study emerged through continuous interaction among empirical observation, contextual problem-solving, mathematical representation, and reflective interpretation within an authentic interdisciplinary learning environment (Junge et al., 2019; Garcia-Piqueras & Ruiz-Gallardo, 2021; Tarigan et al., 2021).

The comparatively lower performance of the STEAM with Scientific Approach group should therefore not be interpreted as evidence that scientific inquiry is inherently less effective for developing mathematical reasoning. Rather, the difference appears to result from the degree to which inquiry was coupled with sustained mathematical modelling and recursive representation use. Both groups engaged students in observation, experimentation, data collection, and interpretation; however, the Aquaponics-Based PjBL-STEAM intervention extended these processes into a continuous project architecture in which each round of data collection generated a new mathematical representation, each representation informed interpretation and prediction, and each prediction was subsequently evaluated against new empirical evidence. In the STEAM with Scientific Approach condition, inquiry was comparatively organized around discrete investigative episodes, meaning that students had fewer opportunities to carry forward previous representations and systematically revise mathematical models in response to longitudinal changes. Consequently, although both approaches promoted inquiry and evidence-based learning, only the Aquaponics-Based PjBL-

STEAM environment consistently positioned mathematical representations as mediating tools between successive inquiry cycles. This distinction is particularly important for function graph literacy because understanding functions requires students to coordinate how quantities change together over time, rather than merely identify patterns within a single dataset. The same distinction is relevant to mathematical critical thinking because evaluating a mathematical claim requires repeated comparison between predictions and evidence, followed by justification or revision when discrepancies emerge. Thus, the higher outcomes of the Aquaponics-Based PjBL-STEAM group are best explained by the recursive integration of inquiry, mathematical modelling, representation, and decision-making rather than by the presence of STEAM components alone.

Rather, the difference appears to reflect the distinct structure and continuity of learning opportunities provided by the two interventions. Although the scientific approach engaged students in observation, experimentation, data collection, and interpretation, these activities were comparatively less organised around sustained longitudinal modelling, iterative representation transformation, predictive reasoning, and evidence-based revision. Consequently, students had fewer opportunities to repeatedly connect empirical observations with mathematical representations and to use those representations to guide subsequent inquiry. In contrast, Aquaponics-Based PjBL-STEAM integrated these processes into a continuous project cycle in which data collection, mathematical modelling, graph construction, interpretation, prediction, evaluation, and decision-making were recursively connected. The superior performance of the PjBL-STEAM group therefore appears to arise from the continuity and epistemic integration of these processes rather than from the simple presence of STEAM or PjBL.

Consequently, the construction and transformation of mathematical representations from authentic data remain underdeveloped (Chen & Yang, 2021; Amin, 2021). In contrast, students in the Aquaponics-Based PjBL-STEAM group engaged in a complete inquiry cycle involving problem identification, project planning, continuous data collection, visualization, interpretation, collaborative reflection, and contextual decision-making. This comprehensive cycle facilitated a shift from procedural understanding toward more sophisticated conceptual, analytical, and representational reasoning (Kohen & Orenstein, 2021; Suh et al., 2021; Ruf et al., 2024). The superior performance of the Aquaponics-Based PjBL-STEAM group over the STEAM with Scientific Approach group can be explained not simply by the presence of STEAM integration, but by differences in the epistemic structure, temporal continuity, and degree of student agency embedded in the two learning environments. More specifically, the two interventions provided students with opportunities to engage in inquiry, but they differed substantially in how empirical data were generated, represented, interpreted, and subsequently used to inform further inquiry. In the STEAM with Scientific Approach condition, students primarily engaged in relatively discrete sequences of observation, experimentation, data collection, interpretation, and conclusion. These activities supported scientific inquiry and provided meaningful opportunities to interpret evidence; however, the mathematical representations generated from the data were not continuously reintroduced into subsequent

cycles of investigation. Consequently, students had fewer opportunities to repeatedly transform empirical observations into tables, graphs, equations, and predictive models and then evaluate those representations against newly emerging evidence. By contrast, the Aquaponics-Based PjBL-STEAM condition embedded these processes within a longitudinal project cycle in which students repeatedly collected authentic data from the same living system, constructed mathematical representations, interpreted changes across variables, generated predictions, evaluated discrepancies, and used the results to determine subsequent project decisions. Thus, the critical difference between the two interventions was not whether students engaged in inquiry, but whether inquiry was organized as a sustained mathematical modelling process in which each cycle of evidence generation became the basis for the next cycle of representation, evaluation, and decision-making.

This distinction provides a more direct explanation for the observed differences in function graph literacy and mathematical critical thinking. In the Aquaponics-Based PjBL-STEAM group, students were simultaneously positioned as data producers, mathematical model builders, interpreters, and decision-makers. Because the data were generated repeatedly by the students themselves, mathematical representations acquired an epistemic function: graphs and equations were used not only to display results but also to test assumptions, compare variable relationships, identify anomalies, predict subsequent conditions, and justify decisions. The qualitative evidence supports this interpretation. The high frequency of excerpts associated with data-driven mathematical reasoning (42 excerpts), construction of functional relationships (39 excerpts), coordination of multiple representations (37 excerpts), evidence-based graph interpretation (35 excerpts), and contextual problem solving (30 excerpts) indicates that these competencies developed as interconnected practices rather than as isolated skills. This pattern was also reflected in the project outcomes, where 83.7% of students actively used observational data to explain variable changes, 79.1% interpreted graph slope as a rate of change, 88.4% transformed empirical observations into tables, graphs, and equations, and 72.1% used these representations to make subsequent predictions. In contrast, the STEAM with Scientific Approach condition provided inquiry opportunities but comparatively fewer occasions for students to sustain this recursive sequence of data production–representation–interpretation–prediction–revision. Therefore, the advantage of Aquaponics-Based PjBL-STEAM is more plausibly attributed to the continuity and recursive integration of mathematical reasoning within the project cycle than to STEAM integration itself.

The aquaponics context further amplified this difference because it functioned as a continuously changing epistemic environment rather than as a one-time experimental setting. Variables such as plant growth, pH, temperature, and fish development evolved over time and were interdependent, requiring students to revisit previous interpretations when new data deviated from their initial expectations. This temporal dependency created repeated opportunities for covariational reasoning and model revision. For example, when students observed that changes in pH did not produce a proportional change in plant growth, they were required to reconsider their initial linear assumptions and reinterpret the relationship using subsequent observations. Such recursive engagement transformed mathematical

representations into tools for evaluating the adequacy of explanations rather than merely recording experimental results. The scientific approach, although capable of developing observation and evidence-based reasoning, did not provide the same degree of longitudinal continuity between one investigative cycle and the next. Accordingly, the observed superiority of Aquaponics-Based PjBL-STEAM should be interpreted as the consequence of a more tightly integrated epistemic learning architecture in which authentic data generation, mathematical modelling, representational transformation, critical evaluation, and contextual decision-making were repeatedly coordinated over time. Whereas the scientific approach primarily organised learning around discrete cycles of observation, experimentation, data interpretation, and conclusion, the Aquaponics-Based PjBL-STEAM intervention positioned students within a sustained modelling ecosystem in which empirical data were continuously generated, interpreted, represented, evaluated, and used to inform subsequent decisions. This distinction is theoretically important because function graph literacy and mathematical critical thinking require more than observing phenomena or conducting experiments; they require students to coordinate changes across variables over time, transform empirical observations into mathematical representations, evaluate the adequacy of those representations, and revise explanations in response to new evidence. The longitudinal nature of the aquaponics project therefore created repeated opportunities for students to develop covariational reasoning, functional thinking, representational coordination, and evidence-based argumentation. In contrast, the scientific approach provided opportunities for inquiry but did not necessarily establish the same continuity between data generation, mathematical modelling, representation transformation, prediction, and revision. Thus, the advantage of PjBL-STEAM appears to lie in the cumulative and recursive nature of its learning cycle rather than in the mere addition of project-based or STEAM components.

A second distinguishing mechanism concerns the role of students as producers and users of mathematical evidence. In the Aquaponics-Based PjBL-STEAM condition, students did not receive data solely as information to be interpreted; they generated data themselves through repeated measurements of plant growth, pH, temperature, and fish development and subsequently used these data to construct tables, graphs, equations, predictions, and context-based decisions. This epistemic ownership strengthened the connection between empirical evidence and mathematical representation. Students were consequently required to ask not only "What does the graph show?" but also "Why does this pattern occur?", "Does the representation adequately explain the observed phenomenon?", and "What decision can be justified from the evidence?". Such recursive questioning transforms graphical activity from descriptive reading into mathematical sense-making and critical evaluation. The scientific approach, although inquiry-oriented, involved comparatively less sustained responsibility for constructing and revising mathematical models from continuously evolving data. The observed difference therefore suggests that the critical mechanism was not inquiry alone, but inquiry coupled with longitudinal data production, mathematical modelling, representational transformation, and evidence-based revision.

Furthermore, the aquaponics context may have amplified the effectiveness of PjBL-STEAM by providing an authentic system in which mathematical relationships were consequential rather than hypothetical. Changes in pH, temperature, plant growth, and fish development were interconnected and could not be fully understood through isolated observations. Students therefore had to coordinate multiple variables and reconcile mathematical representations with the behavior of a living system. This created productive cognitive tension when empirical patterns deviated from initial predictions, requiring students to reconsider assumptions and revise their models. Such iterative model evaluation provides a stronger mechanism for the development of mathematical critical thinking than procedural experimentation alone because students must simultaneously analyze evidence, evaluate competing explanations, infer relationships, and justify decisions. Accordingly, the higher outcomes observed in the Aquaponics-Based PjBL-STEAM group should be interpreted as the consequence of a more continuous and epistemically demanding learning architecture, in which authentic data, mathematical modelling, representation, collaboration, and reflective decision-making operate as an integrated cycle. Repeated engagement with authentic aquaponics data enabled students to connect empirical observations with mathematical abstraction through covariational reasoning, the formation of functional relationships, and the coordination of multiple representations, including tables, graphs, equations, and verbal explanations (Antonini & Lisarelli, 2021; Sproesser et al., 2022; Kop et al., 2021; Ruamba et al., 2025). In this context, graphs were no longer perceived as static visual outputs but as analytical instruments for explaining phenomena, validating predictions, and supporting evidence-based argumentation (Chang et al., 2024; Rolfes et al., 2022).

The effectiveness of this model is not solely attributable to the integration of STEAM disciplines, but more fundamentally to its epistemic learning structure, which positions students as active investigators within a meaningful, sustainability-oriented, and data-driven context (Roehrig et al., 2021; Bautista, 2021; Tarigan et al., 2021). The magnitude of the adjusted means and effect sizes indicates that the intervention is not only statistically significant but also pedagogically meaningful, as it engages students in collaborative inquiry, contextual problem-solving, evidence-based interpretation, and reflective reasoning that collectively foster higher-order thinking and conceptual understanding (Hattie, 2023; Bell, 2010; Guo et al., 2020; Chang et al., 2024). These findings reinforce the growing body of evidence that PjBL-STEM/STEAM environments grounded in authentic problem contexts can enhance critical thinking, mathematical reasoning, representational fluency, and problem-solving through active, collaborative, and contextually situated knowledge construction (Allanta & Puspita, 2021; Wilson et al., 2021; Widiyono & Ghufron, 2024; Sofiani & Abdullah, 2025).

Critical thinking should not be conceptualized as a static learning outcome, but rather as a gradual developmental process grounded in reflective, argumentative, and evidence-based thinking practices that emerge through sustained learning experiences, collaborative dialogue, and iterative problem-solving (Chen et al., 2024; Rapanta et al., 2021). However, the initial implementation of STEAM-based instruction often presents challenges, particularly in relation to instructional design complexity, interdisciplinary integration, technological mediation, and

the need for strongly anchored authentic contexts (Roehrig et al., 2021; Perignat & Katz-Bounincontro, 2019). In the present study, the use of authentic aquaponics-based data contexts strengthened students' ability to interpret quantitative information and graphical representations by enhancing cognitive engagement, conceptual relevance, and analytical reasoning (Çakıroğlu & Güler, 2021; Phadke et al., 2022; Garcia-Piqueras & Ruiz-Gallardo, 2021; Radermacher, 2021). Students directly processed empirical data on plant growth, water temperature, pH levels, and fish development, thereby transforming mathematical representations into analytical tools for understanding dynamic phenomena rather than abstract symbols. This process ultimately reinforced graph literacy through iterative cycles of construction, transformation, and interpretation of representations (Antonini & Lisarelli, 2021; Rolfes et al., 2022; Sproesser et al., 2022; Ruf et al., 2024).

Furthermore, the PjBL-STEAM cycle comprising planning, data collection, visualization, modelling, evaluation, and reflection provided a substantially deeper learning experience compared to conventional scientific approaches, which tend to be more procedural in nature. This aligns with robust evidence indicating that sustained PjBL yields stronger academic outcomes through contextualized, data-informed problem-solving processes (Bell, 2010; Kokotsaki et al., 2016; Guo et al., 2020; Chen & Yang, 2021; Helle et al., 2006). The effectiveness of the intervention can also be explained through the integration of contextual mathematical modelling and data-driven inquiry, which enabled students to construct functional relationships, interpret graphs, and generate mathematically justified arguments grounded in empirical evidence. These processes are closely aligned with the development of graph literacy, representational competence, and mathematical critical reasoning in STEM learning environments (Antonini & Lisarelli, 2021; Kohen & Orenstein, 2021; Kohen & Nitzan-Tamar, 2022; Rolfes et al., 2022; Sproesser et al., 2022; Ruamba et al., 2025; Ruf et al., 2024). Repeated engagement in representational transformation (tables, graphs, equations, and contextual interpretations) further strengthened representational coordination as a core component of advanced mathematical reasoning (Kop et al., 2021; Qetrani & Achtaich, 2022; van Dijke-Droogers et al., 2021), while data visualization activities supported students' abilities to identify patterns, interpret trends, and draw evidence-based conclusions (Chang et al., 2024; Jungjohann et al., 2022).

The sustainability context embedded in aquaponics further enhances students' engagement and interdisciplinary understanding by linking mathematics to authentic social and environmental issues (Junge et al., 2019; Greenfeld et al., 2022; Tallapragada et al., 2021; Zguir et al., 2021; Kopnina, 2020). Within this setting, the aquaponics system operates as an epistemic environment that generates meaningful quantitative relationships for mathematical analysis, while simultaneously requiring students to interpret, predict, and make decisions grounded in real-world constraints (Suh et al., 2021; Hartmann et al., 2021; Verschaffel et al., 2020). These findings align with meta-analytic evidence indicating that PjBL and STEAM approaches yield stronger learning outcomes when students are actively engaged in collaborative problem-solving, technology-enhanced inquiry, and iterative knowledge construction (Guo et al., 2020; Diana et al., 2021; Roehrig et al., 2021; Wilson et al., 2021; Chang et al., 2024). They also

reinforce the role of structured discourse and argumentation in fostering critical thinking (Kocak et al., 2021; Allanta & Puspita, 2021), as well as the importance of interactive technologies and data visualization tools in sustaining student engagement (Belland et al., 2017; Chiu, 2021; Santos-Trigo et al., 2021). From an Education 4.0 perspective, these results underscore the growing necessity of integrating data literacy, critical thinking, collaboration, and digital competence into contemporary mathematics education (González-Pérez & Ramírez-Montoya, 2022; OECD, 2021; UNESCO, 2023). Accordingly, mathematics instruction should move beyond procedural symbol manipulation toward contextualized, data-driven learning experiences that are authentic, interdisciplinary, and oriented toward sustainability-oriented problem solving.

Qualitative findings indicate that the development of students' function graph literacy cannot be attributed solely to exposure to graphical representations. Rather, it emerges primarily through sustained engagement in a data-driven investigative cycle embedded within the Aquaponics-Based PjBL-STEAM intervention. What develops is not merely the ability to read graphs, but the capacity to construct functional meaning from dynamically evolving empirical data. How this development occurs is through iterative cycles of data collection, modelling, interpretation, evaluation, and evidence-based revision conducted in an authentic learning environment. This pattern is consistent with research demonstrating that PjBL and STEAM approaches effectively foster higher-order thinking skills through authentic and collaborative contexts (Bell, 2010; Blumenfeld et al., 2021; Chen & Yang, 2021; Guo et al., 2020). At the initial stage of the intervention (when), most students demonstrated a predominantly procedural understanding of graphs. Graphs were interpreted as static visual objects rather than relational representations of variables changing over time. This aligns with prior findings showing that students frequently struggle to connect graphical representations with their underlying quantitative meaning (Ruf et al., 2024; Chang et al., 2024; Sproesser et al., 2022). Only 25.6% of students were able to mathematically relate temporal change to plant growth, whereas the majority relied on superficial descriptions such as "the graph is increasing," indicating limited representational and interpretive sophistication. This suggests that, in the absence of authentic modelling experiences, graph literacy tends to remain at a descriptive rather than analytical level (Antonini & Lisarelli, 2021; Kop et al., 2021).

A substantial shift occurred when students engaged in longitudinal data collection within the aquaponics system (where: learning context), involving real variables such as plant height, water pH, temperature, and fish growth. In this environment, students did not merely observe phenomena but actively constructed mathematical relationships among variables using empirical data. This process facilitated the emergence of data-driven mathematical reasoning, defined as the ability to use empirical evidence as a foundation for constructing and validating mathematical claims (Suh et al., 2021; van Dijke-Droogers et al., 2021). In addition, the PjBL-STEAM approach consistently supports the development of critical thinking skills through active engagement in inquiry-based problem solving (Allanta & Puspita, 2021; Amin, 2021; Sofiani & Abdullah, 2025). The improvement in function graph literacy occurred concurrently with the development of mathematical critical thinking through an iterative interpret–evaluate–

revise cycle. Students began to critically examine data consistency, identify anomalies, and revise initial predictions based on emerging evidence. For instance, when plant growth patterns no longer exhibited linear relationships with changes in pH, students recognized a mismatch between their initial assumptions and observed data. This reflects the emergence of epistemic cognition, namely the ability to evaluate the validity of representations and refine models based on evidence (Borji et al., 2021; Hartmann et al., 2021). Within a PjBL framework, such evidence-based revision constitutes a key indicator of reflective and argumentative thinking development (Belland et al., 2017; Hattie, 2023).

The development of graph literacy in this study is not linear but progressively constructed through the reinforcement of interconnected mathematical representations. The dominant theme, *data-driven mathematical reasoning* (42 excerpts), indicates that students consistently relied on empirical data as the basis for mathematical inference. This was followed by *construction of functional relationships* (39 excerpts), suggesting that students gradually moved beyond descriptive interpretations toward relational understanding of variables in functional terms. This finding supports the view that mathematical modelling in authentic contexts facilitates a shift from procedural to relational thinking (Kohen & Orenstein, 2021; Qetrani & Achtaich, 2022). The emergence of *coordination of multiple representations* (37 excerpts) further demonstrates students' ability to translate across representational forms, including tables, graphs, equations, and verbal explanations. This translational competence is central to functional understanding (Rolfes, 2021; Kop et al., 2021). Its importance lies in the fact that graph literacy is not merely the ability to read or interpret a single representation, but also the capacity to flexibly integrate multiple representations into a coherent conceptual structure (Rosenblum et al., 2021; Ruamba et al., 2025). Furthermore, *evidence-based graph interpretation* (35 excerpts) reflects students improved inferential reasoning in explaining and predicting patterns based on empirical data, which is a key indicator of advanced statistical and graphical literacy (Çakıroğlu & Güler, 2021; Phadke et al., 2022). Finally, *contextual problem solving* (30 excerpts) confirms students' growing ability to transfer mathematical knowledge to dynamic real-world situations, consistent with the literature on mathematical modelling and authentic problem-solving (Verschaffel et al., 2020; Kohen et al., 2021).

The development of function graph literacy in this study can be explained through the interaction of three interdependent mechanisms: (1) the authentic aquaponics context, (2) the data-driven PjBL-STEAM learning cycle, and (3) structured scaffolding in mathematical modelling. The aquaponics system functioned not merely as a thematic context but as an epistemic environment continuously generating empirical data for analysis. This condition enabled sustained mathematical inquiry grounded in real measurements, thereby supporting meaningful knowledge construction (Greenfeld et al., 2022; Wang et al., 2023; Yep & Zheng, 2019). These findings reinforce prior evidence that project-based STEAM learning integrated with authentic data significantly enhances students' graph literacy, representational competence, and critical thinking skills (Diego-Mantecon et al., 2021; Bautista, 2021; Wilson et al., 2021). The development of mathematical critical thinking was strongly reflected in students' data-driven mathematical argumentation during project-based decision-making.

Rather than relying on intuition, students increasingly constructed claims grounded in empirical evidence derived from graphs, tables, numerical trends, and comparative pattern analysis (Bell, 2010; Chen & Yang, 2021; Wilson et al., 2021). Within the Aquaponics-Based PjBL-STEAM environment, students consistently developed reasoning based on observed data to determine optimal environmental conditions for plant growth, indicating a clear shift from procedural execution toward evaluative and reflective thinking (Allanta & Puspita, 2021; Sofiani & Abdullah, 2025).

In this process, mathematical representations functioned as epistemic tools rather than mere visual outputs, enabling students to evaluate evidence, construct inferences, and justify context-based decisions (Antonini & Lisarelli, 2021; Rolfes et al., 2022). The aquaponics environment, which generated continuous and dynamic data, further strengthened this process through sustained observation of interacting variables such as pH, plant growth, and fish development, requiring iterative interpretation and validation. In contrast to the scientific approach group, which was limited to short-term observation and discrete experimentation, the PjBL-STEAM group engaged in continuous inquiry involving iterative data interpretation, predictive testing, and evidence-based meaning negotiation (Guo et al., 2020; Helle et al., 2006; Chen & Yang, 2021). This mechanism was further supported by scaffolding strategies in STEM learning, which gradually enhanced the alignment between evidence and reasoning processes (Belland et al., 2017). This epistemic shift from procedural computation to evidence-based reasoning indicates that students increasingly used mathematics as a tool for justification and decision-making rather than mere calculation (Kocak et al., 2021; Rapanta et al., 2021; Verschaffel et al., 2020). Moreover, graphs were reconceptualized as dynamic analytical tools for testing assumptions, examining variability, and generating predictions through iterative representation changes (Kop et al., 2021; Sproesser et al., 2022; Rolfes et al., 2021). This development aligns with core dimensions of critical thinking, including analysis, evaluation, inference, argumentation, and decision-making (Hattie, 2023). Overall, the findings extend previous evidence that PjBL-STEAM fosters critical thinking through authentic problem-solving and collaborative reasoning processes (Amin, 2021; Allanta & Puspita, 2021; Wilson et al., 2021). In addition, sustained engagement with empirical data in the aquaponics system created an epistemic learning environment that deepened evaluative reasoning and strengthened the connection between mathematical models and real-world variability (Kohen & Nitzan-Tamar, 2022; Suh et al., 2021; van Dijke-Droogers et al., 2021). Consequently, Aquaponics-Based PjBL-STEAM can be understood as an epistemic learning ecosystem that reconstructs how students generate, validate, and apply mathematical knowledge in a more evidence-based, flexible, and contextually grounded manner.

Classroom observation data indicated that 36 students (83.7%) actively used observational data to explain growth patterns and variable changes during group discussions. Analysis of project artifacts further revealed substantial improvement in graph interpretation skills. At the beginning of the intervention, most students interpreted graph slopes merely as visual features. However, by the end of the project, 34 students (79.1%) were able to interpret slope as a rate of change and apply this understanding to compare plant growth under different

environmental conditions. One student reflected: *"At first, I only connected points on the graph. After collecting weekly data, I realized that a steeper line means faster plant growth because height increases more within the same time period."* Another student explained: *"When pH values changed, the growth graph also changed. From the graph, I could estimate which condition was most suitable for plant growth."* These responses indicate that students no longer perceived graphs as static visual representations, but as analytical tools capable of expressing causal relationships between variables based on empirical evidence. Repeated interaction with authentic data appeared to strengthen students' covariational reasoning, enabling them to understand how changes in one variable systematically influence another over time.

Additional evidence of conceptual development was observed in students' ability to transform mathematical representations. Analysis of final project reports showed that 38 students (88.4%) consistently converted observational data into tables, graphs, and simple equations. Furthermore, 31 students (72.1%) successfully used these representations to predict plant growth in subsequent observation periods. Figure 8 presents an example of a student-generated function graph constructed from six weeks of aquaponics growth data.

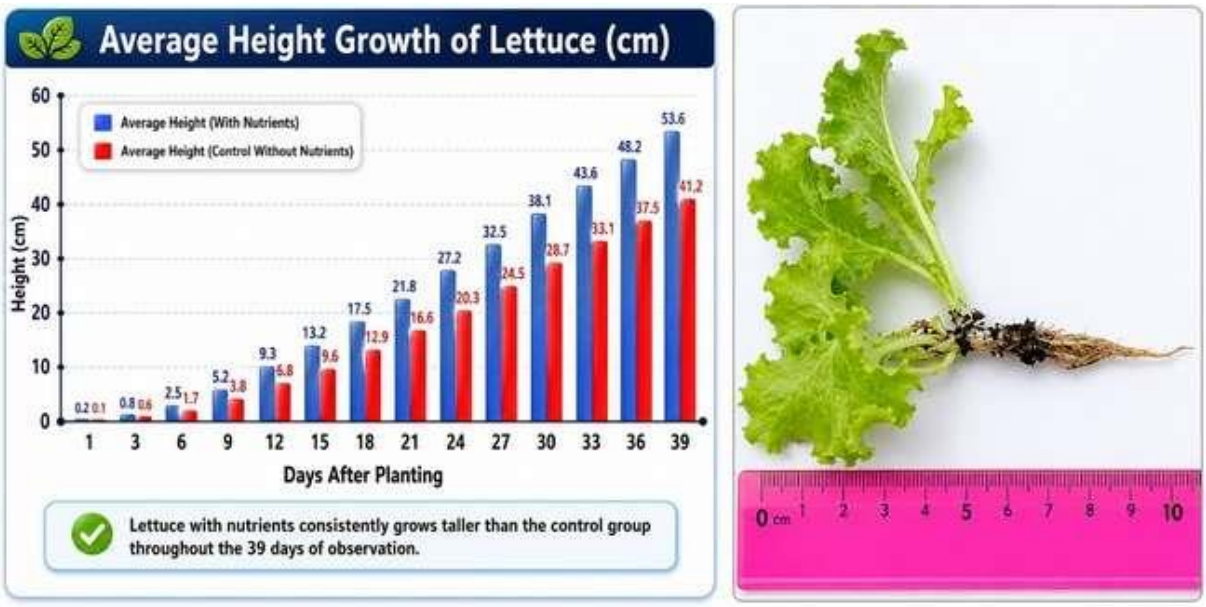


Figure 8. Student-Constructed Function Graph Based on Aquaponics Data

The graph not only displays observational results but also incorporates trend identification, interpretation of growth rate, and prediction of future values based on observed functional patterns. This transformation reflects a shift from procedural manipulation of graphs toward a more conceptual and relational understanding of mathematical representations.

The superior performance of the Aquaponics-Based PjBL-STEAM group can be explained through the distinctive epistemic and pedagogical structure of its learning environment illustrated in Figure 9. In contrast to conventional instruction, which typically separates procedural practice from contextual meaning-making, this intervention situates students within an authentic, data-rich ecosystem where mathematical concepts emerge directly from lived empirical phenomena. This design aligns with prior research demonstrating that

PjBL integrated with STEAM fosters deeper conceptual understanding and improved mathematical performance when grounded in real-world contexts (Amin, 2021; Chen & Yang, 2021; Guo et al., 2020; Diana et al., 2021). Function graph literacy developed primarily through sustained engagement in collecting, processing, and analyzing authentic aquaponics data. These activities operationalized data-driven mathematical reasoning, defined as the capacity to interpret empirical evidence as the basis for mathematical reasoning, modelling, and decision-making. This process is consistent with previous findings indicating that STEM- and PjBL-based environments enhance higher-order reasoning by embedding mathematical activity in meaningful, data-oriented tasks (Bell, 2010; Helle et al., 2006; Suh et al., 2021). In this study, students were continuously exposed to dynamic variables such as plant height, pH levels, water temperature, and fish growth, requiring them to interpret interdependent changes over time rather than static numerical values.



Figure 9. STEAM Project on Aquaponics

Evidence-based graph interpretation emerged as a key competency enabling students to explain trends, generate predictions, and construct data-supported justifications. This finding is consistent with research showing that statistical and graphical literacy improves significantly when students engage in authentic and contextualized data interpretation tasks (Çakıroğlu & Güler, 2021; Phadke et al., 2022; Radermacher, 2021). Consequently, graphs were no longer perceived as static visual representations, but rather as analytical tools for understanding change, uncertainty, and prediction. Overall, the effectiveness of the Aquaponics-Based PjBL-STEAM intervention lies in the integration of four interdependent mechanisms: (1) the generation of authentic data through a living ecological system, (2) iterative modelling and representational transformation, (3) collaborative interpretation and reasoning, and (4) contextual, evidence-based decision-making. This integration reflects the Education 4.0 framework, which emphasizes data literacy, computational reasoning, and interdisciplinary problem-solving as core twenty-first-century competencies (González-Pérez & Ramírez-Montoya, 2022; UNESCO, 2023; OECD, 2021).

Importantly, these characteristics were largely absent in the direct instruction group and only partially observed in the STEAM with scientific approach group. Although the scientific approach involved observation and experimentation, students were not sufficiently engaged in longitudinal data modelling, iterative representational transformation, or predictive reasoning in authentic contexts. This limitation aligns with prior studies suggesting that fragmented inquiry experiences are insufficient to develop deep representational competence and modelling literacy (Borji et al., 2021; Antonini & Lisarelli, 2021). From a pedagogical perspective, the effectiveness of Aquaponics-Based PjBL-STEAM can be attributed to a complete mathematical modelling cycle in which students simultaneously acted as data producers, interpreters, and model builders. In terms of who, students worked in collaborative groups; in what, they collected data on plant growth, pH, temperature, and environmental variables; in where and when, data were continuously gathered within a living aquaponics system functioning as an extended laboratory; in why, students connected variable changes to functional relationships and rates of change; and in how, data were transformed into tables, graphs, and mathematical models for analysis and prediction.

This cyclical structure created a cognitive space that facilitated the transition from procedural knowledge to conceptual understanding (Borji et al., 2021; Qetrani & Achtaich, 2022). More specifically, the superior outcomes of the experimental group, compared to both the scientific approach and direct instruction groups, indicate that it is not merely STEAM integration that drives learning gains, but rather the intensity and continuity of engagement in authentic inquiry. This interpretation is consistent with Kohen and Orenstein (2021), Suh et al. (2021), and van Dijke-Droogers et al. (2021), who emphasize the centrality of sustained modelling experiences in developing mathematical understanding. Within this context, the aquaponics system functioned as a living laboratory that continuously generated dynamic data for modelling, thereby strengthening the relevance of STEM learning within sustainability-oriented contexts (Garcia-Piqueras & Ruiz-Gallardo, 2021; Sasaki & Sawada, 2026; Tallapragada et al., 2021; Junge et al., 2019). Nevertheless, several limitations warrant cautious interpretation of the findings. First, the study was conducted in a single school involving three classes and 126 students. Although the sample size provides sufficient observations for the present comparative analysis, the single-school setting limits the external validity of the findings because school-level characteristics, teacher expertise, classroom culture, technological infrastructure, and students' prior familiarity with project-based and technology-enhanced learning may have influenced the observed outcomes. Therefore, the superiority of Aquaponics-Based PjBL-STEAM should not yet be interpreted as universally generalizable across schools, regions, or student populations. Multi-site studies involving diverse schools, teachers, socioeconomic contexts, and levels of technological readiness are needed to examine the robustness and contextual dependency of the intervention effects.

Second, the intervention was implemented over a relatively limited period, restricting the extent to which the study can establish whether improvements in function graph literacy and mathematical critical thinking are sustained over time. Longitudinal follow-up studies are therefore necessary to determine whether the observed conceptual and representational gains

persist after the project ends and whether students can transfer these competencies to unfamiliar mathematical and real-world contexts. Third, the study focused primarily on function graph literacy, leaving open the question of whether the same learning mechanism would be equally effective for other mathematical domains, such as statistics, algebraic modelling, geometry, or calculus-related concepts. Fourth, because the intervention simultaneously incorporated authentic aquaponics contexts, PjBL, STEAM integration, IoT-supported data collection, collaborative learning, and mathematical modelling, the present design cannot isolate the independent contribution of each component. The observed effects should therefore be attributed to the integrated learning architecture rather than to any single component in isolation. Future research should employ factorial, mediation, or multilevel designs to disentangle these mechanisms and examine whether longitudinal data engagement, mathematical modelling, student agency, or representational transformation serves as the primary mediator of learning outcomes. Such research would provide stronger causal evidence regarding why and under what conditions Aquaponics-Based PjBL-STEAM produces superior mathematical learning outcomes.

Conclusion

Students' initially low levels of function graph literacy and mathematical critical thinking underscore the need for mathematics instruction that moves beyond procedural manipulation toward authentic, data-informed reasoning. This study examined an Aquaponics-Based PjBL-STEAM intervention in which students engaged with authentic aquaponics data through measurement, graph construction, mathematical modelling, interpretation, and evidence-based decision-making. Quantitative results showed that the intervention group achieved greater improvements than both STEAM with a scientific approach and direct instruction, with N-Gain values of 0.69 for function graph literacy and 0.67 for mathematical critical thinking. These results provide empirical support for the potential of embedding mathematics learning within an authentic sustainability context to develop students' capacity to interpret, represent, and reason with quantitative information.

The qualitative findings further illuminate the learning processes associated with these outcomes. Students repeatedly moved among empirical data, graphical representations, mathematical models, and contextual interpretations as they identified patterns, established functional relationships, interpreted graphs, and justified decisions using evidence. This iterative coordination of representations suggests that the intervention created opportunities for students to develop mathematical understanding through engagement with dynamic phenomena rather than through isolated manipulation of mathematical procedures. However, these qualitative findings should be understood as process evidence that contextualizes the quantitative results, not as evidence of causal mechanisms. Thus, the study does not establish the independent causal contributions of PjBL, STEAM integration, or IoT-supported data collection to the observed gains.

Theoretically, the study contributes to PjBL, STEAM, and mathematical modelling research by illustrating how an authentic, data-rich sustainability context can connect

mathematical concepts with dynamic real-world phenomena. The aquaponics environment positions empirical data as an epistemic resource for constructing functional relationships, coordinating representations, developing mathematical models, and evaluating interpretations. Practically, the aquaponics system can serve as a "living laboratory" that supports inquiry-oriented mathematics learning and provides opportunities to integrate mathematical modelling, data literacy, graph interpretation, and evidence-based reasoning within meaningful contexts.

These findings should nevertheless be interpreted within the study's contextual boundaries. The research involved 126 students from a single school and was conducted over a relatively short intervention period, limiting generalizability across schools, populations, curricula, and sustainability contexts. Future research should therefore employ multisite and longitudinal designs with larger and more diverse samples to examine the stability and transferability of the observed outcomes. Experimental or factorial designs could further disentangle the contributions of PjBL, STEAM integration, and IoT-supported data collection, while mediation analysis or structural equation modelling could examine whether authentic-data engagement, representation coordination, mathematical modelling, and evidence-based reasoning statistically mediate instructional effects. Overall, Aquaponics-Based PjBL-STEAM shows promise for shifting mathematics learning from predominantly procedural execution toward more authentic, contextualized, and data-driven mathematical reasoning, while further research is required to establish causal mechanisms and broader applicability.

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Conflicts of Interest

The authors declare no conflicts of interest and confirm that this manuscript is original, free from plagiarism, and not involved in any form of data fabrication, falsification, duplicate submission, or redundant publication.

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