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PREFACE

Welcome to the Southeast Asian Journal of STEM Education (SAJSE), a prominent online platform established by SEAMEO STEM-ED, dedicated to the advancement of STEM education in Southeast Asia. As an open-access publication, SAJSE is an invaluable repository for insights, ideas, and innovations that define the future of STEM education in the region.

At SEAMEO STEM-ED, we believe in the power of collaboration and knowledge exchange to advance STEM education. The articles in SAJSE reflect this belief, offering a wealth of quality knowledge that transcends regional boundaries. Our dedication to openness is demonstrated by our usage of Creative Commons licencing, which allows for the free use, distribution, and replication of our published content with due credit.

We are excited to announce that we are opening up opportunities for teachers and students to share their voices and reflections from the classroom. Teachers are invited to share their innovative practices, challenges, and insights in teaching STEM subjects, providing valuable perspectives that can benefit educators across Southeast Asia. Similarly, students are encouraged to share their experiences and reflections on STEM science projects, highlighting the impact of hands-on learning experiences on their education and personal development.

This initiative aims to echo the voices of teachers and students, providing a platform for them to share their unique perspectives and contribute to the broader conversation on STEM education in Southeast Asia. By amplifying these voices, we hope to inspire others and drive positive change in STEM education practices and policies.

Authors who submit their papers to SAJSE will benefit from the journal's rigorous peer-review process, ensuring the quality and integrity of published articles. Additionally, published papers will be freely accessible to educators, researchers, and policymakers, facilitating the dissemination of innovative practices and ideas in STEM education.

We invite educators, researchers, and innovators from across Southeast Asia to join us in this quest to elevate STEM education. Together, let us construct a cooperative and inclusive learning ecosystem that equips the future generation of innovators and solution seekers, propelling Southeast Asia towards a future characterised by innovation and excellence.

Thank you for being a part of this journey.

Warm regards,

SEAMEO STEM-ED

EDITORIAL

Welcome to SAJSE, the leading platform for advancing STEM education and encouraging innovation in Southeast Asia. Our journal exemplifies the spirit of collaboration, creativity, and capacity building. We are dedicated to making STEM education accessible to all, while also offering chances for educators and students to share their research, teaching techniques, and new ideas. This open-access journal serves as a beacon for researchers, educators, policymakers, and students seeking excellence in STEM education.

A Platform for Diverse Voices

The Southeast Asian Journal on STEM Education transcends its role as a mere repository of information, establishing itself as a vibrant forum that embraces a plurality of perspectives. This journal curates a comprehensive array of contributions, encompassing seminal research articles from seasoned scholars, innovative pedagogical methodologies from educators, and introspective analyses on integrated STEM disciplines authored by students. It operates as a platform that acknowledges and values the diverse viewpoints of all constituents within the educational sphere, thereby facilitating a collective ethos of learning and developmental synergy.

Bridging Policy and Practice

A distinctive feature of this journal is its specialised policy section, designed to stimulate dialogue on the development and enactment of educational policies, with a particular emphasis on STEM disciplines. This section covers a broad spectrum, from theoretical propositions to empirical research and the exchange of best practices. The journal aims to contribute to and impact policy-making processes that determine the trajectory of educational advancement. It represents an effort to reconcile policy with practice, guaranteeing that educational innovations are firmly anchored in the practical landscape and meet the requirements of learners.

Global Perspectives with a Local Focus

Although the journal invites submissions from educators, policymakers, teachers, and students globally, it prioritises local implementations, research, or practices from Southeast Asian countries. This emphasis underscores a dedication to tackling the distinct challenges and seizing the opportunities present in the region, advocating for solutions that are informed by global perspectives yet tailored to local contexts.

A Call to Action

We warmly invite all stakeholders, particularly teachers and students, to contribute to the Southeast Asian Journal on STEM Education. Your contributions to research, practices, and reflections do more than enrich our collective knowledge; they play an active role in sculpting

a future where STEM education is universally accessible, inclusive, and profoundly influential. This journal stands as a testament to the strength of collaborative effort, reinforcing the notion that every contribution, regardless of its size, is instrumental in unlocking the vast potential of STEM.

The Southeast Asian Journal on STEM Education serves as a beacon, illuminating the path toward a more enlightened future via the progression of STEM education. It summons all who are dedicated to nurturing scientific thought and leveraging scientific inquiry to elevate the quality of teaching and learning. United in purpose, let us venture forth on this path of exploration and innovation, laying the foundations for future generations to build upon.

Best regards,

SAJSE Editors

POLICY

SECTION

STRUCTURING DIGITAL AND AI-ENABLED STEM REFORM IN VOCATIONAL COLLEGES: A MULTI-LAYER INSTITUTIONAL FRAMEWORK WITH APPLICATION TO SLIM RIVER VOCATIONAL COLLEGE

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ABSTRACT

Malaysia's vocational colleges face increasing pressure to produce digitally fluent, STEM-capable graduates able to operate in artificial intelligence (AI)-augmented and Fourth Industrial Revolution (4IR) workplaces, yet STEM implementation across vocational programmes remains uneven. Despite strong national policy commitments to digitalisation and AI, colleges continue to encounter structural barriers including fragmented curricula, uneven digital infrastructure, and variable teacher digital competence. This study adopts a conceptual and policy-oriented methodology, synthesising contemporary literature on AI-enabled STEM education, TVET transformation, and digital governance alongside analysis of national policy documents and institutional insights from Slim River Vocational College (SRVC). Based on this synthesis, the paper proposes a five-layer institutional framework for digital and AI-driven STEM integration, centred on learner STEM competencies and comprising pedagogical and curriculum innovation, teacher professional development, digital infrastructure, industry and certification alignment, and governance. Application of the framework to SRVC demonstrates its diagnostic and planning value by revealing operational strengths, systemic gaps, and sequencing priorities across programmes with differing levels of digital readiness. The findings indicate that sustainable digital and AI-enabled STEM transformation depends on coordinated alignment across institutional layers rather than isolated technology adoption. The paper concludes that Malaysia's TVET reform agenda requires unified national AI and STEM competency standards, predictable infrastructure financing, structured teacher digital competence pathways, and strengthened industry partnerships to enable coherent, scalable, and equitable system-wide transformation.

Keywords: STEM Education, TVET, Digitalisation, Artificial Intelligence, Vocational Colleges, Malaysia

1. Introduction

STEM education and technical and vocational education and training (TVET) have become central pillars of national development strategies across Southeast Asia. As countries shift toward technology-intensive production and digital service ecosystems, vocational institutions are expected to cultivate advanced digital, analytical, and problem-solving competencies (UNESCO-UNEVOC, 2024). Malaysia mirrors this trend through initiatives such as the Shared Prosperity Vision 2030, the Malaysia Digital Economy Blueprint, and the National Fourth Industrial Revolution (4IR) Policy, all of which emphasise digitalisation, automation, and artificial intelligence (AI) as drivers of economic competitiveness. These national ambitions

place substantial demands on vocational colleges to modernise pedagogical models, infrastructure, and curricula.

Despite ongoing multi-ministry TVET reforms coordinated by the National TVET Council, the integration of digital and AI-enhanced STEM practices remains uneven. Studies highlight persistent challenges, including fragmented curricula, inconsistent exposure to emerging technologies, and limited teacher readiness to design STEM-rich, digitally mediated learning experiences (Liew and Teoh, 2022; Yunos, 2023; Paryono and Mashod, 2024). At the same time, employers increasingly expect graduates to navigate AI-supported diagnostics, IoT-enabled systems, data-driven maintenance processes, and human–machine collaboration, expectations not yet embedded systematically across vocational programmes. Beyond institutional reform, these shifts reshape the very architecture of STEM learning, situating this work squarely within the core concerns of contemporary STEM education research.

Digitalisation and IR 4.0 agendas have expanded STEM education beyond traditional science and engineering domains toward interdisciplinary, simulation-based, and AI-enabled learning (Holmes et al., 2019 Luckin, 2018). However, without coherent institutional mechanisms, AI integration risks deepening disparities between well-resourced and underserved colleges. Structural constraints such as outdated equipment, limited connectivity, and insufficient digital laboratories continue to restrict Malaysia's vocational institutions (Azman et al., 2025), while teacher digital competence varies widely, particularly in trade-oriented programmes where long-standing practical routines dominate.

To clarify how these challenges are conceptualised in this study, Technology refers to the use of digital infrastructure, artificial intelligence tools, simulation platforms, and data systems that support vocational learning, while Engineering is conceptualised as applied design, diagnostics, optimisation, and problem-solving practices embedded within vocational trades such as welding, automotive, and electrical technologies. The proposed framework explicitly integrates these two dimensions within institutional pedagogy, curriculum, and governance rather than treating them as standalone components.

Viewed through this Technology and Engineering lens, curriculum architecture reinforces these constraints. Programmes in welding, automotive, electrical, and business often operate in silos, reducing opportunities for interdisciplinary STEM learning and limiting students' engagement with authentic industrial problem contexts. This fragmentation restricts the development of higher-order cognitive and digital capabilities needed for IR 4.0 workplaces and underscores the need for systemic frameworks that align infrastructure, pedagogy, teacher learning, industry engagement, and governance (Yang and Wu, 2024). These challenges point toward the value of sociotechnical and ecosystemic perspectives that conceptualise vocational colleges as interconnected systems. This paper therefore adopts a multi-layer conceptual stance centred on learner STEM competencies and operationalised through five interdependent institutional layers: pedagogical and curriculum innovation, teacher professional development, digital infrastructure, industry alignment, and governance.

A conceptual framework is urgently needed to clarify what digital and AI-enabled STEM integration entails, how institutional layers interact, and which policy levers support sustainable implementation. In rapidly evolving domains such as AI-in-TVET, theoretically grounded models are essential for guiding planning and institutional decision-making. Slim River Vocational College (SRVC) is used as an illustrative anchor case to the framework. Its programme diversity, heterogeneous digital readiness, and evolving industry partnerships typify the broader Malaysian vocational ecosystem and offer an applied context through which to examine institutional implementation challenges.

The purpose of this paper is threefold: to synthesise current literature on digital and AI-driven STEM and TVET transformation; to propose a five-layer institutional framework anchored in

learner STEM competencies; and to apply this framework to SRVC to generate policy insights for Malaysia's national TVET transformation agenda. The core contribution is a theoretically grounded model that links national digital and AI aspirations to concrete pedagogical, organisational, and governance decisions within vocational colleges. The paper is structured as follows: Section 2 reviews global and regional literature on STEM, TVET, digitalisation, and AI in education; Section 3 outlines the methodological orientation; Section 4 presents the proposed framework; Section 5 applies the framework to SRVC; Section 6 discusses policy implications; and Section 7 concludes with future directions.

2. Literature Review

2.1 Digital and AI-Driven STEM Education

Recent scholarship documents rapid advances in artificial intelligence (AI) and digital technologies in STEM learning, particularly through intelligent tutoring systems, adaptive analytics, automated feedback, and generative AI–supported inquiry. Reviews consistently show that AI tools can enhance personalisation and higher-order reasoning, while raising concerns about ethics, data governance, and institutional readiness (Xu and Ouyang, 2022; Akhmetova et al., 2025; Chng et al., 2023). Intelligent tutoring and AI-driven feedback systems demonstrate measurable learning gains when embedded within coherent instructional design (Villegas-Ch et al., 2025; Li et al., 2025).

Parallel work on learning analytics highlights their value for curriculum refinement and early detection of learners requiring support; however, institutional capacity to interpret and act on data remains uneven in resource-constrained settings (Ahmad et al., 2024; Wang et al., 2024). Digital tools such as robotics, data-logging systems, and coding platforms further support computational thinking and interdisciplinary STEM engagement, although most studies assume stable infrastructure and teacher expertise, these conditions are not uniformly present in TVET. This underscores the need to examine how AI-supported STEM approaches can be adapted for trade-based, applied learning contexts.

2.2 VR/AR, Simulations, and Extended Reality in Vocational STEM

VR, AR, and extended reality (XR) systems have become increasingly prominent in skills-based vocational training. Evidence from welding demonstrates that immersive simulations improve weld consistency, safety, and psychomotor preparation, while lowering consumable costs and providing high-frequency practice with real-time feedback (Heibel et al., 2023; Ahmad et al., 2024; Wang et al., 2024). XR-enabled welding in the UAE also shows strong engagement benefits but highlights challenges in cost, teacher capability, and assessment integration (Alhajri, 2023). Beyond welding, AR overlays support troubleshooting and visualisation of complex phenomena such as electrical current flow and sensor behaviour, skills essential in automotive and electrical trades (Desai et al., 2022; Chng et al., 2023). Regional platforms stress that XR adoption requires coordinated curriculum redesign and teacher support, not one-off procurement or isolated pilots (ASEAN Secretariat, 2025).

2.3 STEM in TVET and Vocational Contexts

Across Southeast Asia, STEM is increasingly linked to TVET modernisation, driven by regional strategies emphasising smart manufacturing, digital economies, and cross-disciplinary workforce development (SEAMEO VOCTECH, 2022). UNESCO-UNEVOC similarly reports growing experimentation with blended and digital TVET, although institutional readiness varies widely. Empirical studies reveal persistent misalignment between vocational curricula and evolving industrial expectations. In Malaysia, IR 4.0 content remains unevenly embedded, with

digital topics frequently positioned as add-ons rather than cross-cutting competencies integrated with trade-specific learning (Rajamanickam et al., 2024). Comparable patterns across Southeast Asia indicate that innovations in VR welding, simulation, and automation remain local pilots rather than systemic practice (Heibel et al., 2023; Ahmad et al., 2024). This highlights the need for institutional frameworks that organise STEM integration coherently across programmes.

2.4 Teacher Readiness and Professional Development

Teacher readiness is consistently identified as a decisive factor in digital and AI-enabled STEM integration. Studies across Asia find that many TVET educators possess only moderate readiness for IR 4.0 tools, with gaps in both technical proficiency and digital pedagogical strategies suited for practice-oriented instruction (Paryono and Mashod, 2025). Reviews of TVET teacher digital competence emphasise that transformation requires institutional cultures, leadership support, and sustained professional learning communities rather than sporadic workshops (Zhong and Juwaheer, 2024).

Malaysian studies report uneven digital skills, limited exposure to VR or AI tools, and structural constraints such as heavy teaching loads and limited equipment (Ahmad et al., 2024; Wang et al., 2024). Promising interventions, such as digital platform initiatives at UTHM and UNESCO-UNEVOC's training modules, show improvements in educators' ability to design digital content and manage online or blended practical instruction (UNESCO-UNEVOC, 2022). Recent frameworks call for explicit digital competence standards, micro-credentials, and institutional mechanisms that support continuous upskilling (Li et al., 2025).

2.5 Policies and Frameworks for STEM, TVET, and IR 4.0

Southeast Asian governments have introduced multiple strategies to leverage IR 4.0 technologies, including AI, IoT, automation, and advanced manufacturing to strengthen economic competitiveness. Regional analyses note significant variation in institutional maturity and highlight the need for coherent roadmaps that integrate infrastructure planning, curriculum redesign, and workforce upgrading (Paryono and Mashod, 2024). Malaysia's policy landscape includes the Malaysia Digital Economy Blueprint, the National Fourth Industrial Revolution Policy, DSTIN 2021–2030, and Industry 4WRD, all of which prioritise digital talent and innovation ecosystems. Governance reforms via the National TVET Council and the National TVET Policy 2030 aim to unify standards and strengthen industry relevance (Cheok and Li, 2023). However, these policies often provide high-level direction without offering operational guidance on how vocational colleges should prioritise pedagogy, infrastructure, teacher development, and industry engagement to build integrated digital–STEM ecosystems.

2.6 Synthesis and Gap

Across these strands of literature, three consistent patterns emerge. First, research on AI-enabled STEM education shows strong potential for intelligent tutoring, analytics, and immersive simulations to enhance learning. Second, studies on TVET institutions in Southeast Asia and Malaysia document enduring constraints, fragmented curricula, inadequate infrastructure, and uneven teacher competence, despite growing interest in IR 4.0 technologies. Third, national and regional policies articulate ambitious digitalisation goals but provide limited guidance for institutional implementation.

What remains underdeveloped is a context-sensitive conceptual model that integrates these elements into a coherent, institution-wide framework tailored to Malaysian vocational colleges. Existing scholarship typically examines technologies, competencies, or policy narratives in isolation, offering little insight into how digital infrastructure, pedagogical and curriculum

innovation, teacher development, industry alignment, and governance interact as mutually reinforcing layers within a single institution. Few studies explore these interdependencies across multiple vocational programmes such as automotive, electrical, business, and welding, which jointly shape the learning ecosystem.

This gap underscores the need for a multi-layer conceptual framework for digital and AI-driven STEM integration that accounts for institutional complexity and programme diversity. Grounding the model in a real vocational institution such as Slim River Vocational College provides a practical basis for informing institutional planning and supporting Malaysia's broader TVET transformation agenda. This gap indicates the need for an institutional, multi-layered STEM integration framework that moves beyond teacher-centric digital competence models and technology-centric 'roadmaps,' and instead links pedagogy, professional development, infrastructure, industry alignment, and governance into a coherent whole.

3. Methodological Orientation of the Conceptual Paper

This paper is designed as a conceptual and policy analysis rather than an empirical study. It does not report newly collected quantitative or qualitative data. Instead, it develops a multi-layer framework for digital and AI-driven STEM integration in Malaysian vocational colleges by synthesising three main sources of knowledge. The literature reviewed for this conceptual synthesis spans 2018–2025 and includes peer-reviewed articles, policy documents, and technical reports accessed through Web of Science, Scopus, ERIC, UNESCO-UNEVOC, and SEAMEO repositories. Priority was given to research on STEM, AI-enabled learning, and TVET transformation, with emphasis on Southeast Asian contexts. While not a systematic review, the selection followed relevance, conceptual contribution, and policy applicability criteria to ensure a rigorous foundation for the framework.

First, the paper draws on scholarly and grey literature on digitalisation in TVET, AI in education, STEM integration, and teacher digital competence. This includes international mapping studies and reports (e.g., UNESCO-UNEVOC digital transformation and digital skills studies), empirical research on VR/AR-based welding training and extended reality in vocational education, and emerging digital competence frameworks for TVET educators.

Second, it analyses national and regional policy documents that articulate the macro-level direction for digitalisation within STEM and TVET. These include the Malaysia Digital Economy Blueprint (MyDIGITAL), the National Fourth Industrial Revolution Policy, the National Policy on Science, Technology and Innovation (DSTIN) 2021–2030, UNESCO's strategies for TVET, and SEAMEO/SEA-VET frameworks on TVET and IR 4.0. Collectively, these texts provide the policy context and strategic intent within which vocational colleges operate.

Third, the framework is grounded in institutional insights from Slim River Vocational College (SRVC). These insights are derived from SRVC's programme mix (automotive, electrical, business, and welding), institutional documentation and development plans, and practitioner reflections on digital initiatives and constraints. SRVC is therefore used as a practice-based lens that anchors the framework in the realities of a Malaysian vocational college.

SRVC serves as an illustrative anchor case for three reasons. First, its diversity of programmes mirrors the broader vocational college sector, making it a plausible microcosm of national TVET challenges. Second, SRVC is actively engaging with digital and STEM-related initiatives, providing a realistic context in which digital infrastructure, teacher readiness, and industry partnerships intersect. Third, anchoring the framework in a concrete institutional context responds to a recurrent critique of TVET policy discourse: that national strategies often lack clear institutional implementation pathways. Methodologically, the approach is

interpretive and system-oriented. It draws connections between macro-level policies, meso-level institutional processes, and micro-level teaching–learning practices, informed by systems thinking and digital competence perspectives in TVET. The analysis seeks to conceptualise how multiple layers of the system interact, rather than to test specific interventions or hypotheses.

As a non-empirical design, this approach has limitations. The proposed framework is not empirically validated in SRVC or other colleges, and the paper does not claim causal impact or generalisable effectiveness. SRVC's characteristics may differ from other institutions in terms of resourcing, leadership, or local industry ecosystem, which constrains direct transferability. Furthermore, the analysis relies on existing literature and policy texts that may lag behind the most recent technological developments. These limitations underscore the framework's status as a theoretical and strategic guide rather than a tested model. Accordingly, the paper concludes by calling for future empirical work, such as case studies, design-based research, and implementation evaluations, to test, refine, and adapt the framework across diverse Malaysian vocational colleges.

4. The Digital and AI-Driven STEM Integration Framework

Digital transformation in vocational education must be understood as a multi-level sociotechnical process rather than a linear acquisition of tools. Contemporary scholarship emphasises that innovations such as AI, VR/AR, and simulation-based learning only produce meaningful impact when supported by coherent institutional ecosystems that align technology, pedagogy, teacher learning, governance, and labour-market expectations (Yang and Wu, 2024; UNESCO, 2021).

The framework draws primarily on sociotechnical systems theory (Emery and Trist, 1973) and ecological learning models (Bronfenbrenner, 1994). Diffusion of innovation perspectives (Rogers, 2003) are used selectively to illuminate variations in institutional adoption and teacher agency. Together, these perspectives conceptualise digital and AI-driven STEM integration as an iterative process shaped by interactions across organisational, technological, and human layers.

The framework comprises five interdependent institutional layers. It explains how alignment across these layers supports sustainable transformation and how misalignment in any layer can inhibit progress. The subsections that follow outline each layer with reference to global research and Malaysian TVET realities.

4.1 A Concentric Systems Model for Digital and AI-Driven STEM Integration

The framework comprises a central core of learner STEM competencies surrounded by five interdependent institutional layers: pedagogy and curriculum, professional development, digital infrastructure, industry and certification alignment, and governance. The concentric model places learner STEM competencies at its centre: digital literacy, data literacy, computational thinking, and AI-augmented problem-solving. These competencies, emphasised in global digital and AI skill frameworks (UNESCO, 2023), represent essential outcomes for IR 4.0 workplaces.

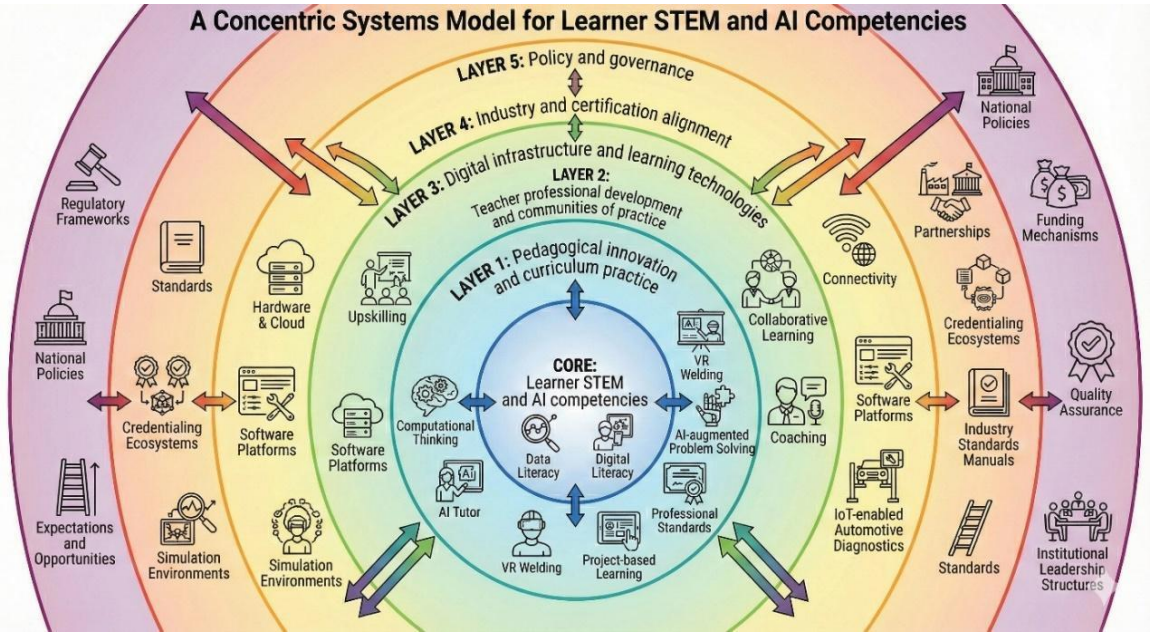
Surrounding this core are five mutually reinforcing institutional layers. These layers are conceptualised through an integrated Technology and Engineering lens, within which, Technology integration is operationalised through digital infrastructure, AI-enabled tools, simulation environments, and data ecosystems that support teaching, learning, and assessment. Engineering integration is realised through pedagogical and curriculum designs

that emphasise applied problem-solving, system optimisation, diagnostics, and design-oriented tasks within vocational trades. These two dimensions are intentionally coupled: technological tools enable engineering reasoning, while engineering practices give purpose and context to technology use, as reflected in the following five institutional layers:

1) **Pedagogical and curriculum innovation:** Design of digitally supported, interdisciplinary tasks; VR/AR simulations; project-based learning; and integration of AI-enabled tools into trade-specific curriculum.
2) **Teacher professional development and communities of practice:** Digital competence, AI-pedagogical readiness, mentoring structures, and sustained professional learning.
3) **Digital infrastructure and learning technologies:** Connectivity, devices, cloud platforms, simulation environments, and data ecosystems that support AI-enhanced instruction.
4) **Industry and certification alignment:** Partnerships, occupational standards, and certification pathways that embed real-world technologies and practices.
5) **Governance and institutional policy:** Leadership, funding mechanisms, legal and regulatory compliance, institutional data governance standards (including data protection, ethical use of AI, and learning analytics governance), and quality assurance processes.

Figure 1 visualises these layers as a nested system radiating outward from the learner. The model mirrors ecological logic, emphasising that each layer is analytically distinct yet practically interdependent. It counters technology-first approaches by situating digital tools within organisational culture, teacher capability, and policy conditions (Voogt and Knezek, 2021). Variation in adoption across Malaysian TVET institutions linked to infrastructure disparities and programme heterogeneity (Cheok and Li, 2023; UNESCO-UNEVOC, 2024) underscores the need for this systemic perspective. Unlike teacher-centred models such as DigCompEdu or technology-focused 'digital transformation roadmaps,' this framework provides an institutional, vocational-oriented structure that integrates AI-enabled STEM pedagogy with governance, infrastructure, and industry certification systems.

Figure 1: A Concentric Systems Model for Digital and AI-Driven STEM Integration



4.2 Pedagogical Innovation and AI-Enhanced Curriculum Practice

Pedagogy forms the first layer because learner competencies emerge from the design of tasks and tools in vocational learning environments. In vocational contexts, this pedagogical layer integrates Technology through AI-enabled tutoring systems, VR/AR simulations, and data analytics platforms. It simultaneously advances Engineering through design-based problem solving, fault diagnosis, process optimisation, and systems thinking embedded in trade-specific tasks such as welding parameter selection or automotive diagnostics. Research shows that technology generates value only when embedded in coherent learning designs grounded in cognitive and vocational learning principles (Biggs and Tang, 2011; English, 2016). AI-enabled tools such as intelligent tutoring systems offer adaptive feedback and support complex problem solving (Holmes et al., 2019; Xu and Ouyang, 2022). VR simulations strengthen psychomotor preparation and safety (Heibel et al., 2023; Ahmad et al., 2024; Wang et al., 2024), while AR overlays assist in visualising hidden processes such as electrical flow or sensor behaviour (Desai et al., 2022; Chng et al., 2023). Effective integration requires shifting from demonstration-oriented routines to inquiry-driven, data-rich, interdisciplinary tasks that mirror industrial problem contexts. Such approaches strengthen modelling, computational reasoning, and cross-trade collaboration, which competencies align with IR 4.0 workforce expectations (Kelley and Knowles, 2016; Luckin, 2018).

4.3 Teacher Professional Development and Learning Ecosystems

Teacher professional development (PD) is the second layer and a recognised determinant of digital transformation (Paryono and Mashod, 2025; Zhong and Juwaheer, 2024). PD is not merely skill acquisition but an organisational process shaped by collaboration, shared norms, and access to relevant tools (OECD, 2025). In TVET contexts, educators require mastery of both general digital skills and trade-specific technologies such as VR welding systems, AI diagnostics, PLC automation, and cybersecurity simulations. While DigCompEdu (Redecker, 2017) and UNESCO-UNEVOC models provide useful benchmarks, multi-programme colleges such as SRVC also need cross-trade communities of practice to reduce silos and support collaborative curriculum design. Sustained PD requires institutional recognition, allocated time, and alignment with micro-credential and promotion pathways.

4.4 Digital Infrastructure and Learning Technologies

Infrastructure forms the third layer and includes connectivity, devices, cloud systems, cybersecurity, and simulation platforms. These elements shape what teachers and students can do and how they interact with digital systems (Tawil and Miao, 2024). In Malaysian TVET, historical variability in resource allocation has produced uneven digital ecosystems (Ministry of International Trade and Industry, 2018; (Cheok and Li, 2023). For colleges like SRVC, strengthening infrastructure requires coordinated planning across programmes to avoid “technology islands” and ensure that digital tools support learning across welding, automotive, electrical, and business programmes.

4.5 Industry and Certification Alignment

The fourth layer situates STEM integration within wider skill ecosystems. Strong industry linkages ensure that vocational instruction remains authentic and aligned with emerging technologies in automation, IoT, data analytics, and AI-assisted diagnostics (Finegold, 1999; CEDEFOP, 2025). Certifications such as AWS welding, Cisco networking, Siemens automation, signal occupational relevance and provide portable credentials. However, alignment requires balance. Industry input must inform curriculum without narrowing it to immediate labour needs, preserving broader STEM competencies essential for adaptability (Wheelahan et al., 2012).

4.6 Policy and Governance

The outer layer recognises that institutional transformation is shaped by national regulation, leadership, and resource allocation. While Malaysia's digital and TVET policies articulate strong aspirations, gaps remain in operational guidance (UNESCO-UNEVOC, 2022; Paryono and Mashod, 2024). Governance involves both regulatory elements standards, QA frameworks, data governance and developmental supports such as digital transformation committees, leadership training, and multi-year funding. Governance interacts dynamically with all other layers: policies shape infrastructure investment; infrastructure supports teacher learning; teacher competence enables pedagogical redesign; and pedagogical outcomes inform policy cycles. Section 6 translates these systemic principles into national and institutional policy recommendations.

5. Application to Slim River Vocational College

This section applies the framework to Slim River Vocational College (SRVC) as an illustrative anchor case, demonstrating how the five institutional layers reveal operational strengths, gaps, and sequencing priorities, while also showing how the five-layer digital and AI-driven STEM framework can operate within a Malaysian vocational institution. As a mid-sized multi-programme college offering Welding, Automotive, Electrical, and Business, SRVC reflects the structural diversity of the national Vocational College (KV) system. Its transformation depends on coordinated alignment across pedagogy, teacher learning, infrastructure, industry linkages, and governance, rather than the acquisition of isolated digital tools. The subsections below summarise how each layer manifests within SRVC.

5.1 Pedagogical and Curriculum Innovation at SRVC

Pedagogical redesign is the primary driver of digital and AI-enabled STEM integration at SRVC. Moving beyond demonstration-oriented instruction requires the college to embed digital tools within coherent, problem-centred, and interdisciplinary learning sequences that explicitly cultivate the STEM competencies identified at the core of the framework. Within the SRVC context, the framework envisages Engineering integration through learners' progressive engagement with digitally supported tasks such as designing welding procedures, diagnosing weld defects, optimising heat input parameters, and troubleshooting automotive sensor systems, while Technology integration is planned to be realised through VR simulators, AI-assisted diagnostics, and digital data platforms that support these engineering decisions.

In Welding Technology, VR simulators are envisaged to provide analytics-rich environments through which learners can diagnose heat input, travel angle, and arc stability before transitioning to live welding. Automotive programmes are envisaged to deploy AI-assisted fault simulations to scaffold diagnostic reasoning and strengthen students' ability to interpret sensor data and algorithmic fault patterns.

Cross-programme collaboration deepens interdisciplinary engagement. Business students developing basic data dashboards for workshop operations, or Electrical students assisting with automotive sensor calibration, illustrate how digital tools can connect traditionally siloed trades. Electrical Technology can further integrate AR overlays to visualise voltage and current pathways, supporting conceptual reasoning, while Business programmes may incorporate data analytics, digital productivity tools, and AI-supported decision-making platforms to strengthen students' analytical and computational thinking.

Across these disciplines, SRVC must cultivate a learning culture that supports experimentation, iterative problem solving, and structured use of digital tools. Digital and

AI-enabled activities must be integrated into curriculum sequences rather than functioning as isolated add-ons, ensuring that learners consistently encounter data-rich, inquiry-oriented tasks aligned with IR 4.0 expectations. These innovations only scale sustainably when paired with professional development, maintenance budgets, and governance oversight, highlighting the interdependence of all layers.

5.2 Teacher Professional Development at SRVC

Teacher readiness remains the most decisive influence on SRVC's capacity to operationalise digital and AI-driven STEM practices. While Business lecturers typically demonstrate stronger digital fluency, welding, automotive, and electrical instructors possess deep trade expertise but require greater exposure to emerging technologies. A layered professional development (PD) strategy is therefore essential.

Foundational PD should build baseline digital competence, including LMS use, digital content creation, and introductory data analytics. Trade-specific PD must focus on tools that reflect authentic workplace practice: VR simulator operation and analytics interpretation for welding; OEM diagnostic software and AI-supported troubleshooting for automotive; PLC programming, sensor systems, and circuit simulation for electrical; and digital productivity platforms, financial analytics tools, and AI-supported business decision systems for Business.

Sustained implementation requires institutionalised communities of practice that bring cross-trade educators together to co-design interdisciplinary modules, experiment with digital pedagogies, and reflect on learner data. These structures are unlikely to persist without supportive governance. SRVC must embed PD participation into workload policies, recognise trade-specific digital upskilling in performance evaluations, and link development opportunities to career progression, ensuring long-term institutional coherence.

5.3 Digital Infrastructure and Learning Technologies at SRVC

SRVC's digital infrastructure displays the unevenness common across Malaysian vocational colleges. Business laboratories benefit from stronger connectivity and modernised devices, while welding and automotive workshops continue to rely on analogue equipment, limiting opportunities for data-driven and AI-supported learning. Targeted, programme-specific investment is necessary to operationalise the framework. Welding requires VR simulation systems to support iterative practice and develop students' capacity to interpret performance analytics. Automotive programmes need digital diagnostic platforms and AR-enabled tools particularly for hybrid and electric vehicles to strengthen computational reasoning and AI-informed decision-making. Electrical programmes benefit from PLC rigs, sensor kits, and simulation environments that allow learners to model and analyse system behaviour. Business programmes require upgraded computer labs, data analytics platforms, financial modelling software, AI-supported decision tools, and secure cloud-based productivity systems to reflect contemporary digital business environments. However, irregular funding cycles, maintenance challenges, and variable connectivity restrict sustained implementation. Infrastructure planning must therefore be strategic, coordinated, and educationally aligned to avoid fragmented upgrades that hinder pedagogical innovation. Without consistent infrastructural support, SRVC cannot fully develop the learner STEM competencies that anchor the concentric framework.

5.4 Industry and Certification Alignment at SRVC

Industry and certification alignment ensures that SRVC's digital and AI-enabled STEM practices remain responsive to evolving occupational demands. Welding programmes can partner with fabrication firms employing robotic or automated welding systems, giving learners

exposure to sensor data, heat mapping, and automated performance analytics. Automotive programmes can collaborate with workshops servicing hybrid and electric vehicles to integrate high-voltage diagnostics and advanced sensor systems. Electrical programmes may partner with smart-building, automation, and renewable energy companies to design learning tasks involving IoT-enabled energy systems, while Business programmes can engage with industry partners in digital finance, data analytics, e-commerce, and business technology services to develop authentic capstone and project experiences. Mapping curricula to recognised certifications such as Microsoft Office Specialist (MOS), Google Analytics, AWS Cloud Practitioner, financial modelling certifications, Siemens automation, Autodesk, and trade-specific welding or electrical standards provides learners with portable credentials and reinforces the occupational relevance of digital STEM integration. These partnerships create realistic learning contexts that expose students to contemporary technologies, data flows, and diagnostic processes, thereby strengthening the alignment between classroom learning and workplace practice.

5.5 Governance, Constraints, and Phased Implementation at SRVC

Governance determines whether SRVC can coordinate the preceding layers of the framework into a coherent institutional strategy. As the SRVC case shows, structural constraints such as irregular funding cycles, limited technical support capacity, and uneven staff digital readiness create conditions in which large-scale transformation must proceed gradually. A phased implementation strategy is therefore essential to ensure organisational learning, institutional stability, and alignment with the college's absorptive capacity. This sequencing reflects the ecological logic outlined in Section 4, where sustainable digital and AI-driven STEM integration emerges through cumulative adjustments across interacting institutional layers.

A feasible progression for SRVC includes the following stages.

1) Short Term (Year 1)
    - Stabilise core infrastructure, particularly connectivity and essential digital tooling.
    - Pilot small-scale digital and simulation initiatives (e.g., VR welding, basic digital diagnostics).
    - Establish cross-trade professional learning communities to begin breaking down programme silos.
2) Medium Term (Years 2-3)
    - Expand VR/AR platforms, digital diagnostic tools, and simulation systems across trades.
    - Institutionalise structured, multi-year professional development linked to micro-credential pathways.
    - Introduce interdisciplinary STEM modules that foreground data literacy, computational reasoning, and AI-mediated problem solving.
3) Long Term (Years 4-5)
    - Develop analytics-informed instructional systems and AI-supported assessment practices.
    - Formalise institutional data governance structures and digital quality assurance mechanisms.
    - Institutionalise cross-trade capstone projects co-supervised by industry partners, embedding authentic AI-intensive tasks in programme culmination.

This phased approach illustrates how governance serves as the coordinating mechanism that aligns infrastructure, pedagogy, teacher development, and industry engagement over time. The SRVC case thereby exemplifies the wider systemic adjustments required across

Malaysian vocational colleges to move from isolated, tool-driven initiatives toward durable, institution-wide digital ecosystems that meaningfully support AI-enhanced STEM learning. The dynamics observed at SRVC mirror systemic patterns across Malaysian vocational colleges, forming the basis for the national and institutional policy implications outlined in the next section.

6. Policy Implications for Malaysia

Anchoring the five-layer framework within SRVC's institutional realities highlights wider systemic implications for Malaysia's TVET transformation, particularly in the context of industry challenges arising from rapid digitalisation and the growing adoption of artificial intelligence across the regional workforce. Employers increasingly report gaps in graduates' ability to operate AI-enabled systems, interpret data-driven diagnostics, and adapt to digitally mediated production and maintenance environments. As argued in Section 4, digital and AI-driven STEM integration does not emerge from isolated technological adoption but from the interaction of multiple institutional layers. Effective reform therefore requires policy alignment that spans pedagogy, professional development, infrastructure, industry collaboration, and governance. The SRVC case demonstrates how misalignment in any single layer can stall institutional capacity to respond to industry digitalisation demands, reinforcing the need for coordinated, long-term strategies rather than short-lived, project-driven initiatives.

6.1 National-Level Implications

Malaysia's TVET transformation is increasingly shaped by industry challenges arising from rapid digitalisation and the growing adoption of artificial intelligence across manufacturing, services, and technical trades. Employers across sectors report persistent workforce gaps in areas such as AI-enabled diagnostics, data-driven decision-making, digitally mediated maintenance processes, and human–machine collaboration. These challenges underscore the need for policy responses that move beyond isolated technology adoption and instead build systemic capacity for an AI-ready and digitally fluent workforce. Within this context, the proposed five-layer framework is positioned as a policy instrument that translates industry workforce demands into coordinated institutional reform.

In response to these industry challenges, national TVET policies should treat Technology and Engineering as explicitly integrated competencies, ensuring that investments in AI and digital infrastructure are matched by curricular support for applied engineering problem-solving within vocational trades. While current national policies emphasise IR 4.0 and digitalisation, they provide limited clarity on the specific AI literacy, data analytics capability, simulation proficiency, and ethical decision-making competencies required across welding, automotive, electrical, and business programmes. A unified national AI and digital STEM competency standard for vocational graduates would therefore provide clearer guidance for curriculum renewal, shape assessment practices, and align certification pathways with evolving industry requirements, while offering institutions a transparent benchmark for self-evaluation.

A second national-level implication concerns financing architecture. Industry-driven digital transformation requires sustained access to modern equipment, simulation platforms, and data-enabled learning environments. However, the SRVC case illustrates the fragility of project-based or episodic grants, which often yield short-term gains without ensuring continuity, maintenance, or equitable distribution. Moving toward predictable, recurrent funding models supported by minimum digital infrastructure standards, coordinated procurement mechanisms, and shared technical support ecosystems would better enable colleges to respond to industry digitalisation demands, particularly in rural and semi-urban regions.

A third implication relates to industry participation in workforce development. Despite growing demand for AI- and digitally skilled graduates, current patterns of engagement remain uneven and frequently rely on informal networks. Structured incentives—such as tax benefits, co-funded technology laboratories, apprenticeships in AI-intensive fields, and competitive innovation grants—would formalise industry involvement and strengthen the alignment between vocational programmes and rapidly evolving technological environments.

Finally, addressing industry workforce challenges requires systematic investment in teacher digital competence. National reforms must institutionalise teacher professional development through a dedicated Digital Competence Framework for TVET Educators, embedded within micro-credential systems, promotion criteria, and mandatory professional development requirements. Such a framework would enable partnerships between colleges, universities, and industry to support advanced, trade-specific digital upskilling, ensuring that educators are equipped to translate industry digitalisation demands into meaningful learning experiences. As highlighted in Section 4, teacher capability remains the foundation upon which all other layers of systemic transformation depend

6.2 Institutional-Level Implications

While national policy establishes strategic direction, institutional governance determines how effectively vocational colleges respond to industry challenges associated with digitalisation and the growing use of AI in the workplace. The SRVC analysis shows that colleges require internal structures capable of coordinating the five layers of the framework to ensure that curriculum, pedagogy, infrastructure, and professional development are aligned with evolving industry skill requirements.

Strengthening institutional governance is therefore a central priority. Dedicated digital transformation committees or STEM–AI task forces can synchronise planning across pedagogy, professional development, infrastructure, and industry partnerships, ensuring that institutional responses remain responsive to industry digitalisation demands. These coordinating bodies help avoid duplication, maintain alignment with national aspirations, and provide structured feedback channels with ministries, agencies, and industry partners.

For institutional leaders, these governance mechanisms require clear mandates and operational scope. Such committees should function as cross-departmental decision-making bodies responsible for prioritising digital investments, aligning curriculum innovation with infrastructure planning, overseeing staff digital upskilling, and coordinating industry engagement. Such committees typically include senior management, programme heads, IT personnel, and industry representatives to ensure that pedagogical, technical, and workforce considerations are addressed holistically.

In parallel, institutional data governance structures are critical to support AI-enabled STEM implementation. These structures should define policies for data collection, storage, access, and ethical use, particularly where learning analytics, simulation data, and AI-assisted assessment are involved. Clear data governance frameworks enable institutions to use learner and system data for instructional improvement and quality assurance, while also managing institutional risk and ensuring compliance with privacy, security, and regulatory requirements. Such governance structures also ensure institutional compliance with national legal requirements and data standards, including regulations on data protection, cybersecurity, and the ethical deployment of AI in education.

Curriculum restructuring represents another critical institutional response to industry workforce challenges. Digital and AI-enabled STEM learning requires curricula that accommodate interdisciplinary project work, simulation-rich activities, and AI-supported pedagogical tools aligned with real-world industrial problem contexts. Cross-department curriculum teams serve

as a mechanism for translating national competency standards and industry expectations into locally adapted programme designs. Without such structures, integration risks remaining marginal and disconnected from workplace realities.

Sustained teacher learning ecosystems are equally essential. Industry demand for AI-capable graduates cannot be met through one-off workshops or isolated upskilling initiatives. Institutions must instead commit to multi-year professional development pathways that include workload allocation, formalised communities of practice, mentoring, and recognition of trade-specific digital upskilling, including VR welding analytics, AI-based diagnostics, and PLC automation. As demonstrated in Section 4, institutional capacity to respond to industry digitalisation depends heavily on teachers' ability to cultivate core learner STEM competencies.

Finally, infrastructure planning must be educationally strategic rather than procurement-driven. To meet industry expectations for digitally fluent graduates, investments should prioritise programme relevance, maintenance feasibility, and alignment with learning competencies. Coordinated procurement, scheduled maintenance, and shared access across departments are necessary to prevent fragmented "technology islands" and to ensure that infrastructure investments directly support pedagogical and curriculum transformation.

Through these governance, curriculum, professional development, and infrastructure mechanisms, institutions such as SRVC can move beyond isolated innovations and develop cohesive, durable digital ecosystems that respond effectively to industry digitalisation and AI-driven workforce demands.

6.3 Summary of Policy Directions

Table 1 synthesises the required policy actions across the five domains of the framework by distinguishing national responsibilities from institutional responsibilities. It summarises key national- and institution-level policy actions, with particular emphasis on governance and management mechanisms that are directly actionable by institutional administrators.

Table 1: Policy recommendations for digital and AI-driven STEM integration in Malaysian vocational colleges

Policy Domain	National-Level Actions	Institution-Level Actions
Pedagogical and Curriculum Innovation	Define national AI and STEM competency standards; embed digital and AI-driven STEM integration in curriculum reforms	Redesign modules for data analytics, simulation, and interdisciplinary projects; implement integrated assessment practices
Teacher Professional Development	Create a Digital Competence Framework; establish micro-credential pathways; link PD to incentives	Embed PD into workload; support trade-specific digital upskilling; develop communities of practice
Digital Infrastructure	Set minimum digital standards; provide recurrent funding; centralise procurement and support	Prioritise VR/AR and AI tools based on programme needs; implement maintenance and replacement cycles
Industry Alignment	Offer tax incentives, co-funded labs, and apprenticeship schemes; align national certification pathways	Map certifications to curriculum; build formal partnerships; engage industry in co-teaching and capstone supervision
Governance and Data Policy	Issue digital governance guidelines; define quality indicators and data standards	Establish digital transformation committees; develop institutional data governance structures and analytics dashboards

Collectively, these implications reaffirm that Malaysia's TVET transformation requires a whole-system orientation that aligns standards, financing, professional learning, curriculum reform, industry engagement, and governance. A multi-layered approach is essential if digital and AI-driven STEM aspirations are to translate into coherent, scalable, and equitable improvements across the vocational college system.

7. Conclusion

Malaysia's vocational colleges are under increasing pressure to produce digitally fluent, STEM-capable graduates who can operate confidently in AI-augmented and IR 4.0-oriented workplaces. Yet, as demonstrated through the SRVC case, many institutions continue to function within fragmented learning ecosystems characterised by uneven digital infrastructure, siloed programme structures, and inconsistent teacher readiness. These conditions limit the effectiveness of reforms that focus primarily on acquiring new technologies without addressing the wider pedagogical, organisational, and policy environments in which those technologies are embedded. This framework advances STEM education scholarship by clarifying how AI-enabled pedagogical and institutional redesign can be operationalised in vocational settings, extending discourse beyond generic digitalisation narratives.

This paper proposed a five-layer conceptual framework that reconceptualises digital and AI-driven STEM integration in vocational colleges as a sociotechnical and ecological process. Centred on the development of core learner STEM competencies, the model emphasises that pedagogical and curriculum innovation, teacher professional development, digital infrastructure, industry and certification alignment, and governance must function as mutually reinforcing institutional layers. The framework therefore rejects linear, technology-first assumptions and instead positions transformation as an emergent property of systemic alignment across these layers.

The application of the model to SRVC illustrates its diagnostic and planning value. SRVC's experiences show how simulation environments, data-rich and inquiry-oriented pedagogies, cross-trade learning activities, and sustained teacher learning ecosystems can advance integrated digital and AI practices. At the same time, the case exposes structural constraints such as intermittent funding, limited technical support, and variable digital competence that require phased and sequenced implementation strategies consistent with institutional absorptive capacity. These insights reinforce the argument that sustainable transformation depends on coherent, long-term institutional planning rather than short-term, technology-centric interventions.

Section 6 further demonstrated that institutional transformation is inseparable from national policy conditions. Malaysia's digital and TVET agendas must therefore be accompanied by unified AI and STEM competency standards, predictable infrastructure financing, structured teacher digital-competence policies, and incentives that sustain industry engagement. Aligning macro-level direction with institutional governance is essential if digital and AI-driven STEM integration is to evolve into a system-wide reform rather than a patchwork of isolated initiatives.

Together, the framework and the SRVC case provide a transferable analytical lens for Malaysia and other Southeast Asian TVET systems seeking to bridge national digital aspirations with "last-mile" implementation realities. The model offers policymakers and institutions a structured way to diagnose system gaps, design coherent interventions, and sequence reforms across pedagogical, organisational, and infrastructural domains.

This study is inherently limited by its conceptual orientation and its focus on a single illustrative institution. Future research should empirically test and refine the framework through multi-site case studies, design-based implementation research, and mixed-methods evaluations of AI-supported STEM teaching. Further work is needed to examine how digital and AI-driven reforms affect equity across differently resourced colleges and among diverse learner groups, including rural and underserved populations. Future empirical research should incorporate student and teacher perspectives to test the assumptions embedded within the institutional layers and to refine the framework's applicability across diverse vocational contexts. Longitudinal studies on learner outcomes, institutional capability building, and system-level impacts would deepen understanding and support Malaysia's transition toward a digitally enabled, AI-driven vocational education system capable of meeting future labour-market demands.

References

Ahmad, A. R., Ali, D. F., & Othman, N. F. (2024). Technological innovations in welding education: A review of teaching and learning approaches. *International Journal of Academic Research in Progressive Education and Development, 13*(4). https://doi.org/10.6007/IJARPED/v13-i4/23801

Akhmetova, A. I., Sovetkanova, D. M., Komekbayeva, L. K., Abdrakhmanov, A. E., Yessenuly, D., & Serikova, O. S. (2025). A systematic review of artificial intelligence in high school STEM education research. *Eurasia Journal of Mathematics, Science and Technology Education, 21*(4), em2623. https://doi.org/10.29333/ejmste/16222

Alhajri, S. M. (2023). *The potential of extended reality in welding training in the UAE: Opportunities and challenges* (Doctoral thesis, University of Gloucestershire). University of Gloucestershire Research Repository. https://eprints.glos.ac.uk/15097/

ASEAN Secretariat. (2025). *Promotion of business engagement models for upskilling and reskilling the ASEAN workforce* (Report). ASEAN Secretariat. https://asean.org/wp-content/uploads/2025/06/ASEAN_Upskilling_Report_20062025.pdf

Azman, A., Ahmad, A. M., Widiastuti, T., Kholidah, H., & Sa'aid, H. B. (2025). Toward inclusive digital teaching in Malaysia: Challenges, strategies, and future directions. *International Journal of Research and Innovation in Social Science (IJRISS), 9*(10), 7591–7603. https://doi.org/10.47772/IJRISS.2025.910000619

Biggs, J., & Tang, C. (2011). *Teaching for quality learning at university* (4th ed.). McGraw-Hill Education.https://books.google.co.th/books/about/Teaching_For_Quality_Learning_At_Univers.html?id=XhjRBrDAESkC&redir_esc=y

Bronfenbrenner, U. (1994). Ecological models of human development. *Readings on the Development of Children, 2*(1), 37-43. https://docs.edtechhub.org/lib/P7AUMPEJ

CEDEFOP. (2025). *VET needs to go digital: Upgrading the backbone of Europe's twin transition (Policy Brief)*. European Centre for the Development of Vocational Training. https://www.cedefop.europa.eu/files/9200_en.pdf

Chng, E., Tan, A. L., & Tan, S. C. (2023). Examining the use of emerging technologies in schools: A review of artificial intelligence and immersive technologies in STEM education. *Journal for STEM Education Research, 6*, 385-407. https://doi.org/10.1007/s41979-023-00092-y

Desai, S. B., Bhosale, V. P., & Kolekar, A. B. (2022). Augmented reality in engineering education: A review. *Journal of Emerging Technologies and Innovative Research, 9*(8), 52–55. https://www.jetir.org/papers/JETIRFQ06011.pdf

English, L. D. (2016). STEM education K–12: Perspectives on integration. *International Journal of STEM Education, 3*(1), Article 3. https://doi.org/10.1186/s40594-016-0036-1

Emery, F. E., & Trist, E. L. (1973). *Towards a social ecology: Contextual appreciation of the future in the present*. Springer New York. https://doi.org/10.1007/978-1-4615-8082-9

Finegold, D. (1999). Creating self-sustaining, high-skill ecosystems. *Oxford Review of Economic Policy, 15*(1), 60–81. https://doi.org/10.1093/oxrep/15.1.60

Heibel, B. H., Anderson, R. G., & Drewery, M. L. (2023). Virtual reality in welding training: A literature review. *Journal of Agricultural Education, 64*(4), 15–32. https://doi.org/10.5032/jae.v64i4.38

Holmes, W., Bialik, M., & Fadel, C. (2019). *Artificial intelligence in education*. Center for Curriculum Redesign. https://curriculumredesign.org/publication/artificial-intelligence-in-education/

Kelley, T. R., & Knowles, J. G. (2016). A conceptual framework for integrated STEM education. *International Journal of STEM Education, 3*, Article 11. https://doi.org/10.1186/s40594-016-0046-z

Li, S., Zeng, C., Liu, H., Jia, J., Liang, M., Cha, Y., Lim, C. P., & Wu, X. (2025). A meta-analysis of AI-enabled personalized STEM education in schools. *International Journal of STEM Education, 12*, Article 58. https://doi.org/10.1186/s40594-025-00566-y

Liew, Y. F., & Teoh, H. K. (2022). STEM education in Malaysia: An organisational development approach?. *International Journal of Advanced Research in Future Ready Learning and Education, 29*(1), 1–19. https://doi.org/10.37934/frle.29.1.119

Luckin, R. (2018). *Machine learning and human intelligence: The future of education for the 21st century*. UCL IOE Press. https://www.ucl-ioe-press.com/books/machine-learning-and-human-intelligence/

Ministry of International Trade and Industry. (2018). *Industry4WRD: National Policy on Industry 4.0*. https://www.miti.gov.my/miti/resources/Industry4WRD/Industry4WRD_National_Policy_on_Industry_4.0.pdf

OECD. (2025). *Preparing teachers for digital education: Continuing professional learning on digital skills and pedagogies* (OECD Education Policy Perspectives, No. 122). OECD Publishing. https://doi.org/10.1787/af442d7a-en

Paryono, P., & Mashod, H. (2024). *The readiness of TVET institutions for IR 4.0 in Southeast Asia* (Regional report). SEAMEO VOCTECH Regional Centre. https://voctech.org/wp-content/uploads/2023/05/Regional-Report_Mar-2025-The-Readiness-of-TVET-Institutions-for-IR-4.0-in-Southeast-Asia.pdf

Paryono, P., & Mashod, H. (2025). *Responses of technical and vocational education and training institutions to the needs of industry's digital transformation in South-East Asia* (ILO Working Paper No. 138). International Labour Organization. https://researchrepository.ilo.org/esploro/outputs/encyclopediaEntry/995648976202676

Rajamanickam, S., Che' Rus, R., & Abdul Raji, M. N. (2024). Enhancing TVET for a digital-ready workforce: A systematic literature review. *International Journal of Modern Education, 6*(23), 865–881. https://doi.org/10.35631/IJMOE.623060

Redecker, C. (2017). *European framework for the digital competence of educators: DigCompEdu*. Publications Office of the European Union. https://publications.jrc.ec.europa.eu/repository/handle/JRC107466

Rogers, E. M. (2003). *Diffusion of innovations* (5th ed.). Simon & Schuster. https://books.google.com.my/books?id=9U1K5LjUOwEC&source=gbs_navlinks_s

SEAMEO VOCTECH. (2022). *Annual report 2021–2022: Preparing TVET for Industry 4.0*. https://voctech.org/wp-content/uploads/2023/05/AR-2021-2022.pdf

Tawil, S., & Miao, F. (2024). Steering the digital transformation of education: UNESCO's human-centered approach. *Frontiers of Digital Education, 1*, 51–58. https://doi.org/10.1007/s44366-024-0020-0

UNESCO. (2021). *UNESCO strategy for TVET (2022–2029): Transforming TVET for successful and just transitions*. https://unevoc.unesco.org/pub/unesco_strategy_for_tvet_2022-2029_discussion_document.pdf

UNESCO. (2023). *Guidance for generative AI in education and research*. https://unesdoc.unesco.org/ark:/48223/pf0000386693/PDF/386693eng.pdf.multi

UNESCO-UNEVOC. (2022). *Trends mapping study: Digital skills development in TVET teacher training*. https://unevoc.unesco.org/pub/trends_mapping_study_digital_skills_development_in_tvet_teacher_training.pdf

UNESCO-UNEVOC. (2024). *Elevating TVET for a just and sustainable future for all: UNESCO-UNEVOC medium-term strategy 2024-2026*. https://unevoc.unesco.org/pub/unevoc_mts-iv_en.pdf

Villegas-Ch, W., Buenano-Fernandez, D., Maldonado Navarro, A., & Mera-Navarrete, A. (2025). Adaptive intelligent tutoring systems for STEM education: Impact and effectiveness. *Smart Learning Environments, 12*, Article 41. https://doi.org/10.1186/s40561-025-00389-y

Voogt, J., & Knezek, G. (2021). Learners and learning contexts: International perspectives on new alignments for the digital age. *Educational Technology Research and Development, 69*, 2083–2089. https://doi.org/10.1007/s11423-021-09985-4

Wang, S., Wang, F., Zhu, Z., Wang, J., Tran, T., & Du, Z. (2024). Artificial intelligence in education: A systematic literature review. *Expert Systems with Applications, 252*, 124167. https://doi.org/10.1016/j.eswa.2024.124167

Wheelahan, L., Moodie, G., & Buchanan, J. (2012). *Revitalising the 'vocational' in flows of learning and labour* (Discussion paper). National Centre for Vocational Education Research (NCVER). https://www.ncver.edu.au/__data/assets/file/0015/3228/2535.pdf

Xu, W., & Ouyang, F. (2022). The application of AI technologies in STEM education: A systematic review from 2011 to 2021. *International Journal of STEM Education, 9*, Article 59. https://doi.org/10.1186/s40594-022-00377-5

Yang, X., & Wu, W. (2024). Advancing digital transformation in TVET through international cooperation: Approaches by the UNESCO Chair on Digitalization in TVET. *Vocation, Technology & Education, 1*(2). https://doi.org/10.54844/vte.2024.0585

Yunos, S. (2023). Strategic planning to transform Malaysian TVET students into future ready professionals. *TVET@Asia*, *(20)*. https://tvet-online.asia/wp-content/uploads/2023/01/syunos_tvet20.pdf

Zhong, Z., & Juwaheer, S. (2024). Digital competence development in TVET with a competency-based whole-institution approach. *Vocation, Technology & Education, 1*(2). https://doi.org/10.54844/vte.2024.0591

TEACHER

SECTION

FIELD-BASED STEM EDUCATION FOR BIODIVERSITY LITERACY: LESSONS FROM INDONESIA

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ABSTRACT

This study applies a field-based inquiry approach supported by the Model of Educational Reconstruction (MER) to help students reconstruct their understanding of bioindicators while strengthening inquiry practices in STEM learning. A total of 59 tenth-grade students in Bangka, Indonesia, investigated two contrasting aquatic ecosystems: a clear post-mining lake with low biodiversity and a naturally turbid river rich in aquatic life. Students designed and used observation worksheets, collected field data, participated in guided discussions, and reflected on their findings. Data were obtained through pre- and post-assessments, field notes, and student reflections. The results show substantial conceptual gains, with the mean score increasing from 49.21 to 81.27, and 92% of students meeting the Minimum Competency Standard. Students shifted from surface-level assumptions based on water clarity toward scientifically grounded reasoning that emphasised biodiversity and indicator species such as frogs, dragonflies, shrimp, and snails. These outcomes indicate that contextual field experiences effectively challenge misconceptions and support conceptual reconstruction. The study concludes that situating learning in authentic ecological settings strengthens key STEM practices, including observation, evidence-based reasoning, and reflection. By drawing on local biodiversity, the approach offers a practical and accessible model for integrating sustainability and systems thinking into STEM education in Southeast Asia, while fostering biodiversity literacy, scientific understanding, and environmental responsibility.

Keywords: STEM Education, Bioindicators, Inquiry-based learning, Biodiversity Literacy, Southeast Asia

1. Introduction

Understanding the intricate relationship between biodiversity and environmental quality is a central objective in science and STEM education, particularly in the context of increasing environmental challenges and the global movement toward sustainable development. Within STEM learning, inquiry and observation are emphasised as essential practices, yet many students still struggle to apply them to authentic ecological problems. One relevant concept that links science content with real-world inquiry is bioindicators organisms whose presence, absence, or abundance reflects specific environmental conditions (Siddig et al., 2016). A proper grasp of bioindicators is vital not only for academic achievement but also for cultivating ecological awareness and fostering environmental responsibility, skills that are increasingly important for students in Southeast Asia, where biodiversity is both rich and under threat.

Despite this importance, both research and classroom observations suggest a persistent conceptual disconnect between students' everyday reasoning and scientific perspectives.

Many students equate environmental quality solely with visual clarity of water, disregarding ecological complexity, species diversity, and the functional roles of indicator organisms (Smith et al., 2023; Stevenson et al., 2014). Scientists, however, regard bioindicators as biological tools capable of signalling subtle and often invisible forms of pollution that cannot be detected through physical or chemical analysis alone. This gap highlights the need for STEM education approaches that go beyond memorisation and engage students in authentic scientific inquiry.

The concept of bioindicators was selected for its dual scientific and educational relevance. Scientifically, bioindicators are used globally to monitor ecosystem health and detect environmental pollutants (Parmar et al., 2016). Educationally, they provide a powerful entry point for connecting students with ecological reasoning, systems thinking, and inquiry-based STEM practices. At the policy level, this topic also aligns with UNESCO (2024), which emphasise sustainability learning through real-world and locally relevant contexts. Clarifying bioindicators as both scientific constructs and educationally significant themes ensures that instructional efforts are grounded in disciplinary accuracy while remaining pedagogically meaningful.

To address this gap, this study draws upon the Model of Educational Reconstruction (MER), a framework that emphasises the integration of scientific knowledge, student conceptions, and pedagogical design. MER begins with a critical analysis of subject matter and its educational significance, followed by research into how students actually think and learn about the topic, including common misconceptions and cognitive challenges (Duit et al., 2012). These insights then inform the design of learning environments that are empirically grounded and pedagogically responsive, ensuring that instruction not only delivers content but also actively reconstructs student understanding through inquiry.

Applying this framework, the present study engaged tenth-grade students from SMA Negeri 1 Puding Besar, Indonesia, in contextual field observations of two contrasting aquatic ecosystems: a post-mining lake with clear but biodiversity-poor water, and a naturally turbid river rich in aquatic life. These real-world settings were used to challenge simplistic associations between water clarity and ecosystem health, and to highlight the significance of biodiversity and ecological functions as indicators of environmental quality (Carson, 1962).

A key challenge in biology and STEM education is students' misconception that environmental quality can be judged by water clarity alone, often neglecting biodiversity and ecological function. This mismatch between students' everyday interpretations and scientific perspectives can lead to shallow reasoning and weak inquiry practices. The present study addresses this misconception using MER to guide field-based learning and concept reconstruction. By engaging students in contrasting aquatic ecosystems, this research not only strengthens biodiversity literacy but also demonstrates how STEM inquiry can be meaningfully integrated into environmental education in Southeast Asia.

2. Literature Review

2.1 Student Misconceptions in Environmental and Water System Education

Students' misconceptions about environmental quality often stem from visual or surface-level interpretations of ecosystems. One prevalent misunderstanding is that clear water automatically indicates a healthy environment. Research has shown that many students, even at the undergraduate level, fail to grasp the complexity of the urban water cycle and ecological health indicators. Schmid and Bogner (2018) found that German freshmen incorrectly believed that wastewater is cleaned to drinking water quality standards and recirculated directly, ignoring its discharge into and transformation within natural systems. Similarly, Gunckel et al.

(2012) described a learning progression study showing that students across age groups struggled to conceptualise invisible or cyclical elements of the water system, such as groundwater movement, evaporation, and biotic interdependence often defaulting to simplified and linear mental models.

In the context of ecological education, these misconceptions are further exacerbated by an overreliance on physical appearance (e.g., water clarity) rather than understanding the role of biodiversity and biological indicators in assessing ecosystem health. Without targeted interventions, such misconceptions hinder students' ability to develop systemic environmental thinking, which is essential for sustainability education.

2.2 Bioindicators as a Gateway to Ecological Literacy

Bioindicators are organisms whose presence or absence provides information about environmental conditions, particularly pollution levels, biodiversity stability, and ecosystem functioning (Parmar et al., 2016; Siddig et al., 2016). Teaching bioindicators in biology education has been recognised as a valuable strategy to help students connect observable species with ecological processes. Internationally, Eriksen et al. (2021) have highlighted the relevance of using riverine macroinvertebrates across continents, including Asia, for ecological monitoring and public education.

Locally, Fajeriadi et al. (2025) proposed a model that integrates ecological education into community-based agricultural practices in Indonesia. Their study emphasises how insects and local biodiversity serve as accessible ecological entry points for students and farmers alike, helping to bridge science education with real-world ecological roles. This kind of collaborative learning strengthens conservation values and food security while grounding scientific literacy in local realities.

2.3 Experiential and Field-Based Learning for Conceptual Change

Field-based learning has long been recognised as a powerful approach to challenge students' misconceptions and promote deep conceptual understanding. Studies such as those by Hale and Swearer (2017) and Cabello and Savec (2018) underscore how out-of-school environments act as a "third educator" that fosters more authentic engagement with ecological content. These immersive contexts provide sensory-rich and emotionally salient experiences that are difficult to replicate in the classroom.

Ayotte-Beaudet et al. (2023) found that contextualised outdoor science education significantly improved students' grasp of ecosystem relationships, particularly when students were prompted to observe biotic interactions in real time. These experiences facilitate conceptual change, particularly in how students define "healthy environments" beyond aesthetic or static indicators like water colour or cleanliness.

2.4 The Model of Educational Reconstruction (MER)

The Model of Educational Reconstruction (MER) provides a theoretical and methodological framework for transforming students' everyday conceptions into scientifically grounded understanding (Duit et al., 2012). MER comprises three interconnected components: (1) clarification and analysis of scientific content, (2) investigation of students' conceptions, and (3) design and evaluation of learning environments. This model emphasises that effective instruction must be informed by both disciplinary knowledge and empirical research on learners' thinking.

While earlier MER-based research in science and ecology education largely focused on documenting students' reliance on surface-level or static features of phenomena and the persistence of misconceptions, more recent work has demonstrated the potential of MER as a design-oriented framework for supporting conceptual reconstruction. For instance, Johann et al. (2024) developed and evaluated MER-informed, analogy-based learning activities in cell membrane biology by tracing students' conceptual development as thinking pathways during instruction. Through iterative cycles of design, enactment, and analysis, the activities helped students revise fragmented conceptions such as "barrier," "gatekeeper," and "environment," and reorganise them into a more coherent understanding of the functional relationship between membrane structure and biological processes. This line of evidence indicates that MER not only reveals students' initial conceptions, but also provides a theoretically grounded basis for designing and refining learning activities that foster deeper conceptual development in authentic learning contexts.

In this current study, MER guided the reconstruction of students' understanding of bioindicators through structured fieldwork, pre/post assessment, and reflective discussion. This approach aligns with prior MER research in other disciplines (e.g., Kersting et al., 2018; Sam et al., 2015), confirming the model's flexibility and impact in addressing complex scientific concepts through research-informed instructional design.

2.5 Environmental Education and Sustainability Goals

At the global policy level, environmental education is increasingly expected to support sustainable development goals (SDGs) by fostering eco-literacy, critical thinking, and behavioural change. UNESCO (2024), urges national curricula to include climate action and biodiversity conservation, emphasising that education must be rooted in real-world applications and local ecological contexts.

Campos-Ugaz et al. (2022) and Pena-Vega et al. (2022) highlight the growing body of research connecting youth participation in environmental learning with climate action and eco-citizenship. Indonesian reviews by Prayogo et al. (2024) similarly stress the need for experiential and locally grounded sustainability education to meet the challenges of ecological degradation and social transformation.

By engaging students in authentic learning through field-based comparisons of contrasting ecosystems, this study contributes to environmental education goals by strengthening students' abilities to assess ecological health scientifically and critically. It also promotes systems thinking and fosters the kind of environmental agency needed to meet long-term sustainability goals.

3. Methodology

The research employed a qualitative-descriptive design situated within a constructivist paradigm and was supported by quantitative pre- and post-test analysis. The qualitative dimension focused on describing and interpreting how students' conceptual understandings of bioindicators evolved through contextual, MER-guided learning experiences (Kersting et al., 2018). The quantitative data were used to complement this interpretation by examining changes in students' test performance before and after the learning intervention. The study was conducted at SMA Negeri 1 Puding Besar, Indonesia, involving 59 tenth-grade students from Class 10A and Class 10D, who participated in field-based learning integrated with MER phases. Participants were selected using purposive sampling based on their availability and school assignment, and all classes were taught by the same teacher to minimise instructional bias.

MER framework implementation phases include as shown in table 1: (1) Clarification and Analysis of Scientific Content: Core bioindicator concepts were selected through literature review and translated into student worksheets tailored for field observations. This phase ensured alignment with current ecological and environmental science frameworks; (2) Research on Teaching and Learning: Students' initial conceptions were explored via pre-tests and observations at two contrasting aquatic ecosystems (a reclaimed lake and a natural river). Their evolving understandings were analysed through post-tests, field notes, and reflections; and (3) Design and Evaluation of Learning Environments: Learning environments were designed to foster experiential learning, this phase not only structured the learning activities, but also served as an entry point for integrating engineering-oriented design practices into students' inquiry work. The MER approach was evaluated through both qualitative (student reflections, observations) and quantitative (pre and post-test comparisons) data (Duit et al., 2012).

An engineering-oriented design component also incorporated within the learning process the MER framework. Students were guided to design and refine their field-observation worksheets, including the selection of indicators, data categories, and recording formats used during ecosystem observations. This design stage required students to identify the problem context, define observation criteria, organise the structure of the data table, and iteratively adjust the tool based on feedback emerging from its use in the field. In doing so, the activity reflected authentic engineering practices in STEM learning, particularly the design–implementation–refinement cycle that supports purposeful tool construction and evidence-based data collection in real contexts (Belcher et al., 2025; English, 2016; National Research Council, 2012)

Data collection was conducted through pre-learning surveys of students' conceptions, assessments, and post-learning reflections to measure changes in students' conceptions. Student worksheets were used to record field observations, interviews were conducted to explore students' understanding, and documentation in the form of photos and videos was collected during field activities (Wang and Liang, 2022). Field observations were facilitated by Biology teachers at SMA Negeri 1 Puding Besar, who provided technical guidance to students during the research. This ensured that students could understand the worksheet instructions and accurately identify environmental indicators.

A rich array of data sources was used in this research, including pre/post conceptual assessments, student field observation worksheets, guided reflections, and interview transcripts. These multiple sources enabled a comprehensive picture of student learning. Methodological triangulation was used to validate findings and reduce bias, comparing assessment results, worksheet data, and interview insights to enhance credibility.

The locations included a reclaimed tin mining lake, which had clear water but low biodiversity, and the Upang River, which had less clear water but rich biodiversity. During the observations, students were asked to record the physical environmental conditions, biodiversity, and ecological relationships identifiable at each location (Pozuelo-Muñoz et al., 2023).

Four main stages of the research procedure consisted: planning, implementation, observation, and reflection (McKenney and Reeves, 2021). The planning stage involved the preparation of MER-based student worksheets, identification of research locations, and coordination with supervising teachers. The implementation stage included the pre-test, field observations, and online discussions. A 90-minute virtual meeting was used as a forum to align students' observations with scientific concepts. During the observation stage, students' participation in the learning process was recorded in detail. The reflection stage was used to analyse learning outcomes and evaluate the conceptual gaps that were successfully addressed.

Table 1: Implementation of MER Phases in the Learning Design

MER Phases	Main Activities in This Study	Expected Outcomes
Phase 1: Clarification and Analysis of Science Content	Selection and clarification of bioindicator concepts from scientific literature; integration of biodiversity and ecological reasoning into student worksheets and discussions.	Scientifically accurate and educationally significant learning materials that connect biodiversity with environmental quality.
Phase 2: Research on Teaching and Learning	Pre-tests to assess misconceptions; field observations at two ecosystems; student reflections and interviews to capture conceptual shifts.	Documentation of students' initial conceptions and identification of conceptual change throughout the learning process.
Phase 3: Design and Evaluation of Learning Environments	Field-based learning activities integrating the collaborative design, use, and refinement of the observation worksheet as a STEM-oriented, engineering-related design practice. These activities were followed by online discussions, reflection activities, and post-tests to evaluate learning outcomes.	Research-informed learning design that supports conceptual reconstruction and aligns with sustainability education goals.

Source: (Duit et al., 2012)

Data were analysed using qualitative content analysis (Mayring, 2014), involving data reduction, coding, and category development to identify conceptual patterns. To enhance internal validity, the study employed methodological triangulation, comparing students' conceptual gains across pre/post-tests, field notes, reflection essays, and interviews to confirm that learning outcomes were consistent across instruments and not limited to one mode of evaluation.

In addition to the qualitative analysis, quantitative data from the pre-test and post-test were analysed using descriptive statistics (mean and standard deviation). Effect size was calculated using Cohen's d to estimate the magnitude of improvement between the two tests (Brydges, 2019). Furthermore, normalised gain (N-gain) was computed to describe the relative increase in students' performance with respect to the maximum attainable score, following Hake's classification criteria (Nagarsheth and Sharma, 2020).

This research was conducted in November 2024, where both the researcher and an assisting Biology teacher were present during fieldwork. While the researcher oversaw the study, the teacher helped manage student interactions and activities, ensuring smooth observations. Online discussions led by the researcher further supported the comprehensive reconstruction of students' conceptions.

All participants provided informed consent, and ethical approval was obtained from the relevant institutional review board. Student identities were anonymised to protect privacy

4. Results and Discussion

This study aimed to bridge the conceptual gap between students and scientists regarding bioindicators using MER. The results show a substantial increase in students' performance between the pre-test and post-test. None of the students achieved the Minimum Competency Standard (MCS ≥ 70) in the pre-test, whereas 54 out of 59 students (approximately 92%) met or exceeded the MCS in the post-test (Figure 1). The distribution of scores across performance categories is presented in Table 2, while summary statistics, including effect size and N-gain, are shown in Table 3.

4.1 Student Assessment Results: Conceptual Gains Through MER Implementation

The analysis of pre-test and post-test scores demonstrates a significant improvement in student understanding. The mean pre-test score was 49.92, whereas the mean post-test score increased to 81.17, reflecting an average improvement of 31.25 points.

4.1.1 Score Distribution Comparison

The pre-test results show that most students (21 out of 59) scored below 50, indicating limited initial understanding of bioindicators, whereas in the post-test, 40 out of 59 students scored above 80, demonstrating substantial conceptual improvement (see Table 2).

Table 2: Distribution of Assessment Results

Score Range	Pre-Test (Number of Students)	Post-Test (Number of Students)
30-39	9	0
40-49	12	0
50-59	15	1
60-69	14	4
70-79	9	14
80-89	0	25
90-99	0	15

This distribution shows that prior to the study, students exhibited significant misconceptions or limited knowledge of bioindicators, with none of the students achieving the Minimum Competency Standard (MCS ≥ 70) in the pre-test (0%). Following the intervention, however, 92% of students (54 out of 59) met or exceeded the MCS, as illustrated in Figure 1.

Figure 1: Proportion of Students Achieving the Minimum Competency Standard (MCS ≥ 70) in The Pre-test and Post-test (n=59)

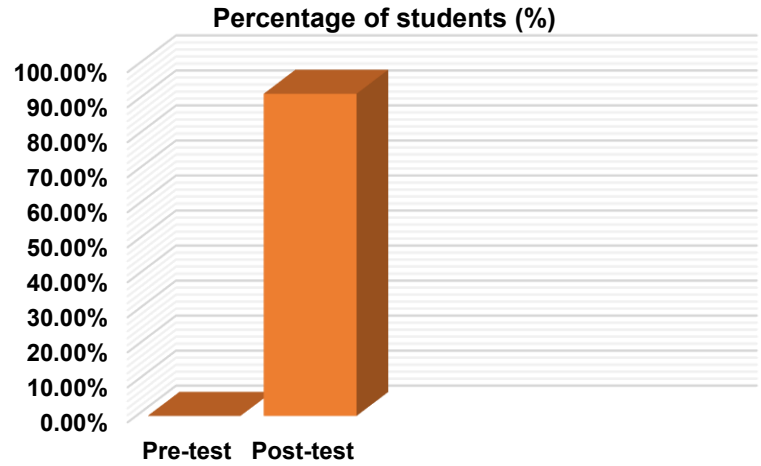

Table 3: Summary of Learning Gain Statistics

Measure	Pre-test M (SD)	Post-test M (SD)	Cohen's d	N-gain
Student's conceptual understanding	49.92 (11.74)	81.17 (9.53)	2.92	0.59

To complement the score distribution presented in Table 2, summary statistics of students' learning gains were calculated. As shown in Table 3, the mean pre-test score was 49.92 (SD = 11.74), whereas the post-test mean increased to 81.17 (SD = 9.53). A very large effect size was obtained (Cohen's d = 2.92), indicating substantial improvement in students' conceptual understanding following the MER-based field learning intervention. Consistent with this result, the mean N-gain score was 0.59, which falls within the medium improvement category.

4.1.2 Conceptual Shifts: Insights from Student Reflections and Field Observations

To further illustrate these conceptual shifts, a Before–After comparison of key concepts is presented in Table 4, demonstrating how students' understanding evolved through MER-based learning.

Table 4: Before and After Comparison of Key Concepts

Concept	Pre-Test Understanding	Post-Test and Reflection Understanding
Water Clarity and Health	Clear water means a clean, healthy environment.	Clear water can be misleading; biodiversity is a more reliable indicator of ecosystem health.
Role of Bioindicators	Limited awareness of species like frogs, dragonflies, and shrimp as indicators.	Recognised bioindicators as key to assessing environmental quality.
Importance of Biodiversity	Focused mainly on plant-based indicators of ecosystem health.	Understood that biodiversity, including aquatic organisms, plays a crucial role in ecosystem stability.
Human Impact Awareness	Pollution was seen primarily as visible waste.	Acknowledged that pollutants can be invisible and affect bioindicator species.

In addition to conceptual shifts, students' engagement with the collaborative design and refinement of the observation worksheet also emerged as a meaningful part of the learning process, although this aspect is elaborated further in the interpretation section.

This comparative analysis highlights how students moved from surface-level misconceptions to a scientifically aligned understanding of bioindicators and ecosystem health.

Students' pre-field reflections and initial survey responses revealed recurring misconceptions about environmental health and the role of bioindicators. Many associated clear waters with ecosystem quality and had limited awareness of organisms like frogs, dragonflies, and shrimp as indicators.

> *"Air yang jernih pasti bersih dan sehat." (Clear water must mean clean and healthy.) – SN (10th A, pre-test)*

> *"Yang penting tidak ada sampah plastik, berarti lingkungannya baik." (As long as there's no plastic trash, the environment must be healthy.) – RRS (10th D, pre-test)*

After the field activities and online discussions, students revised their understanding. Their post-field reflections indicate a more nuanced, scientifically aligned view:

> *"Saya baru sadar bahwa air yang jernih belum tentu sehat jika tidak ada keanekaragaman makhluk hidup di dalamnya." (I realised that clear water is not necessarily healthy if it lacks biodiversity.) – E (10th D, reflection)*

> *"Saya belajar bahwa bioindikator seperti udang kecil atau siput bisa memberi tahu kita tentang kondisi air." (I learned that bioindicators like small shrimp or snails can tell us about water conditions.) – FGK (10th D, reflection)*

This contrast between initial misconceptions and reconstructed understanding illustrates the effectiveness of MER in fostering meaningful conceptual change. It also highlights how real-world ecological contexts can challenge oversimplified student beliefs and support eco-literacy development.

Furthermore, the integration of student reflections and field observations reveals key conceptual changes.

4.1.3 Understanding Bioindicators and Water Quality

Student Reflections: Students such as NSY, FGK, and MA emphasised that frogs, dragonflies, shrimp, and snails are critical bioindicators. They learned that these organisms help assess ecosystem health beyond just water clarity.

> *"Saya belajar bahwa bioindikator seperti udang kecil atau siput bisa memberi tahu kita tentang kondisi air." (I learned that bioindicators, such as small shrimp or snails, can provide valuable insights into the condition of water.) – FGK (10th D, reflection)*

Field Observations: During site visits, students observed that biodiversity-rich water bodies (e.g., natural rivers) appeared healthier than artificial lakes that were clear but lacked species diversity.

4.1.4 Misconceptions About Water Clarity and Environmental Health

Student Reflections: Students like J, E, and SN noted that clear water is not always a sign of environmental health.

> *"Saya baru sadar bahwa air yang jernih belum tentu sehat jika tidak ada keanekaragaman makhluk hidup di dalamnya." (I have come to realise that clear water is not necessarily healthy if it lacks biodiversity within it.) – E (10th D, reflection)*

Field Observations: Students compared a slightly turbid river to an artificial lake with clear water. The river supported greater biodiversity, reinforcing that ecosystem health is not solely determined by visual clarity.

4.1.5 Importance of Biodiversity in Ecosystem Balance

Student Reflections: Students including KF, MI, and YA realised that biodiversity contributes to a balanced ecosystem.

> *"Keanekaragaman makhluk hidup di sungai itu penting, karena kalau hanya ada sedikit jenisnya, mungkin lingkungannya sedang tidak baik-baik saja." (The diversity of organisms in the river is important. If there are only a few species, it might indicate environmental stress.) – YA (10th A, reflection)*

Field Observations: Rivers with high species diversity (fish, insects, amphibians) appeared more resilient and dynamic, highlighting biodiversity's role in maintaining ecological stability.

4.1.6 Shift in Perception About Environmental Health

Student Reflections: Initially, students such as C, MB, and RRS believed environmental health meant cleanliness and clear water.

> *"Sungai yang terlihat keruh ternyata bisa lebih alami dan mendukung kehidupan dibandingkan danau buatan." (A river that appears turbid can, in fact, be more natural and supportive of life compared to an artificial lake.) – C (10th D, reflection).*

Field Observations: Rivers with natural systems, with their complex biogeochemical processes, often possess greater ecological integrity and capacity to support life than anthropogenically modified water bodies designed for aesthetic purposes. This culminated in a more sophisticated, function-oriented framework for evaluating environmental health.

4.2 Methodological Triangulation: Validating Learning Gains

The use of triangulation significantly enhanced the validity of this study. By cross-analysing student performance data, worksheet content, and interview narratives, the study was able to verify conceptual changes beyond rote test performance. The consistency of themes emerging from independent data points such as the recognition of biodiversity as a core indicator of environmental quality confirms the authenticity of learning gains. This methodological strength supports the reliability of findings and aligns with best practices in educational research (Arias Valencia, 2022).

4.3 Interpretation of Findings

The learning environment centred around field visits to contrasting ecosystems was deliberately designed based on the MER framework. Drawing on research about misconceptions and eco-literacy, the activities aimed to shift student thinking from visual assessment (water clarity) to ecological reasoning (biodiversity and bioindicators). The design was iteratively refined based on observations and post-activity reflections, and its success was evaluated through triangulated assessment data. In this way, the learning environment served both as an instructional tool and a subject of empirical research.

The assessment results demonstrate that the implementation of the Model of Educational Reconstruction (MER) significantly improved students' understanding of bioindicator concepts. Most students achieved competency benchmarks, with the majority scoring between 80-90. Quantitative findings strengthen this interpretation, very large effect size and medium N-gain indicate that the improvement was not limited to a small subset of students, but reflected a consistent and substantial shift in conceptual understanding across the cohort. This suggests that the MER-based field learning design did not merely support incremental knowledge acquisition, but facilitated a broad conceptual reconstruction that was reinforced through students' engagement with authentic ecological contexts. This indicates also that the learning strategy, which combined field observations with reflective discussions, helped students not only grasp the basic definition of bioindicators but also expand their understanding of the ecological role of bioindicators in assessing environmental health (Ludvigsen et al., 2020).

Consistent with Rohmah et al. (2023), conceptualised contextual learning as an integrated system involving learning outcomes, processes, resources, assessment, and collaboration with community-based programmes, authentic environments function not only as learning settings but also as substantive sources of meaning-making for students. In such approaches, real-world programmes and local issues provide learning resources that connect students' activities with purposeful experiences and support the development of knowledge, skills,

attitudes, and values in situated contexts. In line with this perspective, the present study situates learning within authentic ecological settings, where direct observations of two contrasting ecosystems the reclaimed lake and the natural river enabled students to examine firsthand the relationship between water quality, biodiversity, and ecosystem conditions. These contextual learning experiences played a central role in supporting conceptual reconstruction, demonstrating how engagement with real environments can deepen students' understanding of scientific concepts and strengthen their ecological reasoning. These experiences not only support biology content goals but also align with international frameworks promoting eco-literacy and sustainability, as outlined in the Greening Curriculum Guidance (UNESCO, 2024).

Student reflections also reveal significant shifts in thinking. Previously, many students associated a healthy environment solely with the absence of trash or clear water. After the learning process, students began to understand that clear water does not always signify a healthy environment, as seen in their observations of the reclaimed lake, which had clear water but low biodiversity. Conversely, they recognised the importance of biodiversity as an indicator of ecosystem quality, as observed in the natural river, which had murky water but rich biodiversity (Hale and Swearer, 2017). This reflects students' ability not only to absorb new information but also to integrate it into a more complex framework of thinking. This transformation aligns with the goals of MER, which aims to bridge students' initial conceptions with scientific concepts through experience-based conceptual reconstruction (Sam et al., 2015).

In addition to supporting conceptual reconstruction, the learning process also fostered students' engagement with design-oriented thinking as part of their inquiry work. Through the collaborative design and refinement of the observation worksheet used during fieldwork, students were required to define indicators, organise data categories, and iteratively adjust the tool based on their field experiences. This design–evaluate–improve cycle mirrors engineering-oriented practices in STEM learning, where the construction of purposeful artefacts or tools functions as a catalyst for deeper engagement with disciplinary knowledge and evidence-based reasoning in authentic contexts (Belcher et al., 2025; English, 2016; National Research Council, 2012). These findings suggest that students' learning did not only occur at the conceptual level, but also at the level of design activity embedded in the learning process.

Furthermore, these findings underscore that MER-based learning, which incorporates direct observations and reflective discussions, can be an effective approach to addressing student misconceptions. Field experiences not only provide students with opportunities to validate the concepts they learn but also encourage them to question and evaluate their initial understanding (Ayotte-Beaudet et al., 2023). Through this approach, students demonstrated progress in understanding ecosystem complexity and the importance of scientific methods in assessing environmental conditions. This narrative aligns with student reflections, which reveal a newfound awareness of more comprehensive ecological indicators (Chang, 2019).

Overall, the interpretation of these findings confirms that integrating MER with contextual learning activities fosters understanding that is not only scientifically relevant but also beneficial in building students' ecological awareness. This approach can serve as a replicable learning model for various ecological topics, especially those requiring direct observation of environmental phenomena. Students not only gain scientific understanding but also acquire the tools to contribute to environmental conservation in the future (Thor and Karlsudd, 2020).

5. Conclusion

This study demonstrates that MER-guided, field-based STEM learning can effectively support the reconstruction of students' conceptual understanding of bioindicators by engaging them with authentic ecological contexts. The learning process enabled students to move beyond surface-level interpretations of environmental conditions toward scientific reasoning grounded in biodiversity evidence and indicator species.

The findings also indicate that the design dimension of the learning process played an important role, as students collaboratively designed and refined the observation worksheet used in the field. This process positioned fieldwork not only as an inquiry activity, but as an engineering-informed learning experience in which design, refinement, and evidence-based reasoning were closely integrated with students' engagement with real environments.

These results highlight the potential of MER-informed approaches for strengthening biodiversity literacy and STEM practices in school contexts, particularly in regions where local ecosystems can be meaningfully incorporated into learning. Future studies may extend this work by examining how similar learning designs operate across different contexts and by exploring more systematic ways of assessing students' design-oriented competencies.

Declaration of AI Assistance

The authors confirm that generative AI tools were not used to generate original ideas, research findings, data analysis, or interpretations in this study. Limited digital tools such as reference-management software (e.g., Mendeley) were used to organise citations and format the bibliography, and language-checking tools were employed only for minor editorial refinement after the full manuscript was drafted by the authors. All intellectual contributions, arguments, and conclusions remain the responsibility of the authors, and the manuscript has been carefully reviewed to ensure accuracy and originality.

References

Arias Valencia, M. M. (2022). Principles, scope, and limitations of methodological Triangulation. *Investigación y Educación en Enfermería*, *40*(2), e03. https://pmc.ncbi.nlm.nih.gov/articles/PMC9714985/

Ayotte-Beaudet, J.-P., Chastenay, P., Beaudry, M.-C., L'Heureux, K., Giamellaro, M., Smith, J., Desjarlais, E., & Paquette, A. (2023). Exploring the impacts of contextualised outdoor science education on learning: the case of primary school students learning about ecosystem relationships. *Journal of Biological Education*, *57*(2), 277–294. https://doi.org/10.1080/00219266.2021.1909634

Belcher, M., Confrey, J., Krupa, E. E., & Borden, M. L. (2025). The design & pitch challenges in STEM: A theoretical framework for centering mathematics learning in entrepreneurial pitch competitions. *Education Sciences*, *15*(6), 651. https://doi.org/10.3390/educsci15060651

Brydges, C. R. (2019). Effect size guidelines, sample size calculations, and statistical power in gerontology. *Innovation in Aging, 3*(4), 1–8. https://doi.org/10.1093/geroni/igz036

Cabello, V. M., & Savec, V. F. (2018). Out of school opportunities for science and mathematics learning: Environment as the third educator. *LUMAT: International Journal on Math, Science and Technology Education*, *6*(2), 3–8. https://doi.org/10.31129/LUMAT.6.2.353

Campos-Ugaz, W. A., Saavedra-López, M. A., Sierra-Liñan, F., Garay-Argandoña, R., Aguilar,

O. O. Á., Hernández, R. M., & Rodríguez-Vargas, M. C. (2022). Education in environmental health: scientific contributions of the last 20 years. *Boletin de Malariologia y Salud Ambiental*, *62*(5), 1067–1078. https://www.scopus.com/pages/publications/85143289710

Carson, R. (1962). *Silent Spring* (Crest Rper.). Fawcett Publications. https://library.uniteddiversity.coop/More_Books_and_Reports/Silent_Spring-Rachel_Carson-1962.pdf

Chang, B. (2019). Reflection in learning. *Online Learning*, *23*(1), 95–110. https://doi.org/10.24059/olj.v23i1.1447

Duit, R., Gropengießer, H., Kattmann, U., Komorek, M., & Parchmann, I. (2012). The model of educational reconstruction: A framework for Improving Teaching and Learning Science. In D. Jorde & J. Dillon (Eds.), *Science Education Research and Practice in Europe: Retrospective and Prospective* (Vol. 5, pp. 13–37). Sense Publishers. https://doi.org/10.1007/978-94-6091-900-8_2

English, L. D. (2016). STEM education K–12: Perspectives on integration. *International Journal of STEM Education*, *3*, Article 3. https://doi.org/10.1186/s40594-016-0036-1

Eriksen, T. E., Brittain, J. E., Søli, G., Jacobsen, D., Goethals, P., & Friberg, N. (2021). A global perspective on the application of riverine macroinvertebrates as biological indicators in Africa, South-Central America, Mexico and Southern Asia. *Ecological Indicators*, *126*, Article 107609. https://doi.org/10.1016/j.ecolind.2021.107609

Fajeriadi, H., Nugroho, B. A., Fahmi, F., & Arisandi, R. (2025). The ecological roles of diurnal flying insects in agriculture and their potential for collaboration in biology education. *Jurnal Penelitian Pendidikan IPA*, *11*(5), 860–868. https://doi.org/10.29303/jppipa.v11i5.11041

Gunckel, K. L., Covitt, B. A., Salinas, I., & Anderson, C. W. (2012). A learning progression for water in socio-ecological systems. *Journal of Research in Science Teaching*, *49*(7), 843–868. https://doi.org/https://doi.org/10.1002/tea.21024

Hale, R., & Swearer, S. E. (2017). When good animals love bad restored habitats: how maladaptive habitat selection can constrain restoration. *Journal of Applied Ecology*, *54*(5), 1478–1486. https://doi.org/https://doi.org/10.1111/1365-2664.12829

Johann, L. I., Rusk, F. K. H., Reiss, M. J., & Groß, J. (2024). *Upper secondary students' thinking pathways in cell membrane biology – An evidence-based development and evaluation of learning activities using the Model of Educational Reconstruction*. *Journal of Biological Education, 58*(1), 144–165. https://doi.org/10.1080/00219266.2022.2026805

Kersting, M., Henriksen, E. K., Bøe, M. V., & Angell, C. (2018). General relativity in upper secondary school: Design and evaluation of an online learning environment using the model of educational reconstruction. *Physical Review Physics Education Research*, *14*(1), Article 010130. https://doi.org/10.1103/PhysRevPhysEducRes.14.010130

Ludvigsen, K., Krumsvik, R. J., & Breivik, J. (2020). Behind the scenes: Unpacking student discussion and critical reflection in lectures. *British Journal of Educational Technology*, *51*(6), 2478–2494. https://doi.org/https://doi.org/10.1111/bjet.12922

Mayring, P. (2014). *Qualitative Content Analysis: Theoretical Foundation, Basic Procedures and Software Solution*. https://nbn-resolving.org/urn:nbn:de:0168-ssoar-395173

McKenney, S., & Reeves, T. C. (2021). Educational design research: Portraying, conducting, and enhancing productive scholarship. *Medical Education*, *55*(1), 82–92. https://doi.org/https://doi.org/10.1111/medu.14280

Nagarsheth, H., & Sharma, N. (2020). Relative normalized gain array-based interaction indicator for non-square multivariable control systems: Properties and application.

IFAC- PapersOnLine, *53*(2), 4032–4037. https://doi.org/10.1016/j.ifacol.2020.12.2270

National Research Council. (2012). *A framework for K–12 science education: Practices, crosscutting concepts, and core ideas*. The National Academies Press. https://doi.org/10.17226/13165

Parmar, T. K., Rawtani, D., & Agrawal, Y. K. (2016). Bioindicators: the natural indicator of environmental pollution. *Frontiers in Life Science*, *9*(2), 110–118. https://doi.org/10.1080/21553769.2016.1162753

Pena-Vega, A., Cohen, M., Flores, L. M., Le Treut, H., Lagos, M., Castilla, J. C., Gaxiola, A., & Marquet, P. (2022). *Young people are changing their socio-ecological reality to face climate change: Contrasting transformative youth commitment with division and inertia of governments*. *Sustainability, 14*(22), 15116. https://doi.org/10.3390/su142215116

Pozuelo-Muñoz, J., Calvo-Zueco, E., Sánchez-Sánchez, E., & Cascarosa-Salillas, E. (2023). *Science skills development through problem-based learning in secondary education*. *Education Sciences, 13*(11), 1096. https://doi.org/10.3390/educsci13111096

Prayogo, W., Ratnaningsih, W., Suhardono, S., & Suryawan, I. W. K. (2024). Environmental education practices in Indonesia: A review. *Journal of Sustainable Infrastructure*, *3*(1), 27–37. https://doi.org/10.61078/jsi.v3i1.27

Rohmah, N., Azza, A., & Dewi, I. C. (2023). Development of contextual learning models through collaboration between lecturers, students, and village governments in nursing education. *Korean Journal of Medical Education*, *35*(1), 71–83. https://doi.org/10.3946/kjme.2023.250

Sam, A., Niebert, K., Hanson, R., Twumasi, A. K. (2015). The Model of Educational Reconstruction: Scientists' and Students' Conceptual Balances to Improve Teaching of Coordination Chemistry in Higher Education. *International Journal of Academic Research and Reflection*, *3*(7), 67–77. https://www.idpublications.org/wp-content/uploads/2015/09/Full-Paper-The-Model-of-Educational-Reconstruction.pdf

Schmid, S., & Bogner, F. X. (2018). Is there more than the sewage plant? University freshmen's conceptions of the urban water cycle. *PLOS ONE*, *13*(7), e0200928. https://doi.org/10.1371/journal.pone.0200928

Siddig, A. A. H., Ellison, A. M., Ochs, A., Villar-Leeman, C., & Lau, M. K. (2016). How do ecologists select and use indicator species to monitor ecological change? Insights from 14 years of publication in Ecological Indicators. *Ecological Indicators*, *60*, 223–230. https://doi.org/https://doi.org/10.1016/j.ecolind.2015.06.036

Smith, K. J., Evans, M. J., Gordon, I. J., Pierson, J. C., Mcintyre, S., & Manning, A. D. (2023). Countering ecological misconceptions with strategic translocation and assessment of microhabitat use. *Biological Conservation*, *284*, Article 110143. https://doi.org/10.1016/j.biocon.2023.110143

Stevenson, K. T., Peterson, M. N., Carrier, S. J., Strnad, R. L., Bondell, H. D., Kirby-Hathaway, T., & Moore, S. E. (2014). *Role of significant life experiences in building environmental knowledge and behavior among middle school students*. *The Journal of Environmental Education, 45*(3), 163–177. https://doi.org/10.1080/00958964.2014.901935

Thor, D., & Karlsudd, P. (2020). *Teaching and fostering an active environmental awareness design, validation and planning for action-oriented environmental education*. *Sustainability, 12*(8), 3209. https://doi.org/10.3390/su12083209

UNESCO. (2024). *Greening curriculum guidance: Teaching and learning for climate action*. UNESCO. https://doi.org/10.54675/AOOZ1758

Wang, J., & Liang, K. (2022). A cognitive diagnosis method in adaptive learning system based on preconceptions. *Scientific Programming*, *2022*(1), Article 5011804. https://doi.org/https://doi.org/10.1155/2022/5011804

TRACING THE PATHWAYS OF BS APPLIED PHYSICS GRADUATES OF USTP: EMPLOYABILITY, SKILLS, AND CURRICULUM RELEVANCE IN STEM EDUCATION

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ABSTRACT

This tracer study investigates the employment outcomes, academic pursuits, and skills application of the first three cohorts (2022–2024) of Bachelor of Science in Applied Physics graduates from the University of Science and Technology of Southern Philippines (USTP). An online survey captured responses on employment status, industry placement, graduate studies, and the perceived relevance of programme outcomes. Results show that more than 70% of graduates are employed primarily in the education, manufacturing, and government sectors, while a notable proportion pursued postgraduate studies in physics and related disciplines. Graduates consistently rate programme outcomes such as critical thinking, data analysis, and communication as highly relevant to their professional and academic roles. Despite the limited presence of physics-focused industries in Northern Mindanao, Philippines, alumni demonstrated adaptability by applying their interdisciplinary STEM training across diverse occupational contexts, including finance, administration, and community development. Thematic accounts further revealed that problem-solving, systems thinking, and lifelong learning are central to their success, reflecting the strength of the programme's integration of science, mathematics, and technology with real-world problem-solving. These findings provide evidence of the programme's effectiveness in equipping graduates with both technical and transferable skills that align with labour market needs and advanced study pathways. More broadly, the study contributes to the discourse on STEM education in Southeast Asia by demonstrating how a physics programme designed with outcomes-based and interdisciplinary frameworks can prepare graduates to become adaptable, future-ready professionals.

Keywords: Tracer Study, Employability, STEM Education, Physics Graduates, Curriculum Relevance, USTP

1. Introduction

The role of higher education in national development has never been more crucial than in today's fast-evolving, technology-driven global landscape (World Bank, 2025; World Economic Forum, 2025). As economies increasingly rely on knowledge production, innovation, and interdisciplinary problem-solving, the demand for graduates equipped with relevant technical expertise and adaptive skills has grown exponentially. In response to these realities, the Philippine government, through Republic Act No. 7722 or the Higher Education Act of 1994, mandated the Commission on Higher Education (CHED) to steer higher education institutions (HEIs) toward producing quality and relevant graduates (Higher Education, 1994). Central to this mandate is the adoption of Outcomes-Based Education (OBE), institutional typology, and quality assurance mechanisms as articulated in CHED Memorandum Order (CMO) No. 46, series of 2012 (Commission on Higher Education, 2012).

In line with these national reforms, the Department of Education began the nationwide roll-out of the K–12 Basic Education Curriculum in School Year 2012–2013, pursuant to DepEd Order No. 31 (s. 2012). This reform was later institutionalised through the Enhanced Basic Education Act (Republic Act No. 10533) enacted in 2013 (Department of Education, 2012). The first batch of senior high school graduates, having completed Grades 11 and 12, entered college in Academic Year 2018–2019. This milestone catalysed significant curricular revisions across Philippine HEIs, as institutions recalibrated their undergraduate programmes to accommodate better prepared but also more specialised incoming students. Within this broader national transformation, the University of Science and Technology of Southern Philippines – Cagayan de Oro Campus (USTP-CDO) introduced a curricular shift in its undergraduate physics offering, transitioning from the Bachelor of Science in Applied Physical Sciences to the more discipline-focused Bachelor of Science in Applied Physics programme.

The BS Applied Physics programme was launched in Academic Year 2018–2019 to align with the outcomes-based and industry-responsive education thrust of the university and national education agenda. While the previous BS Applied Physical Sciences programme provided a generalised interdisciplinary foundation, the new BS Applied Physics curriculum was designed to deepen students' understanding of core physical principles while enhancing their practical competencies in areas such as instrumentation, data acquisition and analysis, computational modelling, and applied research. This restructuring was also informed by the university's commitment to cultivating graduate attributes such as innovative thinking, resilience, and scientific communication which are qualities seen as essential in preparing students for complex real-world challenges.

With this significant curriculum enhancement, there emerged a need to evaluate whether the new programme successfully achieved its intended outcomes. The present tracer study was therefore conceptualised to track and assess the early performance of the first three graduating cohorts of the BS Applied Physics programme: those who graduated in 2022, 2023, and 2024. Specifically, the study examined employment status, occupational placement, graduate studies pursued, perceived relevance of programme outcomes, trends in employability, and success stories. The findings aim to provide empirical evidence that supports curriculum review, accreditation, and institutional quality assurance, while also contributing to the broader discourse on STEM education in Southeast Asia.

2. Methodology

The study employed a descriptive research design to trace the employment outcomes and assess the academic and professional trajectories of Bachelor of Science in Applied Physics graduates from the University of Science and Technology of Southern Philippines – Cagayan de Oro Campus (USTP-CDO). Descriptive designs are widely recommended for graduate tracer studies (Cedefop, European Training Foundation and International Labour Office, 2016).

The study covered three cohorts of graduates from Academic Years 2021–2022, 2022–2023, and 2023–2024. A purposive sampling technique was used to reach graduates who could provide information relevant to the study's objectives. The survey was conducted online using Google Forms and was disseminated through social media platforms, email, and messenger groups. Participation was voluntary, and respondents were informed of the confidentiality of their responses.

The instrument used in the study was a structured questionnaire composed of seven parts: (1) Demographic Information, (2) Career Mobility of Graduates, (3) Graduate Studies, (4) Relevance of Skills and Programme Outcomes, (5) Trends in Employability, and

(6) Success Stories. The survey captured both quantitative and qualitative data to assess graduate attributes, academic preparation, and post-graduation milestones. Descriptive statistics such as frequencies, percentages, and means were used to summarise the responses of the participants. Where applicable, effect size was reported to quantify the magnitude of cohort-related variation in categorical outcomes using Cramér's V. In this study, Cramér's V values closer to 0 indicate minimal cohort-related variation, while larger values indicate stronger differences in the distribution of outcomes across cohorts. The magnitude of association was interpreted using conventional guidelines, with values around 0.10, 0.30, and 0.50 indicating small, moderate, and large associations, respectively (REF) Qualitative responses, particularly those from the open-ended section on success stories, were grouped thematically to identify significant insights and patterns in graduate experiences.

3. Results and Discussion

3.1 Demographic Information

Table 1: Survey Return Rate

School Year (SY) Graduated	Percentage
SY 2021-2022	66.67
SY 2022-2023	81.25
SY 2023-2024	87.50
Total 2021-2024	78.79

Note SY = School Year or Academic Year

As shown in Table 1, the tracer study achieved strong participation across the three cohorts of BS Applied Physics graduates from USTP-CDO, yielding an overall response rate of 78.79 percent. The highest proportion of respondents came from the most recent cohort, with 87.50 percent of the 2023–2024 graduates completing the survey. This was followed by 81.25 percent from the 2022–2023 batch and 66.67 percent from the 2021–2022 cohort. The consistently high engagement, particularly among more recent graduates, may be attributed to stronger digital connectivity and more active institutional linkages through alumni networks and online platforms. These participation rates ensure that the study captures a sufficiently representative picture of graduate outcomes across the three academic years. In the context of STEM education research, such strong return rates not only strengthen the reliability of the findings but also reflect the continuing sense of connection between the institution and its graduates, an important factor in sustaining feedback mechanisms for curriculum improvement and programme evaluation.

3.2 Career Mobility of Graduates

The employment patterns of BS Applied Physics graduates shown in Figure 1 reveal a strong balance between workforce participation and further academic pursuits. More than half of the respondents (57.7%) reported being employed full-time, while 11.5% were engaged in part-time work. A small proportion (3.8%) combined full-time employment with graduate studies, and 26.9% were not employed but were pursuing advanced degrees. These findings suggest that the majority of graduates have successfully transitioned into the labour market, while a significant portion have chosen to deepen their academic training. The distribution reflects both the employability of graduates and the programme's capacity to cultivate pathways toward postgraduate education. When disaggregated by cohort, the status distribution showed a moderate association with cohort (Cramér's V = 0.45). This indicates that the relative shares of employment and graduate-study pathways vary to a meaningful extent across the three graduating cohorts, rather than remaining uniform over time.

Figure 1: Employment and Graduate Study Status of BS Applied Physics Graduates.

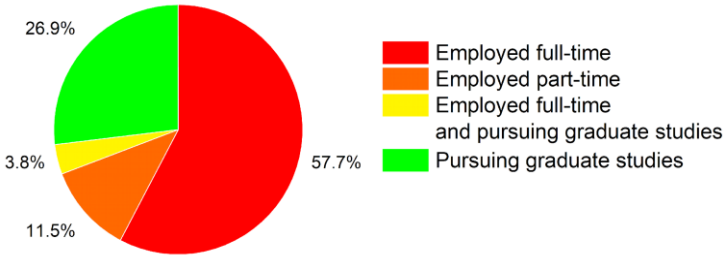


Figure 2: Industry Sectors Entered by BS Applied Physics Graduates.

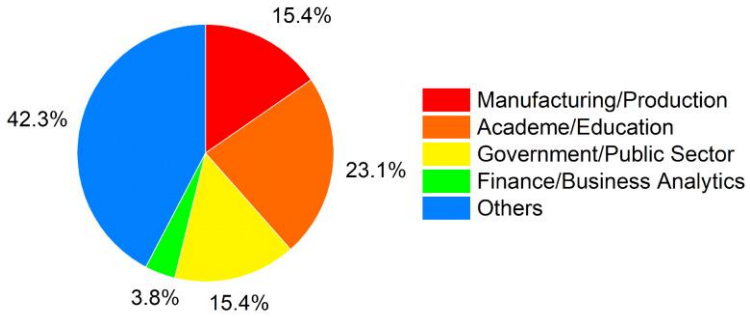


Figure 3: Current Job Titles Held by BS Applied Physics Graduates.

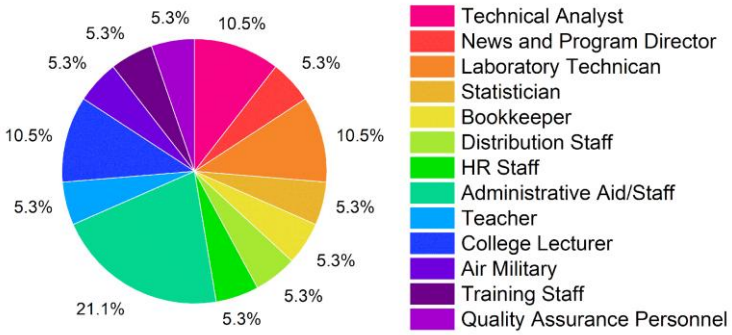
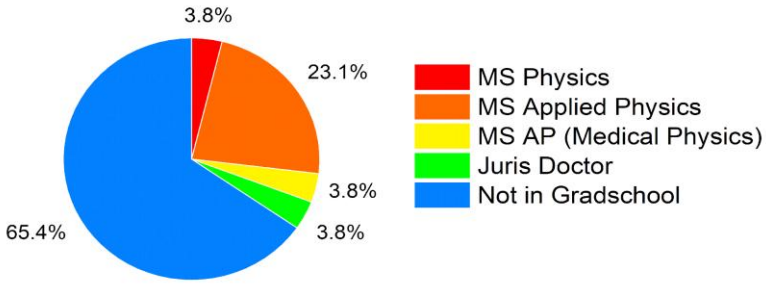


Figure 2 presents the distribution of respondents by industry sector, based on their self-reported employment sector at the time of the survey. The academe and education sector was the most frequently cited destination (23.1%), followed by manufacturing and production (15.4%) and government service (15.4%). A smaller share (3.8%) reported employment in finance and business analytics, while 42.3% indicated work in sectors beyond those listed. A thematic review of the graduates' open-ended sector entries and reported job titles suggests that this "other" category is primarily composed of three recurring clusters: (i) administrative services (e.g., administrative staff, HR personnel, bookkeeping), (ii) media and communications roles (e.g., news and programme director), and (iii) analytics or ICT-oriented roles (e.g., technical analyst, statistician). The presence of graduates across such varied sectors underscores the versatility of physics training, particularly when integrated with interdisciplinary STEM competencies such as data analysis, systems thinking, and problem-solving. Even in regions such as Northern Mindanao, where opportunities in scientific research and high-technology industries are relatively limited, graduates demonstrated the ability to apply their skills in diverse contexts, including education, administration, and business. When disaggregated by cohort, the employment sector showed a large association with cohort (Cramér's V = 0.60), meaning that the sector distribution differed substantially across cohorts instead of showing a similar pattern across graduating years.

Figure 3 summarises the current job titles reported by the respondents at the time of the survey. While some graduates reported roles directly aligned with technical training such as technical analyst, statistician, and laboratory technician, others entered positions such as administrative staff, HR personnel, bookkeeper, or news and programme director. The range of occupations suggests that the programme equips students not only with domain-specific expertise but also with transferable skills valued in multiple professional contexts. Communication, teamwork, and organisational management emerged as equally critical as technical competencies, reflecting the interdisciplinary design of the BS Applied Physics programme. Taken together, these findings illustrate that the programme prepares graduates to succeed in both STEM-focused and non-STEM sectors, reinforcing the importance of physics education as a foundation for adaptable, future-ready professionals.

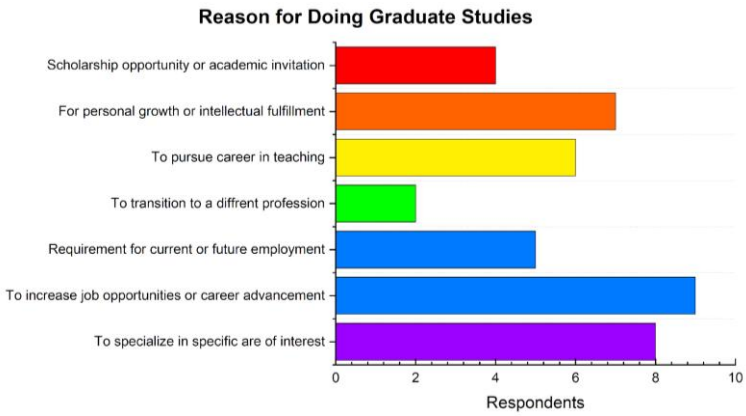
3.3 Graduate Studies Pursued

Figure 4: Percentage of Graduates Pursuing Graduate Studies.



The results in Figure 4 indicate that the majority of BS Applied Physics graduates (65.4%) had not yet enrolled in graduate school at the time of the survey, reflecting a stronger immediate inclination toward employment and other professional pursuits. Nevertheless, a substantial segment of graduates demonstrated interest in continuing their academic development. Among those who pursued advanced studies, the most frequently chosen programme was the Master of Science in Applied Physics (23.1%). Smaller proportions of respondents enrolled in MS Physics, MS Applied Physics with a specialisation in Medical Physics, and Juris Doctor programmes, each accounting for 3.8% of the responses. These findings highlight that while many graduates are currently integrating into the workforce, a meaningful subset remains engaged in deepening their expertise within physics or applying their analytical training to related fields such as law.

Figure 5: Percentage of Graduate Pursuing Graduate Studies



Graduates cited a variety of motivations for pursuing graduate education as shown in Figure 5. The most common reasons were career advancement and the desire to gain specialised knowledge in areas of interest, followed by aspirations for personal growth, intellectual

fulfilment, and meeting professional requirements in teaching or specialised employment. Some respondents also pointed to scholarship opportunities or academic invitations as influential factors in their decision to continue studying. These responses suggest that the BS Applied Physics programme provides a strong disciplinary foundation that not only equips graduates for immediate employability but also fosters academic confidence to pursue postgraduate training. The fact that most of the graduate programmes chosen remain within physics or closely related disciplines underscores the relevance of the undergraduate curriculum and its ability to prepare students for advanced STEM pathways.

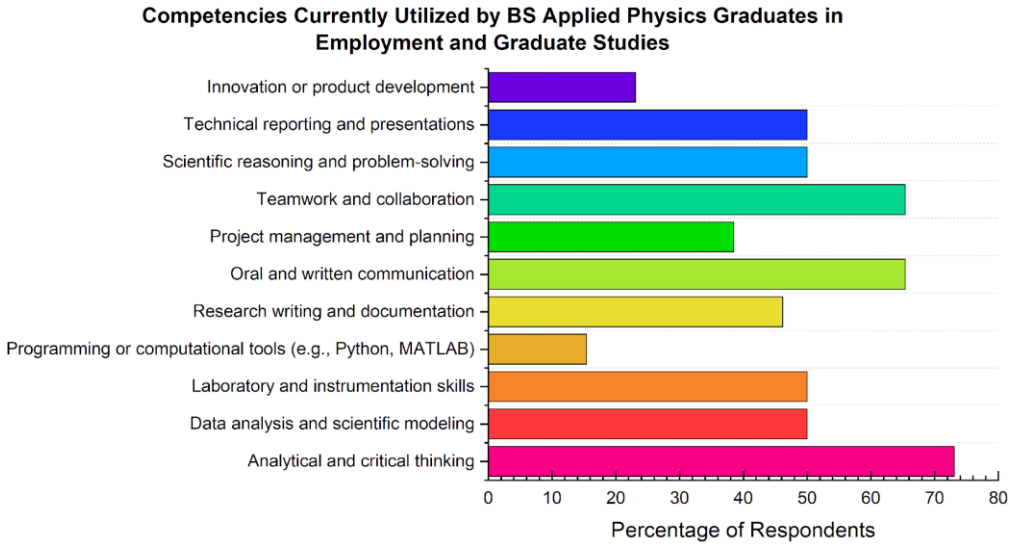
3.4 Relevance of Skills and Programme Outcomes

Graduates rated the applicability of the BS Applied Physics programme outcomes using a five-point Likert scale, and all twelve outcomes were perceived as either relevant or highly relevant to their current professional or academic engagements. The results are shown in Table 2. The highest score was recorded for the outcome on engaging in lifelong learning (4.54), followed by demonstrating professional, social, and ethical responsibility (4.31), and three outcomes tied at 4.12: design and conduct experiments, analyse and interpret data, applying mathematics and science to solve industrial problems, and developing integrated systems. These results underscore the strong emphasis on transferable and interdisciplinary competencies that are valuable across STEM-related and non-STEM career tracks. Core scientific skills, such as experimentation, scientific communication, and the use of technical tools, were also rated highly, affirming the programme's ability to equip students with foundational STEM practices applicable in multiple contexts.

Table 2: Weighted Mean and Interpretation of Graduates' Self-Assessment on the Relevance of Programme Outcomes to Current Work or Further Studies

Code	Programme Outcome	Weighted Mean	Standard Deviation	Interpretation
PO1	Use and apply scientific and technical tools for physical science	3.77	3.41	Relevant
PO2	Design and conduct experiments, analyse and interpret data	4.12	3.76	Relevant
PO3	Present scientific data and conclusions in written/oral form	4.00	3.64	Relevant
PO4	Articulate the latest developments in physical science	3.54	3.19	Relevant
PO5	Conduct independent scientific investigations	3.85	3.50	Relevant
PO6	Apply math and science to solve industrial problems	4.12	3.72	Relevant
PO7	Develop and improve integrated systems (people, materials, info, energy)	4.12	3.67	Relevant
PO8	Propose innovative solutions using physical science	3.92	3.55	Relevant
PO9	Demonstrate professional, social, and ethical responsibility	4.31	3.84	Relevant
PO10	Collaborate with others, including multidisciplinary groups	4.23	3.79	Relevant
PO11	Engage in lifelong learning	4.54	4.05	Highly Relevant
PO12	Preserve and promote Filipino historical and cultural heritage	3.81	3.40	Relevant

Figure 6: Percentage of BS Applied Physics Graduates Applying Specific Competencies in Employment or Graduate Studies.



Interestingly, the lowest score, though still within the "relevant" range, was assigned to the outcome on articulating the latest developments in physical science (3.58). This may reflect the employment distribution of graduates, many of whom are working in fields where direct engagement with cutting-edge physics research is less immediate. Nevertheless, the emphasis placed on lifelong learning and ethical responsibility suggests that the programme cultivates graduates who are adaptable, reflective, and capable of continuing professional development which are qualities critical to sustaining careers in dynamic STEM environments. Beyond programme outcomes, respondents identified frequently applied competencies such as analytical and critical thinking, teamwork, research writing, communication, and data analysis. These were complemented by more specialised skills including instrumentation, programming, and technical reporting. The alignment of these competencies with actual workplace demands validates the relevance of the BS Applied Physics curriculum and its integration of science, mathematics, technology, and applied problem-solving, demonstrating the programme's responsiveness to the interdisciplinary requirements of contemporary STEM professions.

3.5 Trends in Employability

Employment data reveal that most BS Applied Physics graduates initially enter the workforce at entry-level positions, with 66.7% of respondents reporting current employment at this stage. Over time, however, a notable share (22.2%) has advanced to mid-level professional roles, while 11.1% already occupy supervisory or managerial positions. This distribution suggests a positive upward trajectory in career mobility, indicating that graduates can build on their foundational skills to progress toward greater professional responsibility. Such patterns reinforce the idea that the programme provides a strong entry point into the labour market while also preparing graduates for long-term growth.

Figure 7: Employment Levels of BS Applied Physics Graduates.

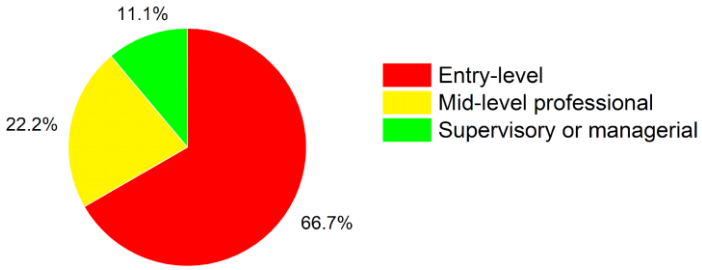
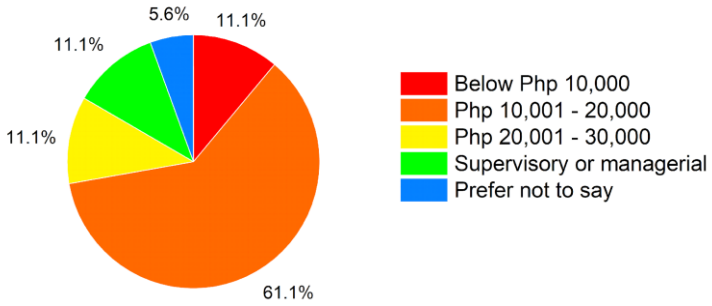


Figure 8: Monthly Salary Range of BS Applied Physics Graduates.



Income distribution in Figure 8 reflects similar trends. Most graduates (61.1%) reported earning between Php 10,001 and Php 20,000 monthly, figures that are typical of entry-level salaries in the Northern Mindanao region. Smaller proportions earned below Php 10,000 (11.1%) or within the Php 20,001–30,000 range (11.1%), while a small group (5.6%) opted not to disclose their earnings. It is important to note that many respondents are employed in Cagayan de Oro City, where salary scales are lower than those in metropolitan centres such as Manila or Cebu. Despite these regional differences, the findings indicate that graduates can secure stable employment consistent with local labour market conditions, while also demonstrating potential for advancement into higher-paying roles as they gain more experience.

These employability patterns highlight the effectiveness of the BS Applied Physics curriculum in equipping graduates with both technical and transferable skills that facilitate entry into the workforce. The steady progression from entry-level to supervisory roles further suggests that the programme develops capacities for leadership, problem-solving, and adaptability which are competencies that are central to sustained career development in STEM-related and interdisciplinary fields.

3.6 Graduate Success Stories

The personal accounts shared by BS Applied Physics graduates reveal the broader impact of the programme on their professional and personal development. Thematic analysis of the narratives identified four dominant themes: critical thinking and problem-solving, adaptability across career paths, strengthened communication and teaching competencies, and the cultivation of lifelong learning.

A recurring theme across responses was the development of critical thinking and problem-solving skills, which graduates consistently described as essential to their success in diverse careers. Whether working in education, technical industries, administration, or media, alumni credited their physics training for cultivating an analytical mindset that allowed them to address challenges systematically. One respondent reflected, “If there are problems arising, technical or not, my curious mind always exists. I will find a way to solve such problems with the help of technology or real-life solutions.” Another, now employed in the radio broadcasting sector, emphasized the transferability of these skills: “Applied Physics is all about problem-solving… This analytical approach is crucial in the fast-paced environment of a radio station.”

Graduates also highlighted their adaptability to professional roles outside of traditional physics-related careers. Alumni who transitioned into fields such as human resources, finance, and community-based development noted that the discipline and systems thinking acquired in physics proved highly applicable in managing complex, non-technical tasks. One graduate shared, “Transitioning into a career as an HR staff may seem unrelated at first, but the discipline and problem-solving mindset I developed during my studies have proven incredibly useful.” Similarly, a programme head in the social welfare sector reflected, “Physics

taught me systems thinking… Just like in experiments, real-world change doesn't come instantly. You test, you fail, you adjust."

Another theme that emerged was the role of the programme in strengthening communication and teaching skills. Graduates who pursued careers in education and outreach consistently pointed to classroom presentations, thesis defences, and oral reporting tasks as formative experiences that built confidence and shaped their professional identity as educators. As one respondent explained, "BS Applied Physics helps me to become an educator to the children. It trained my critical thinking and oral communication to boost confidence."

Finally, many graduates expressed a strong commitment to lifelong learning, attributing their continued pursuit of knowledge to the intellectual culture of the programme. They emphasised that the programme instilled in them a mindset of curiosity, resilience, and openness to new opportunities. One graduate remarked, "Most of my decisions regarding my career goals are affected by my thirst for knowledge poured by the physics department's faculty and students." Another added, "Being open to learning makes it easier for me to take on a job I am not familiar with."

Taken together, these success stories demonstrate how the BS Applied Physics programme fosters not only technical expertise but also a broad set of transferable STEM competencies that empower graduates to thrive across diverse career paths, embrace lifelong learning, and contribute meaningfully to their professions and communities.

4. Conclusion

This tracer study confirms that the BS Applied Physics programme at USTP equips graduates with relevant skills for both employment and advanced studies. Despite the limited presence of physics-focused industries in the region, graduates have found meaningful roles across various sectors, including education, government, and administration. Their ability to apply critical thinking, technical knowledge, and communication skills in diverse fields reflects the strength of the programme's interdisciplinary training.

The high relevance of programme outcomes, as reported by alumni, validates the curriculum's alignment with workplace demands. Success stories further highlight the importance of problem-solving, adaptability, and commitment to lifelong learning. These qualities indicate that the programme has fostered not only technical competence but also personal and professional growth.

To strengthen the programme further, there is a need to enhance industry partnerships, expand opportunities for applied research, and support pathways for graduate studies. The findings of this study offer valuable input for curriculum review, accreditation efforts, and strategic planning. As USTP continues to advance its vision for science and technology education, understanding graduate outcomes remains essential to producing future-ready professionals.

Declaration of Generative AI and AI-assisted Technologies in the Writing Process

AI-assisted tools were used solely for language editing (grammar, clarity, and British spelling). All analyses, interpretations, and final editorial decisions were made by the authors, who remain fully accountable for the content.

Acknowledgement

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References

Cedefop, European Training Foundation & International Labour Office. (2016). Carrying out tracer studies: guide to anticipating and matching skills and jobs. Volume 6. Publications Office of the European Union.https://data.europa.eu/doi/10.2816/938667.

Commission on Higher Education. (2012). *Policy-standard to enhance quality assurance (QA) in Philippine higher education through an outcomes-based and typology-based QA* (CHED Memorandum Order No. 46, s. 2012). https://www.pacu.org.ph/wordpress/wp-content/uploads/2017/03/CMO-No.46-s2012.pdf

Department of Education. (2012, April 17). *Policy guidelines on the implementation of Grades 1 to 10 of the K to 12 basic education curriculum (BEC) effective school year 2012–2013* (DepEd Order No. 31, s. 2012). https://www.deped.gov.ph/2012/04/17/do-31-s-2012-policy-guidelines-on-the-implementation-of-grades-1-to-10-of-the-k-to-12-basic-education-curriculum-bec-effective-school-year-2012-2013/

Higher Education (1994) Act of 1994, Rep. Act No. 7722, 91 Official Gazette 6994 (Phil.). https://elibrary.judiciary.gov.ph/thebookshelf/showdocs/2/2333

Enhanced Basic Education Act of 2013, Rep. Act No. 10533, 109 Official Gazette 5665 (2013) (Phil.) https://elibrary.judiciary.gov.ph/thebookshelf/showdocs/2/55631

World Bank. (2025). *Education overview*. https://www.worldbank.org/en/topic/education/overview

World Economic Forum. (2025). *The future of jobs report 2025*. https://reports.weforum.org/docs/WEF_Future_of_Jobs_Report_2025.pdf

DEVELOPING A SERIOUS GAME ON ALTERNATIVE ENERGY SOURCES THROUGH THE DESIGN THINKING PROCESS

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ABSTRACT

We developed a serious educational card game on alternative energy sources called "Fact or Fiction: Energy Edition". This game aims to bridge the learning gap between Singapore school's science curriculum on energy sources and our national commitment to reach net-zero emissions by 2050. By playing the card game with different gameplays, students are introduced to interesting facts on the seven different renewable and/or clean energy sources. Through the Design Thinking framework, we developed a game-based learning tool that could solve this curriculum gap while focusing on the needs of the teachers and students involved in this process. From the initial pilot testing phase, teachers gave feedback that it was a useful resource that could empower them to engage primary and secondary school students through various gameplays to discuss a complex and multifaceted topic like alternative energy. The gameplays can be played individually or collaboratively. The gameplays which are collaborative in nature encourage students to work together to gain a competitive advantage and reach the game objectives. From playing the various gameplays, students get to learn deeper on the topic and gain opportunities to debate and discuss energy topics. We hope that by sharing this card game action research journey, it would inspire more educators to consider using their own educational card game resources to engage learners better.

Keywords: Educational Card Game, Alternative Energy, Science

1. Introduction

Climate change is increasingly affecting many countries worldwide as global average temperatures reach new highs annually. Since 2015, addressing climate change has been the primary focus of the UN Climate Change Conference, with the Paris Agreement legally binding countries to limit their carbon emission. As part of Singapore's Long-Term Low-Emissions Development Strategy (LEDS), the government has developed a nationwide plan to achieve net zero emissions by 2050 (National Climate Change Secretariat, 2022). This decision was made to meet the national commitment to climate action under the Paris Agreement (Ministry of Foreign Affairs, 2025).

After our team conducted a workshop for primary school teachers on renewable energy sources through Jigsaw learning, the team identified a learning gap in the formal science curriculum that needed to be addressed. We noted that there are not much time and space in the curriculum for students to discuss the energy sources used nationally.

1.1 Learning Gaps Identified in Formal Science Curriculum

Worldwide, there are various experiences of education in renewable energies (UN Department of Economic and Social Affairs, 2021). Germany is often cited as an example of good practice in teaching renewable energies. The country has developed a strong education system that

integrates renewable energy into school, university and vocational training curricula (Wiesner, 2014 and Spangenberger, et al 2021). However, within the international community, significant emphasis has been placed on tertiary and university level programmes (Kandpal and Broman, 2014). In Singapore, the integration of sustainability and alternative energy into the higher education landscape is driven by the need for a curriculum that addresses evolving local, regional, and global demands (Mokhtar, Chong, and Jusuf, 2023). While some initiatives extend this focus to Junior College students, renewable energy education remains limited in scope within primary and secondary school curricula (Widyantoro, et al, 2025).

Singapore's formal science curriculum introduces alternative energy concepts progressively across educational levels. Primary science (Grades 3-6) covers three basic renewable energy sources: solar, wind, and hydroelectric energy (Ministry of Education, 2024a). The lower secondary science curriculum (Grades 7-8) expands this knowledge to include geothermal, biofuel, and nuclear energy sources (Ministry of Education, 2024b). Both curricula emphasise the scientific principles behind energy conversion and environmental impacts, with increasing complexity at higher grades. While civic literacy education at the secondary level specifically focuses on solar energy's advantages and limitations in Singapore as this emphasis reflects the nation's geographical constraints.

1.2 Game-based Learning Approaches

The implementation of educational games in student learning has been proven to enhance learning outcomes and bolster student engagement (Fonseca et al, 2023). By fostering a student-centric environment, game-based learning and gamification facilitate a deeper comprehension of broader concepts. This is evidenced by a study in a German secondary school, which found that students who engaged with a ‘serious game’ on renewable energy acquired significantly more technical knowledge than their peers who did not. (Spangenberger, et al 2021)

We decided to develop a serious game for teachers to educate students about alternative energy sources. Through some rounds of discussions, our team decided that a physical card game would be the best way to engage students on the broad topic of renewable and/or clean energy, which is not emphasised in the formal curriculum. By presenting a diverse range of facts and themes related to various energy sources in the card game, including those not extensively covered in the textbook such as hydrogen, the game seeks to deepen students' understanding and increase their appreciation of this critical energy topic.

After many rounds of iteration with the team and the first trial with teachers and students, we developed four gameplay formats that we tested in a second trial which is discussed in a separate paper (Chen and Heng, 2025). This paper aims to show how the design thinking approach was used to develop and modify game mechanics to suit learners' profiles across different levels and backgrounds.

2. Design Thinking Approach

The development of the game was shaped by the Design Thinking framework (Wood et al., 2021) a solution-based approach to solving problems, while focusing on the needs of teachers and students involved.

2.1 Empathise: Understanding the Needs of Educators and Students

During a teacher professional development workshop in 2023, our research team identified a significant gap in the formal curriculum regarding Singapore's 2050 energy plan. Despite the government's ambitious drive towards a net-zero energy future, there was a notable absence of focused instruction on this energy topic within the standard educational framework.

While informal learning spaces, such as STEM Applied Learning Programme (Ministry of Education, 2024c) and co-curricular activities in schools, have made some progress in addressing alternative energy education, these efforts were found to be limited in scope and reach. Recognising the disparity between national energy goals and current educational offerings, our team proposed the development of an educational game. This approach was chosen for its potential to engage students effectively, foster critical thinking, and provide comprehensive coverage of alternative energy topics in a flexible format. By opting for a game-based learning tool, we aimed to create a resource that could bridge the identified curricular gap and align with contemporary pedagogical theories emphasising active learning and student engagement in complex, multifaceted subjects.

2.2 Define Stage

We defined our problem statement as this: “With the curriculum gaps identified earlier, how can we introduce alternative energy sources in a more interactive and in-depth exploration manner?”

2.3 Ideate Stage

Our team of educators engaged in several brainstorming sessions to generate different game ideas to introduce the various categories of alternative energy sources. After considering multiple formats of game-based learning, including board games, we ultimately decided on creating a card game called "Fact or Fiction: Energy Edition".

"Fact or Fiction: Energy Edition" is a serious educational card game developed to educate primary and secondary students about alternative energy sources available locally and globally. The game employs various game mechanics to enhance critical thinking on sustainability issues. The primary objectives of the game are to enable students to:

1) Describe the advantages, challenges, and limitations of different energy sources;
2) Appreciate STEM concepts in the context of energy production;
3) Demonstrate awareness of environmental and social impacts of energy production; and
4) Identify examples of local, regional, and global initiatives, issues, and trends in energy transition.

2.4 Prototype Stage

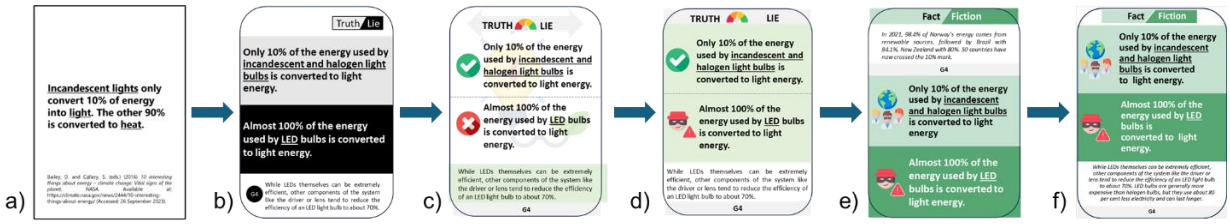
This stage has three parts: the initial card design process, the gameplay mechanisms, and the content development. All three were modified in the prototype stage as we gathered feedback from teachers in schools.

2.4.1 Card Design

The card design for "Fact or Fiction: Energy Edition" underwent several iterations to optimise its educational effectiveness and user-friendliness as shown in Figure 1. Initially the card only featured a factual statement and a reference source, and early trials revealed that participants struggled to craft fictitious statements spontaneously. Recognising this challenge, the design team incorporated a fictional statement on each card to highlight common misconceptions, along with brief background information to provide context and facilitate discussions. An alphanumeric identifier was added on the card for easier categorisation of the reference system. E.g. G4 represents the general category with card number 4.

Subsequent revisions focused on enhancing the visual aspect of the cards. The final design employs a clear visual distinction between fact and fiction statements through contrasting colour schemes: black text on a light background for facts, and white text on a dark background for fiction. Icons were introduced to reinforce this dichotomy: a network of scientists symbolising factual statements backed by scientific research, and a fraudster icon representing fictional claims. This design serves as a visual reminder of the importance of distinguishing between scientifically backed information and misinformation in the context of alternative energy education.

Figure 1: The Initial Card Design Process



2.4.2 The Original Gameplay: Role-Playing

The original gameplay was adapted from the social deduction game, Mafia (also known as Werewolf), while incorporating the elements of environmental education. The game simulates a conflict between two groups: an informed minority, the Bad Guys: Fraudster and Greenwasher and an uninformed majority, the Good Guys: Citizens. The Good Guys comprised citizens with special powers such as POFMA officer, Whistleblower and Auditor, and regular citizens with no special power.

The Good Guys are required to read the fact statements, while the Fraudster will read the fiction statements. The Greenwasher, representing those who prioritise market sustainability over environmental impact, has the flexibility to choose between either fact or fiction statements, adding an additional layer of complexity to the gameplay.

The Police officer's role was redesigned as POMFA Officer, drawing parallels with Singapore's Protection from Online Falsehoods and Manipulation Act (POFMA). This adaptation reflects contemporary efforts to combat misinformation, particularly relevant in addressing online falsehoods affecting public interest during the COVID-19 pandemic (POFMA, 2025). This modification adds an educational value by connecting gameplay elements to real-world policy implementations.

Table 1: Summarising the Role of Good Guys and Bad Guys

Good Guys or Bad Guys	Role	Similar to Mafia Role	Description of Role
Good Guys	POFMA Officer	Police Officer	Has the power to ban the Fraudster or Greenwasher from the game.
Good Guys	Auditor	Doctor	Has the power to save any player
Good Guys	Whistleblower	Detective	Has the power to check the identity of any player
Good Guys	Citizen	Villager	Has no special power
Bad Guys	Fraudster	Werewolf	Read only the Fiction statement. Together with the Greenwasher, has the power to dupe a player.
Bad Guys	Greenwasher	Werewolf	Has the option to read either the Fact or the Fiction statement.

2.4.3 Modified Gameplay: Individual Challenger

To address some implementation challenges, particularly the need for training moderators who may not know the Mafia game, we developed a simplified version called Individual Challenger. This adaptation eliminated the requirement for pre-game training sessions for teachers or facilitators involved. Additionally, it allowed students to have more time to engage and discuss the content of the cards, rather than focus on deducing the identities of the players in the Role-playing game.

In this streamlined format, players are organised into groups of 4-6 participants. The gameplay starts with one player, Player A, who has the option to read either a fact or fiction statement, while other group members take turns challenging his/her statement. The outcomes of these challenges are outlined in Table 2. To ensure balanced participation and prevent monopolisation during discussion, we introduced challenger cards as a resource management mechanism. Players must discard their challenger card after each challenge, effectively limiting their opportunities to challenge other players during a discussion round. The next player starts the next round of discussion by reading either the fact or fiction statement on the card. This goes on until all players have read their statement.

Table 2: Summarising Outcomes of Player A's Actions

Player A's Action	At the End of Discussion Round	Outcome
Player A reads the *Fact* statement	Successfully convinces others that he/she is reading the fact	Nobody gets a point
Player A reads *Fact* statement	Did not convince others that he/she is reading the fact	The challenger loses a point
Player A reads *Fiction* statement	Successfully convinces others that he/she is reading the fact	Player A gets a point
Player A reads *Fiction* statement	Did not convince others that he/she is reading the fact	The challenger gets a point

2.4.4 Content Development

Using various sources, we compiled facts useful for players to learn from the eight categories in the game: Solar, Hydroelectric, Hydrogen, Geothermal, Biofuel, Wind, Nuclear, and General knowledge. This allows players to explore specific themes or randomise energy topics during gameplay, thereby increasing awareness of different available alternative energy sources and potentially influencing behaviour towards sustainable energy practices.

Our team conceptualised a rich informative card deck to educate students about important facts on the various energy categories identified above. Through an iterative development process, we identified these recurring eight energy themes:

1) ASEAN trends
2) Local trends
3) Global trends
4) Technology
5) Science
6) Environmental impact
7) Social and human health impact
8) Policy and regulation

With 80 different information cards, we began the first pilot testing in March 2024.

For our initial pilot testing, we printed on 160 gsm paper, with a standard poker card size of 2.5 in x 3.5 in (63.5 mm x 88.9 mm).

2.5 Phase I Pilot Testing

2.5.1 Teacher Engagements in Phase I

The first pilot testing phase involved teachers recruited through two main channels: existing professional networks and participants from previous professional development workshops conducted by our research team. Upon expressing interest to participate, an on-site game trial session was scheduled at their respective schools. The number of participating teachers per school ranged from one to six, allowing for diverse group dynamics during the trials (refer to Table 3).

Table 3: Total Number of Teachers and Schools that Participated in the Teacher Engagement in Phase I

	Number of Schools	Total Number of Teachers
Primary Level	5	21
Secondary Level	3	6
Total	8	27

Brainstorming with Teachers on Gameplay Modifications. During these engagement sessions, teachers were introduced to two distinct gameplay formats: Role-playing and Individual Challenger. After each round of teacher engagement, our team conducted debriefing sessions to discuss their gameplay experiences, potential modifications to suit the various student profiles and its potential integration in existing curricula. A consensus emerged that the Role-playing version was more suitable for co-curricular activity (CCA) settings, while the Individual Challenger version was deemed more appropriate for classroom implementation.

Each school developed modified versions of the Individual Challenger format to accommodate their specific student demographics. For instance, some schools incorporated token-based point systems to enhance engagement. One teacher reported, "I customised the rules based on the original rule. The game worked well."

New Gameplay: Quiz-Quiz-Trade. A primary school teacher working with low-performing Primary 6 (or Grade 7) students proposed a new format called "Quiz-Quiz-Trade" (QQT), designed to be more accessible for her students. QQT is a cooperative learning strategy that allows students to assess the knowledge of their classmates in an engaging quiz-game format. This strategy pairs students who review content by asking questions of their partner and allow the partner to respond with an answer. If the partner doesn't know the answer, the student gives clues or assistance, and then the question-answer format is repeated. When both partners have answered the assigned questions, they trade partners with other pairs who have completed their respective questions (Wong et al., 2022). In this Fact or Fiction version, each student receives one card, a few tokens and pairs up with a partner. They take turns to share their statements and guess whether they are fact or fiction, then exchange tokens based on correct deduction. After each round, students find new partners and repeat the process.

The teacher provided feedback on the QQT format: "For the Lower Progress group, they can use the cards to test partners - Quiz and Response followed by gain/lose a token. Then move on to another partner, quiz the next partner with the same card or a different card. For my class, each student was given an info and 5 tokens. The students liked guessing FACT or FICTION and then winning a token."

The research team recognised the value of QQT as a fun, cooperative learning strategy that encourages student movement and interaction while synthesising new learning. Students work with multiple partners in a short period of time, and the tactile and kinesthetics aspects of this strategy support and engage a variety of learning styles. During the activity, it helped students to develop academic language and encourage peer to peer interactions. Given its effectiveness, particularly with lower-progress students, QQT was incorporated as an additional gameplay option in the final product.

2.5.2 Student Engagements in Phase I

After the teacher engagement sessions were held at the respective schools, the student engagements were either conducted by the teacher or us during their preferred timing. Table 4 shows the distribution of the schools and total number of students who participated from each level.

Out of the five primary school student engagements for Phase I, all schools played Individual Challenger modes. Three primary school engagement sessions were conducted by us and in those sessions, students got to play both Role-playing and Individual Challenger gameplay formats. One of the student engagements was conducted during recess and two sessions were conducted during their Co-curricular activity time and the final one was conducted during their curriculum time. The number of primary student participants per session ranged from 18 to 900 (see Table 4).

For the Secondary level engagements, all students played the Individual Challenger mode. Only one session was conducted by us while the other two sessions were conducted by the teacher. The first two sessions were held during CCA time, and the final one was conducted during class time. The number of secondary student participants per session ranged from 13 to 50.

Table 4: Summary of the Number of Students and Schools that Participated in the Student Engagement in Phase I

	Number of Schools	Number of Students
Primary Level	5	1200
Secondary Level	3	109
Total	8	1309

2.5.3 Students and Teachers' Feedback and Changes Implemented from Game Play Experience

Two slightly different feedback forms were created to get quantitative and qualitative feedback from teachers and students on their experiences in playing the card game (see Table 9 in Annex). For quantitative feedback received, both groups were asked to rate the game's educational and entertainment value as well as the game's difficulty level and duration. In terms of the qualitative feedback received, both groups were asked to comment what they liked or not liked about the game, what they learnt from playing the game and any other suggestions or feedback. The following sections highlights some of the consolidated feedback and changes implemented from Phase I on three main areas in the card design (Section A), card content (Section B) and gameplays (Section C).

Section A: Card Design and Modifications. We consolidated feedback from three specific questions to evaluate their game play experiences (refer to question 6, 8 and 9 in Table 9 of the Annex). Key issues identified included:

1) Primary students noted they could discern fact from fiction based on the reader's eye movements.
2) The thinness of cards allowed for potential cheating and reduced durability, as reported by both primary and secondary students.
3) Teachers suggested improvements in readability, such as larger font sizes or flip-up designs to reveal fact/fiction status.

One teacher also shared an interesting observation: "A student, however, pointed out that it was quite easy to guess the right response without really knowing the facts because the eye movement of the tester (up or down) was a giveaway as the partner could tell which segment was being read. Nonetheless, my Lower Progress group found it enjoyable and wanted to play on."

The modifications in card design are as shown below based on the above feedback.

Figure 2: Illustrating the Major Card Design Changes from the Original to the Final Card

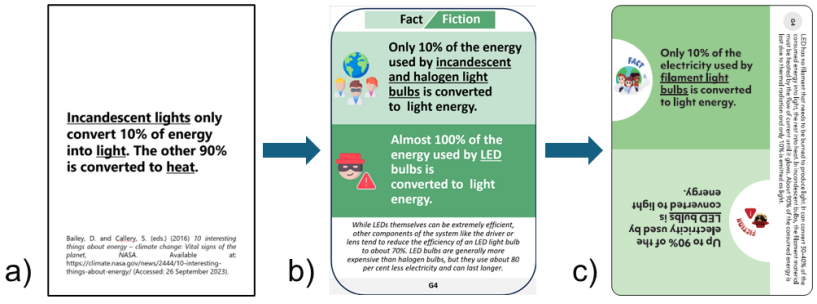
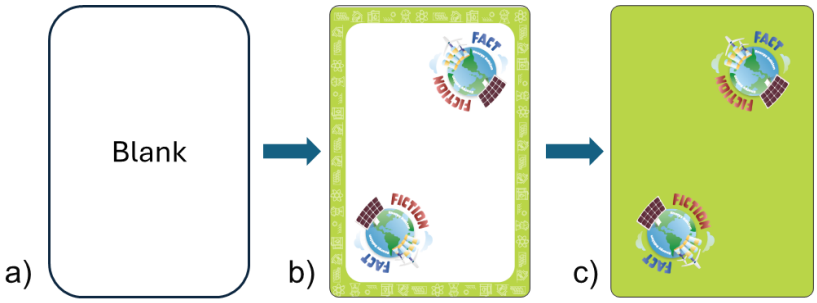


Figure 3: Illustrating the progression of card back design



Firstly, we implemented a poker card-inspired design with rotational symmetry, allowing the cards to be read in any orientation (Figure 2c). This design choice mitigated the eye movement issue and enhanced overall playability.

Secondly, for the back of the card, we chose a simple design of a coloured background with two diagonally placed game logos, rather than our initial concept of bordered alternative energy motifs (Refer to Figure 3). This decision was influenced by our limited print run of 100 copies, as it minimises noticeable printing offsets and maintains focus on the educational content. To ensure durability and prevent text visibility through the card, we selected 256 gsm paper for the final product.

A standard poker card with dimensions 2.5 in x 3.5 in (635 mm x 889 mm) is too small to accommodate our content requirements: (1) fact statement, (2) fiction statement, (3) background information, and (4) reference icons. We also considered other oversized playing cards such as tarot cards with dimensions 2.75 in x 4.75 in (70 mm x 120 mm). Balancing content needs with ergonomic considerations, we ultimately settled on a custom card size of 70 mm x 100 mm. This dimension ensures comfortable handling while providing sufficient space for all necessary information.

Section B: Card Content and Modifications. Teachers generally appreciated the content knowledge delivered through the card game, acknowledging that the facts presented extended beyond the textbook, thus broadening students' understanding (refer to Table 5). However, both students and teachers expressed a preference for simpler phrasing of the information on the cards, particularly to enhance comprehension for primary school students. In response, we consulted primary school students and teachers to refine the card text, focusing on reducing wordiness and improving clarity. This feedback-driven approach ensured that the final card content was both informative and accessible to the target age group.

Table 5: Responses from Students and Teachers on the Content of the Card

Themes	Sub Theme	Illustrative Excerpts from Data
Curricular Impact	Curricular extension	The students learn more about renewable and clean energy. They will gradually increase general knowledge/ Science facts [PT]
	Global literacy	Through reading the cards, the students picked up global knowledge about the different energy sources. [ST]
	Curricular misalignment	Some of the terms mentioned in the cards are not familiar with students as they are not found within the textbook [ST]
Instructional Design	Differentiated learning needs	Have a set of cards for Intermediate and advanced for different abilities as we have all the streams in one class. [ST]
	Inaccessible vocabulary	Maybe make the words a little easier to understand so that children who play will understand [PT]
Learning Mode	Incidental learning	Learnt some important and interesting facts from playing the game [PT]

** Primary school student [PS], primary school teacher [PT], secondary school student [SS], secondary school teacher [ST]*

After the feedback was received, we went onto improve the card text. Some of the key changes made to card's phrasing include (see Table 6):

1) Simplify the words to be more age-appropriate to the primary level
2) Shorten the statements and focus on key ideas
3) Changed the phrasing so that it is easily read out.

Table 6: Some Examples of Card Content Changes

	Pilot	Final	Changes Made
G4	Only 10% of the energy used by incandescent and halogen light bulbs is converted to light energy.	Only 10% of the electricity used by filament light bulbs is converted to light energy	Simplified the words
W5	Wind turbine blades are made of fiberglass and are not recyclable. They will be incinerated or dumped in landfills	The fiberglass blades of wind turbines cannot be recycled.	Shortened the statement to focus on key ideas
B8	Gardens by the Bay collects horticultural waste from across Singapore, incinerates it and generates electricity on-site	Gardens by the Bay collects gardening waste to generate electricity on-site.	Phrasing was modified to be more accessible to primary school students.
B10	The energy conversion for biomass fuel is: Sunlight ⟶ chemical potential energy ⟶ heat energy	The energy conversion for formation of biomass is from light to chemical potential energy.	Simplified the energy conversion to focus on the key changes in energy conversion for biomass fuel.
Gt6	The Philippines and Indonesia are the only two countries in ASEAN tapping on geothermal energy.	Among the ASEAN countries, only Indonesia and The Philippines produce geothermal energy.	Changed the phrasing of the sentences so that it is easier to understand when read out loud.

Section C: Gameplay Formats Feedback and Changes

Role-Playing. The Role-playing format was played in three primary schools: two in informal curricular settings and one during regular lessons. Our research team led one session, while teachers trained by us conducted the others. The provided moderator guide proved effective, resulting in minimal complaints regarding rule comprehension. However, one student reported difficulty understanding the roles of the Whistleblower and Auditor. In response, we refined the moderator guide to clarify the terms used and role descriptions.

Individual Challenger. The Individual Challenger gameplay was hypothesised to demonstrate two primary potential benefits: (1) enhanced learning about alternative energy and (2) encouraged communication.

Table 7: Feedback from Students and Teachers who Participate in the Challenger Mode

Themes	Sub Theme	Illustrative Excerpts from Data
Skill Developing	Building Confidence	Students practice some form of public speaking as they have to read out the information to the group. [ST]
	Audience Awareness	As the students speak to each other, they learn to be aware of the audience. [ST]
Persuasion	Building Confidence	As they try to convince each other, they learn how to speak more confidently to sound convincing. [ST]
	Struggle to 'Sell' Truth	It was hard to convince the people to believe that it is a fact. [PS]
	Knowledge Gap	Many of us had difficulty debating with each other and were going by gut feeling for most cards instead of rational thinking because the knowledge was quite broad and advanced. [SS]
Social Dynamics	Trust Gap	I don't like it when my teammates don't believe me. [PS]
	Engagement Level	Through the Challenge cards, each round only 2 students are actively involved in the discussion. The rest of the students are less engaged, especially when the group is big. [ST]
	Social Balance	Groupings by teachers should have mixture of student profiles (vocal and quiet ones together) [ST]

There was positive feedback on how the card content encouraged student communication in the teams (see Table 7). However, despite its potential as a vehicle for communication, the Individual Challenger version received several negative feedback from both students and teachers. Primarily, the mode of play for this version was not well-tested among students and the rules found to be confusing for gameplay, as it was conceived without a seasoned game model to emulate (see Table 8).

Table 8: Feedback on Game Rules from Students and Teacher Participants in the Challenger Mode

Themes	Sub Theme	Illustrative Excerpts from Data
Game Instruction	Rule Complexity	I did not like how confusing the rules were [SS]
	Onboarding	The rules were a bit confusing at first, but I got used to it after a short period of time. [PS]
Game Design	Confusing Mechanism	Maybe take away the challenger card as it can be confusing, play without the challenger card, test something that they have learnt and relate to more facts pertaining to it [PT]
	Simplify Game	Just make the rules simple to follow. Just use tokens and award the student who receives the most number of tokens as the winner [PT]
	Scoring Confusing	Simpler rules. It is difficult to track when there are positive and negative scoring. Keep only positive scoring. [SS]

Our objective for introducing Individual Challenger gameplay was to incorporate a debate element to encourage students to communicate their thoughts on the information presented. However, from the students' feedback received (see Table 7), we underestimated the impact of public speaking anxiety among peers. The main underlying issue was students' lack of confidence in defending their positions when challenged by their peers. Unless a student possessed a high level of confidence to begin with (e.g., student leaders), it often proved easier for participants to focus solely on reading the fact statement and thus lose the full gaming experience.

Two significant suggestions emerged from the teachers' feedback, indicating potential benefits from collaborative gameplay approaches:

1) A secondary school teacher proposed a round-robin format: "Two players each time. The winning pair will play against another pair. Two players vs. two players (work in pairs)." This suggestion led to the development for Team Challenger gameplay mode (refer to Table 10 in Annex).
2) Another teacher suggested: "Allow ALL students to vote whether the information read is Fact or Fiction. Based on the result, there will be [Vote points] for the game master and/or players. This ensures that all students are listening and trying to guess for every round of the game." This suggestion led to the development of the Presenter Challenger gameplay mode (refer to Table 10 in Annex).

These collaborative gameplay modes could increase student engagement, potentially enhancing the educational value of the game, which we wanted to test out in Phase II Pilot Testing.

2.6 Limitations

While the Design Thinking framework enabled the iterative refinement of gameplay, card content, and card design, the prototyping process was inherently limited by the number of iterations. With the pilot phase restricted to eight schools (five primary schools and three secondary schools), the current finds may not be fully generalisable. Future research should

involve broader outreach to validate the game's efficacy in promoting energy literacy across more diverse demographics. Furthermore, subsequent studies are needed to disaggregate how the game influences specific dimensions of energy literacy, including awareness, conceptual understandings, and socio-behavioural shifts.

3. Conclusion

The Design Thinking framework was instrumental in refining the gameplay, content, and aesthetics of the card game to align with diverse student profiles and specific learning objectives. Throughout the iterative design and pilot phases, we are focused on answering the problem statement: with the curriculum gaps identified earlier, how can we introduce alternative energy sources in a more interactive and in-depth exploration manner?

Furthermore, the collaborative 'think-tank' approach, engaging with peers across various educational settings, provided invaluable networking opportunities and fostered socio-emotional connections among educators. By sharing this action research journey, we hope to inspire colleagues to develop their own game-based tools and pursue cross-departmental and regional collaborations to enhance learner engagement.

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References

Chen, L. Q., and Heng, C. (2025). A serious game that builds energy literacy through communication and collaborative gameplays. *Proceedings of the 19th European Conference on Games Based Learning (ECGBL 2025)* (Vol. 19 No. 2). Academic Conferences and Publishing International Ltd. https://doi.org/10.34190/ecgbl.19.2.4033

Fonseca, I., Caviedes, M., Chantré, J., & Bernate, J. (2023). Gamification and game-based learning as cooperative learning Tools: A systematic review. *International Journal of Emerging Technologies in Learning (iJET)*, *18*(21), 4–23. https://doi.org/10.3991/ijet.v18i21.40035

Kandpal, T. C., & Broman, L. (2014). Renewable energy education: A global status review. *Renewable and Sustainable Energy Reviews*, *34,* 300-324. https://doi.org/10.1016/j.rser.2014.02.039

Ministry of Foreign Affairs. (2025, August 22). *Climate Change*. Retrieved October 2, 2025, from https://www.mfa.gov.sg/SINGAPORES-FOREIGN-POLICY/International-Issues/Climate-Change

Ministry of Education Singapore. (2024a). *Science teaching & learning syllabus primary three to six standard/ foundation.* Retrieved May 7, 2025, from https://www.moe.gov.sg/api/media/ba3562d3-5b31-4459-8693-45cde7b97273/Primary-Science-Syllabus-2023.pdf

Ministry of Education Singapore. (2024b). *Science syllabus: lower secondary express course, normal (academic) course*. Retrieved May 7, 2025, from https://www.moe.gov.sg/api/media/b6d63789-2ad0-4630-b847-42fd380ec404/G2-3-Lower-Secondary-Science-Teaching-and-Learning-Syllabus.pdf

Ministry of Education Singapore. (2024c). *Applied Learning Programme (ALP)*. Retrieved March 7, 2025, from https://www.moe.gov.sg/secondary/schools-offering-full-sbb/school-specific-opportunities/applied-learning-programme

Mokhtar, I. A., Chong, E. Y. T., & Jusuf, S. K. (2023). Incorporating sustainable education in the undergraduate curriculum: The experience of a young university in Singapore. *European Journal of Sustainable Development*, *12*(4), 83-94. https://doi.org/10.14207/ejsd.2023.v12n4p83

National Climate Change Secretariat. (2022). *Singapore Commits to Achieve Net Zero Emissions by 2050*. Retrieved August 7, 2024, from https://www.nccs.gov.sg/media/press-releases/singapore-commits-to-achieve-net-zero/

POFMA Office. (2025, October 8). Protection from online falsehoods and manipulation act (POFMA). Retrieved October 15, 2025, from https://www.pofmaoffice.gov.sg/regulations/protection-from-online-falsehoods-and-manipulation-act/

Spangenberger, P., Matthes, N., Kruse, L., Draeger, I., Narciss, S., & Kapp, F. (2020). Experiences with a serious game introducing basic knowledge about renewable energy technologies: A practical implementation in a German secondary school. *Journal of Education for Sustainable Development*, *14*(2), 253–270. https://doi.org/10.1177/0973408220981445

UN Department of Economic and Social Affairs. (2024). Voluntary national reviews synthesis report. *United Nations Department of Economic and Social Affairs.* Retrieved June 28, 2025, from https://digitallibrary.un.org/record/4082509/files/2024_VNR_Synthesis_Report.pdf

Wiesner, S., and Horizonte, B. (2014). The Development of technicians as a key factor for a sustainable development of renewable energies using an adapted education method based on the successful german dual education (Duale Ausbildung). *Energy Procedia, 57,* 1034-1036. https://doi.org/10.1016/j.egypro.2014.10.069

Widyantoro, C., Han, J. Yi., Ong, J. S. H., Goh, K. H., & Fung, F. M. (2025). Teaching sustainability through green chemistry: an experiential learning approach. *Journal of Chemical Education, 102(7),* 2743-2754. https://doi.org/10.1021/acs.jchemed.4c01476

Wong, H. K., Wong, R. T., & Powley, T. (2022). Quiz, quiz, trade. In The classroom instruction book (p. 125). Harry K. Wong Publications, Inc. Retrieved January 16, 2026, from https://www.effectiveteaching.com/userfiles/kcfinder/files/QRC_29_125_Quiz.pdf

Wood, K., Lauff, C., Yu Hui, W., Teo, K., Png, S., Swee, A., Collopy, A., & Vargas, B. (2021). Design innovation methodology handbook – Embedding design in organizations (1st ed.). Singapore University of Technology and Design–Massachusetts Institute of Technology International Design Centre. SSRN Electronic Journal. https://doi.org/10.2139/ssrn.3860569

Annex

Table 9: The Type of Questions in the Feedback Form

Question	Type of Question	Type of Data Collected
1. Educational value of the game	Rating scale, 1-5	Quantitative
2. Entertainment value of the game	Rating scale, 1-5	Quantitative
3. How would you rate the difficulty level of the game?	Multiple choice (Easy, moderate or difficult)	Quantitative
4. Was the overall game duration too short, too long, or just right?	Multiple choice (too short, too long, or just right)	Quantitative
5. What did you like about the game?	Long response	Qualitative
6. What did you not like about the game?	Long response	Qualitative
7. Were there any rules that were confusing?	Long response	Qualitative
8. What did you learn from playing the game?	Long response	Qualitative
9. If you had a magic wand and could modify any element of the game or your experience, what changes would you make?	Long response	Qualitative
10. Would you recommend the game to others?	Closed question (Yes, No, Maybe)	Quantitative
11. Compliments / Appreciation / Comments / Feedback / Suggestions / Questions?	Open response	Qualitative
12. In your opinion (and context), how can this game promote and enhance students' learning?	Open response (*Only for teachers to answer)	Qualitative

Table 10: Gameplay Instructions for Team and Presenter Challenger

	Team Challenger	**Presenter Challenger**
Size of Group	Groups of 3 or 4	Groups of 3 or 4
Fraud Mechanism Share Phase	One student in the group will share his/her fiction statement. The remaining students will share the fact statement E.g. in a group of 3, 1 student states the fiction, while the remaining two state the fact statement.	
Detecting Mechanism **Guess Phase**	As a group, determine who amongst the sharing group is telling the lie, i.e. the Fraudster. If the group guess correctly, they score a point (token). If they guess wrongly, they lose a point (token)	
Gameplay	● In each round, two teams will face off each other. ● One team will 'share', while the other 'guess'. ● Determine the winning team and exchange token ● The team will swap roles. ● The teams will face off other teams in the next round.	● As the name implied, teams will share one at a time. ● The sharing team will be in the front. ● The remaining teams will guess. ● Each team will have one vote.
Venue and Set Up	A combination of two classes of students in a multi-purpose room. Students were in teams of 3 to 4 students.	One class of students with 10 teams in a classroom. The sharing team will be in the front presenting. The rest of the class remained seated facing the presentation team.
Observations	● The room was noisy because many groups of students were talking simultaneously. ● To facilitate transition after each round, only the even numbered teams moved, while the odd numbered teams remained in the original seats.	● The classroom was orderly. ● Each team presents one at a time. ● The teacher in-charge led/moderated the discussion and voting.

AI MEETS EDUCATION: LEVERAGING CANVA AI TO ENCOURAGE SELF-DIRECTED LEARNING OF ROAD TAX CALCULATION AMONG FORM FIVE STUDENTS

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ABSTRACT

The rapid integration of artificial intelligence (AI) into education presented new opportunities to enhance learner autonomy, conceptual understanding, and procedural fluency. This action research explored the pedagogical impact of a Canva AI–generated Road Tax Calculator on Form Five students' learning of road tax calculation within the Malaysian secondary mathematics curriculum. Grounded in Malaysia's Digital Education Policy, the study examined the effectiveness of AI-supported self-directed learning and the role of teacher-guided scaffolding in improving both factual knowledge and computational proficiency. A cyclical action research design based on Kemmis and McTaggart's framework with two intervention cycles was implemented with a sample of 30 mixed-ability students. Cycle 1 adopted a self-directed learning through independent interaction with the AI-generated calculator, while Cycle 2 incorporated explicit teacher modelling, guided practice and reflective discussion to address identified misconceptions. Quantitative data were collected using achievement tests and a structured perception questionnaire. Data were analysed using paired-samples t-tests. Findings revealed statistically significant improvements in student performance for both factual knowledge (M1 = 6.10; M2 = 7.00; p = 0.001) and calculation proficiency (M1 = 3.37; M2 = 6.67; p = 0.000). Students' perceptions of the calculator's usability and effectiveness also improved significantly (p = 0.000 across all items). Reduced score variability in Cycle 2 further indicated a narrowing of performance gaps among students. Overall, the results demonstrated that while generative AI tools support autonomous exploration, their educational effectiveness was maximised when embedded within structured, teacher-guided learning designs. Although the study was context-specific and limited in statistical generalisability, it offered strong internal validity and meaningful pedagogical insights into AI integration in STEM education. Importantly, the findings highlighted the evolving role of teachers as designers of AI-enabled learning resources and affirmed the critical role of pedagogical mediation in ensuring that AI functions as an augmentative tool for deep mathematical understanding rather than a shortcut to answers.

Keywords: Road Tax Calculator, Canva AI, Self-Directed Learning, AI-assisted Mathematics Learning, Action Research

1. Introduction

In the contemporary educational landscape, the imperative to innovate traditional instructional models had become increasingly evident. The proliferation of digital technologies, particularly artificial intelligence (AI) and generative design platforms, has created new opportunities for reshaping and enriching teaching and learning processes. This study drew upon these developments by examining how the integration of a Canva AI–generated Road Tax Calculator supported students' conceptual and procedural understanding of road tax calculations within the Form Five Mathematics curriculum.

Aligned with the Malaysia Digital Education Policy, which emphasised the cultivation of digitally fluent learners, this action research investigated how conventional pedagogical practices could be transformed through the strategic embedding of digital applications within the school ecosystem. The study foregrounded self-directed learning, the evolving role of the teacher as both facilitator and designer of digital learning resources and the emerging notion of teachers as bespoke developers of instructional applications.

1.1 Canva AI and Digital Design Tools in Education

Design-based technologies such as Canva had increasingly assumed a central role in contemporary educational environments, extending beyond their initial function as presentation tools to serve as pedagogical platforms that supported creativity, learner engagement and the development of visual literacy. Within secondary mathematics education, such platforms offered particular value by enabling the visualisation of abstract concepts, supporting multiple representations, and facilitating exploratory learning processes. Prior studies demonstrated that Canva empowered both teachers and students to design interactive and visually coherent learning materials, thereby promoting active participation, creative expression and learner-centred instructional practices (Putri Riyanto and Dwi Putri, 2025).

Emerging research on Canva AI suggested that its generative design functionalities contributed to the development of higher-order cognitive skills, including computational thinking, problem decomposition and learner autonomy, particularly in scaffolded learning environments (Maulah, Rulyansah, Ibrahim and Rahayu, 2025). From a theoretical perspective, these affordances aligned with constructivist and self-directed learning frameworks, in which learners actively constructed knowledge through interaction with digital tools, as well as with teacher-guided mediation that structured cognitive engagement. Collectively, these findings underscored the growing pedagogical relevance of AI-enhanced design technologies in secondary mathematics classrooms, where visual, multimodal and interactive representations played a critical role in supporting conceptual understanding, procedural fluency and meaningful mathematical learning.

1.2 Self-Directed Learning in the Digital Age

Self-directed learning (SDL) had emerged as a central construct within contemporary digital education, in which learners were increasingly expected to assume responsibility for goal setting, progress monitoring and reflective regulation of their learning, often with limited direct teacher supervision. A systematic review by Navas Bonilla et al. (2025) on AI-enhanced SDL reported that adaptive and personalised artificial intelligence tools were effective in fostering learner autonomy and self-regulatory capacities. Nevertheless, the review emphasised the continued necessity of teacher guidance to scaffold learning processes and sustain meaningful educational engagement. In addition, digital literacy readiness was identified as a critical enabling factor for effective SDL. As observed by Zakir et al. (2025), strong positive correlations were found between students' digital readiness, digital competence and academic performance, underscoring the foundational role of technological proficiency in self-directed digital learning environments.

The contemporary transition from Education 4.0 to the emerging paradigm of Education 5.0 marked a shift towards highly personalised, learner-centred and technology-enhanced educational ecosystems (Ahmad et al., 2023). This progression reflected broader technological and societal developments that foregrounded adaptability, digital fluency and human-centred innovation in modern learning contexts. Empirical research demonstrated that digital technologies had the potential to increase student engagement, expand collaborative opportunities and support flexible learning pathways across diverse educational settings.

However, the realisation of these benefits was contingent upon several structural and contextual conditions, including reliable technological infrastructure, supportive institutional policy frameworks and adequate organisational capacity (Rahman, 2025). Within this transformation, teacher digital-pedagogical competence was consistently identified as a decisive factor influencing successful technology integration. As noted by Ning and Danso (2025), educators' preparedness to design, facilitate and assess digitally mediated learning experiences was essential not only for effective instructional delivery but also for promoting equitable access and inclusive participation. Overall, the digital transformation of education was conceptualised not merely as a technological advancement but as a systemic pedagogical endeavour requiring sustained capacity-building and strategic coordination among educational stakeholders.

1.3 Teachers as Application Developers and Customisers of Digital Resources

A growing strand of digital education research highlighted the emergence of teachers as designers and developers of bespoke digital resources, including interactive learning tools and mobile applications. This development reflected a pedagogical shift from the passive consumption of digital content towards teacher-led innovation that aligned technological solutions with specific learner needs and the contextual realities of the classroom (Cheung and Hew, 2011). Bano et al. (2018) systematic review demonstrated that teacher-developed mobile applications enhanced contextual relevance, learner engagement and curriculum alignment. Nevertheless, empirical evidence concerning the sustained impact, scalability and pedagogical durability of teacher-generated digital solutions remained limited, emphasising the need for longitudinal and implementation-focused research (Trust and Whalen, 2021; Amemasor, et al., 2025).

This trend was consistent with contemporary professional learning frameworks, such as the TPACK model (Koehler and Mishra, 2009) and the DigCompEdu framework (Redecker, 2017), which emphasised teacher agency, creative digital competence and iterative pedagogical design. By engaging in the creation and customisation of digital tools, educators assumed an active role within the educational technology ecosystem, moving beyond passive user status to become co-designers of digital pedagogy. This transition not only enhanced instructional relevance but also positioned teachers as key partners in educational innovation and the broader digital transformation of schooling.

2. Objectives of the Study

This study aimed to investigate how AI could be harnessed to support teaching and learning in mathematics. The focus was placed on the introduction of an AI-generated learning tool designed to assist Form Five students in understanding the calculation of road tax, a topic that required both factual knowledge and procedural competence. Using Canva AI's Code for Me function, a Road Tax Calculator was developed as a digital learning tool. The tool enabled students to visualise calculation steps, experiment with different input values and independently verify their answers. Through this approach, the study sought to determine whether the AI-generated calculator could enhance students' conceptual understanding of road tax computation as well as their factual knowledge. In addition, the study examined students' perceptions of the AI tool in the learning process, providing insights into its perceived usefulness, usability and acceptance as an instructional resource.

3. Method

3.1 Research Design

This study employed a cyclical action research design to promote pedagogical innovation, strengthen reflective teaching practice and enhance student learning outcomes. Guided by the seminal framework of Kemmis and McTaggart (2014), the research followed iterative phases of problem identification, action planning, implementation, observation and reflection. Two intervention cycles were conducted to enable systematic refinement of instructional strategies and to capture changes in student learning across phases. The study was implemented within Topic 4.0: Consumer Mathematics – Taxation, specifically focusing on Learning Standard 4.1.3, which required students to investigate, interpret and perform calculations related to road tax.

To address challenges in students' conceptual understanding and computational accuracy, Canva AI was integrated as a digital instructional design tool. The intervention was designed to foster self-directed learning, digital engagement and deeper conceptual comprehension. In Cycle 1, students engaged in independent learning tasks using Canva AI–generated interactive materials to explore the concepts of road tax calculation. Based on observations and feedback from this cycle, Cycle 2 adopted a teacher-guided approach in which the Canva AI Road Tax Calculator was facilitated through explicit modelling and guided practice. The teacher demonstrated the step-by-step computational reasoning involved in road tax calculation, including the identification of the correct vehicle category, engine capacity and corresponding tax rate. Common misconceptions identified in Cycle 1 such as selecting incorrect location and engine capacity ranges, misunderstanding incremental tax calculations and over-reliance on the calculator's output without verifying logic were addressed through targeted questioning and worked examples. Students were guided to critically interpret the calculator's results by explaining each step verbally and justifying their inputs before confirming the final output. This teacher-mediated approach ensured conceptual understanding while reinforcing procedural accuracy. Cycle 2 consolidated learning through face-to-face instruction, clarification of misconceptions and targeted support, enabling iterative evaluation and improvement of both teaching practices and student performance.

The study also involved the development of a road tax calculator using Canva AI's Code for Me function. The participating teacher had no prior programming experience. However, with the support of the Canva AI application, a functional tool was successfully produced to enhance students' understanding of factual concepts and computational procedures related to road tax. The development process was iterative rather than linear, involving multiple cycles of refinement before achieving a version deemed pedagogically appropriate and effective by the teacher. The calculator was developed in Bahasa Melayu, consistent with the medium of instruction in Malaysian secondary schools.

The final version of the tool met the teacher's instructional specifications and learning objectives. The calculator was made accessible via an interactive online platform (https://eowyeeleng.my.canva.site/dagpeega3rk), enabling students to engage with the material beyond the classroom. It accurately demonstrated road tax calculations based on vehicle type, geographical location and engine capacity, thereby functioning as a practical and pedagogically relevant resource to support both conceptual comprehension and procedural fluency. Additionally, the tool presented the calculation process in a clear, step-by-step format, facilitating learners' understanding of the underlying computational logic.

3.2 Sample of the Study

This study was conducted in a government secondary school located in Iskandar Puteri, Johor, Malaysia. The sample comprised 30 Form Five students. The participants represented a mixed-ability group.

3.3 Instrument

Two research instruments were employed in this study. The first consisted of two achievement tests (Test 1 and Test 2), which were designed to evaluate students' mastery of both factual knowledge and computational proficiency in road tax calculation. These assessments were developed to measure conceptual understanding as well as procedural accuracy, and were explicitly aligned with the prescribed learning outcomes for the taxation topic. The second instrument was a structured perception questionnaire, which was used to capture students' views on the use of the road tax calculator as a digital learning tool. Specifically, the questionnaire assessed students' perceptions of the calculator's usefulness and its supportive value in facilitating understanding of road tax computation. Collectively, these instruments generated complementary cognitive and attitudinal data, thereby enabling a comprehensive evaluation of students' learning performance and their engagement with technology-enhanced instruction.

3.4 Data Collection

Quantitative data were collected at the conclusion of each intervention cycle to evaluate students' mastery of factual knowledge and computational proficiency in road tax calculation. In addition, data capturing students' perceptions of the road tax calculator as a digital learning tool were gathered. Comparative analysis of these data across the two cycles provided insights into the effectiveness of Canva AI–supported self-directed learning, as well as the subsequent impact of teacher-guided reinforcement on students' conceptual understanding and procedural competence in taxation. The assessment instruments were administered consistently following both cycles to ensure the reliability and validity of the measurements.

3.5 Data Analysis

The data were tabulated and analysed using the Statistical Package for the Social Sciences (SPSS) Version 25. A paired-samples t-test was conducted to compare students' mean scores between Cycle 1 (self-directed learning) and Cycle 2 (teacher-guided instruction). This analysis was undertaken to determine whether the observed differences in students' performance and perceptions regarding the usefulness of the road tax calculator were statistically significant, thereby evaluating the impact of the instructional intervention.

4. Results

The findings of this action research demonstrated that the integration of the Canva AI–generated Road Tax Calculator (Figure 1) as a digital learning tool significantly enhanced students' mastery of both factual knowledge and computational proficiency in road tax calculation. The results of the paired-samples t-test, presented in Table 1, indicated significant improvements in participant performance across both assessed domains from Cycle 1 to Cycle 2.

For factual knowledge, a statistically significant increase in mean scores was observed between Cycle 1 ($M = 6.10$, $SD = 1.76$) and Cycle 2 ($M = 7.00$, $SD = 1.10$). The analysis revealed a significant difference, $t = 3.63$, $p = .001$, suggesting that the intervention between

cycles effectively enhanced students' retention of factual information. Similarly, computational proficiency showed a substantial and statistically significant improvement, with mean scores rising from 3.37 (SD = 2.53) in Cycle 1 to 6.67 (SD = 1.13) in Cycle 2. This difference was highly significant, t = 6.74, p < .001, indicating a marked increase in students' calculation proficiency.

Overall, the data demonstrated that the transition from Cycle 1 to Cycle 2 resulted in significant gains in both factual knowledge and computational proficiency. The lower standard deviations observed in Cycle 2 for both measures suggested that students' performance became more consistent as they progressed through the learning process. Table 1 highlighted that students' performance improved markedly from Cycle 1 to Cycle 2, with statistically significant gains recorded for both factual knowledge and computational proficiency (p < .05).

Figure 1: Canva AI-generated Road Tax Calculator

Table 1: Paired Sample t-Test Comparing Scores Between Test 1 and Test 2

Item	Cycle	N	Mean	SD	t	df	Sig.
Factual knowledge	1	30	6.10	1.76	3.63	29	0.001**
	2	30	7.00	1.10			
Calculation	1	30	3.37	2.53	6.74	29	0.000**
	2	30	6.67	1.13			

** *Significant at the 0.05 significance level*

The results of the paired-samples t-test for the Road Tax Calculator Usage Questionnaire, presented in Table 2, demonstrated a statistically significant improvement in students' perceptions across all five evaluative items between Cycle 1 and Cycle 2. The data indicated a marked shift in how students engaged with the calculator's features. Notably, the tool's capacity to enable self-checking of answers improved significantly, t = 7.23, p < .001, with mean scores rising from 2.33 (SD = 1.62) in Cycle 1 to 4.20 (SD = 0.66) in Cycle 2. Similarly, perceptions of the clarity of procedural steps increased from a mean of 2.20 (SD = 1.40) to 4.33 (SD = 0.61), yielding a highly significant difference, t = 9.56, p < .001.

The most substantial improvement was observed in the ease of referring to the road tax table, where the mean score rose by 3.00 points (M1 = 1.87, M2 = 4.87). This item produced the highest statistic within the set, t = 16.43, p < .001, indicating that the intervention between

cycles substantially enhanced the accessibility of reference data. Regarding the technical flexibility of the tool, parameter selection was perceived as significantly more versatile in Cycle 2 (M = 4.37, SD = 0.61) compared to Cycle 1 (M = 2.00, SD = 1.51), t = 10.68, p < .001. Furthermore, the tool's usability without external guidance improved significantly, t = 11.14, p < .001, with Cycle 2 scores (M = 4.50, SD = 0.57) indicating a high level of user autonomy compared to the baseline (M = 2.13, SD = 1.56).

Table 2: Paired-Sample T-test Analysis Comparing Scores from the Road Tax Calculator Usage Questionnaire between Cycle 1 and Cycle 2

Item	Cycle	N	Mean	SD	t	df	Sig.
1. Enables self-checking of answers	1	30	2.33	1.62	7.23	29	0.000**
	2	30	4.20	0.66			
2. Shows steps clearly	1	30	2.20	1.40	9.56	29	0.000**
	2	30	4.33	0.61			
3. Road tax table easily referred to	1	30	1.87	1.43	16.43	29	0.000**
	2	30	4.87	0.35			
4. Flexible parameter selection	1	30	2.00	1.51	10.68	29	0.000**
	2	30	4.37	0.61			
5. Easy to use without guidance	1	30	2.13	1.56	11.14	29	0.000**
	2	30	4.50	0.57			

*** Significant at the 0.05 significance level*

Overall, the results provided compelling evidence that the intervention implemented in Cycle 2 enhanced both the utility and the user-friendliness of the road tax calculator. Notably, there was a marked reduction in the standard deviations across all items in Cycle 2, indicating that the intervention offered students a more consistent and reliable experience.

5. Discussion

The findings of this action research underscored a critical pedagogical shift. Although generative AI (GenAI) tools, such as the Canva AI–generated Road Tax Calculator, offered significant affordances for autonomous exploration, their effectiveness was contingent upon structured teacher facilitation. The transition from Cycle 1 (self-directed learning) to Cycle 2 (teacher-guided intervention) produced statistically significant gains in both cognitive achievement and user perception, suggesting that AI-supported scaffolding was most effective when embedded within a hybrid instructional framework.

The notable improvement in students' factual knowledge and computational proficiency during Cycle 2 aligned with Vygotsky's (1978) concept of the Zone of Proximal Development (ZPD). In Cycle 1, despite access to the Canva AI–generated Road Tax Calculator, students struggled to construct meaning independently, as reflected in the lower mean scores for calculation (M = 3.37). This finding supported Zimmerman (2002) assertion that digital tools alone cannot compensate for insufficient prior knowledge or low readiness for self-directed learning.

Structured teacher guidance functioned as the critical catalyst, transforming the AI tool from a passive resource into an active instrument of cognitive scaffolding. Consistent with Rosenshine (2012), providing clarification and corrective feedback was essential for mastery in STEM-related tasks. The teacher enabled students to navigate the complexities of road tax logic, which had remained opaque during the self-directed learning cycle.

The results further supported the growing consensus that AI should operate as an augmentative partner rather than a substitute for human educators (Singh and Singh,

2025). Within the specific context of Southeast Asian classrooms, where secondary students often operate under high-stakes, examination-oriented pressures, the integration of deliberate learning design was particularly important (OECD, 2021). As framed in the OECD (2023), learning design involves the intentional and systematic creation of educational experiences that leverage digital ecosystems to achieve specific pedagogical goals. In the era of AI, this requires teachers to move beyond content delivery, assuming the role of learning designers within a complex digital infrastructure.

In Cycle 2, the teacher's role evolved from facilitator to designer of AI-supported learning experiences. Teacher mediation addressed the black box effect often associated with unguided AI usage. In educational research, as popularised by Black and Wiliam (2010) in Inside the Black Box, the classroom is conceptualised as a system in which conventional analyses focus on inputs (textbooks, funding, new AI tools) and outputs (test scores, grades) while overlooking the critical processes occurring between teachers and students. Black and Wiliam (2010) argued that improving learning outcomes requires constant feedback and interaction to clarify the learning path.

In this study, Cycle 1 represented a black box in which students engaged with the AI tool and obtained outputs without understanding the underlying reasoning. Through structured guidance in Cycle 2, the teacher translated the AI's opaque outputs into transparent and stepwise logic. This practice reflected the OECD (2023) vision of teachers as learning designers, ensuring that AI functioned as a vehicle for deep comprehension rather than merely a shortcut to answers.

Another salient finding was the reduction in standard deviations during Cycle 2, indicating that teacher-guided hybrid learning naOWrrowed the achievement gap. In Cycle 1, high variance suggested that students with greater digital literacy or prior knowledge could navigate the tool more effectively. The subsequent increases in confidence for self-checking (M = 4.20) and independent usability (M = 4.50) in Cycle 2 indicated that explicit modelling was a prerequisite for developing future autonomy. These findings aligned with Panadero (2017) and Wong et al. (2021), who argued that self-regulated learning with digital tools is a learned competency. By modelling the AI's logic, the teacher reduced cognitive load and enabled students to use the tool autonomously. Thus, it was a hallmark of successful hybrid learning.

Finally, the iterative nature of this action research provided empirical evidence for refining instructional delivery. The reflection phase of Cycle 1 revealed that curiosity alone did not equate to comprehension. By intentionally incorporating face-to-face scaffolding in Cycle 2, the teacher addressed immediate learning needs while fostering long-term technical confidence. This outcome highlighted a core principle of contemporary education in which the most effective digital transformations occur not through the imposition of technology but through its pedagogical integration, guided by continuous teacher reflection and adaptation.

6. Conclusion

Aligned with Malaysia's Digital Education Policy, this study demonstrated that AI-enabled tools can meaningfully enhance mathematics learning by supporting both conceptual understanding and procedural accuracy. However, the findings also emphasised that technology alone is insufficient to ensure deep and sustained learning gains. Students achieved better outcomes when the AI tool was integrated with explicit teacher guidance, particularly during the initial stages of adoption. This reinforces that, while AI has the capacity to promote independent learning, teachers remain central in scaffolding understanding, modelling problem-solving strategies, and providing timely feedback.

The results further revealed that Canva AI can function as an effective platform for developing customised instructional tools that make learning more interactive and contextually relevant. The notable improvement in students' perceptions from Cycle 1 to Cycle 2 indicates that successful AI integration depends not only on technological access, but also on deliberate pedagogical support tailored to learners' digital readiness. Importantly, this approach positions teachers not merely as tool users but as designers of digital learning applications.

Nevertheless, it is imperative to acknowledge that the findings of this action research are context-specific, rooted in the unique dynamics of a secondary-school environment. In accordance with the qualitative and iterative nature of action research, this study prioritises the depth of pedagogical insight and the refinement of instructional practice over broad statistical generalisability. Although the action research results offer high internal validity and practical utility for similar STEM-related situations they may not be directly transferable to different demographic cohorts or unrelated subject areas due to the sample size (N = 30) and the specific focus on road tax calculation.

Future scholarly research should explore varying degrees of instructional scaffolding to determine the precise point at which teacher mediation can be reduced in favour of student autonomy. Additionally, longitudinal studies are required to assess the long-term retention of computational fluency gained through AI-enhanced tools. Further research into adaptive AI systems capable of providing real-time, personalised feedback could offer more nuanced pathways toward equitable and effective AI adoption in diverse school-based learning environments.

References

Ahmad, S., Umirzakova, S., Mujtaba, G., Amin, M. S., & Whangbo, T. (2023). *Education 5.0: Requirements, enabling technologies, and future directions*. arXiv. https://doi.org/10.48550/arXiv.2307.15846

Amemasor, S. K., Oppong, S. O., Ghansah, B., Benuwa, B.-B., & Essel, D. D. (2025). *A systematic review on the impact of teacher professional development on digital instructional integration and teaching practices. Frontiers in Education*, *10*, Article 1541031. https://doi.org/10.3389/feduc.2025.1541031

Bano, M., Zowghi, D., Kearney, M., Schuck, S., & Aubusson, P. (2018). Mobile learning for science and mathematics school education: A systematic review of empirical evidence. *Computers & Education, 121*, 30–58. https://doi.org/10.1016/j.compedu.2018.02.006

Black, P., & Wiliam, D. (2010). Inside the black box: Raising standards through classroom assessment. *Phi Delta Kappan, 92*(1), 81–90. https://doi.org/10.1177/003172171009200119

Cheung, W. S., & Hew, K. F. (2011). Design and evaluation of two blended learning approaches: Lessons learned. *Australasian Journal of Educational Technology, 27*(8). https://doi.org/10.14742/ajet.896

Kemmis, S., McTaggart, R., & Nixon, R. (2014). *The action research planner: Doing critical participatory action research*. Springer Singapore. https://doi.org/10.1007/978-981-4560-67-2

Koehler, M. J., & Mishra, P. (2009). What is technological pedagogical content knowledge? *Contemporary Issues in Technology and Teacher Education*, *9*(1), 60–70. https://citejournal.org/volume-9/issue-1-09/general/what-is-technological-pedagogicalcontent-knowledge/

Maulah, A., Rulyansah, A., Ibrahim, M., & Rahayu, D. W. (2025). Canva AI: Untuk mengeksplorasi computational thinking siswa sekolah dasar. *Jurnal Pemikiran Pendidikan*, *31*(2), 192–206. https://doi.org/10.30587/didaktika.v31i2.10138

Navas Bonilla, C. d. R., Viñan Carrasco, L. M., Gaibor Pupiales, J. C., & Murillo Noriega, D. E. (2025). The Future of Education: A Systematic Literature Review of Self-Directed Learning with AI. *Future Internet*, *17*(8), 366. https://doi.org/10.3390/fi17080366

Ning, Y., & Danso, S. D. (2025). Assessing pedagogical readiness for digital innovation: A mixed-methods study. *arXiv*. https://doi.org/10.48550/arXiv.2502.15781

OECD. (2021). *AI and the future of skills, volume 1: Capabilities and assessments*. OECD Publishing. https://doi.org/10.1787/5ee71f34-en.

OECD. (2023). *OECD Digital Education Outlook 2023: Towards an effective digital education ecosystem*. OECD Publishing. https://doi.org/10.1787/c74f03de-en.

Panadero, E. (2017). A review of self-regulated learning: Six models and four directions for research. *Frontiers in Psychology*, *8*, Article 422. https://doi.org/10.3389/fpsyg.2017.00422

Putri Riyanto, M. A. T., & Dwi Putri, S. J. (2025). *The utilization of Canva application in innovative learning for elementary school teachers. Expert Net: Exploration Journal of Technological Education Trends*, *1*(2), 61–66. https://doi.org/10.59923/expertnet.v1i2.271

Rahman. (2025). The transformation of learning in the digital era: A theoretical review of technology integration in education. *Indonesian Journal of Education and Science, 1*(3), 103–110. https://www.journal.formadenglishfoundation.org/index.php/IJES/article/view/101

Redecker, C. (2017). *European framework for the digital competence of educators: DigCompEdu.* Publications Office of the European Union. https://doi.org/10.2760/159770

Rosenshine, B. (2012). Principles of instruction: Research-based strategies that all teachers should know. *American Educator*, *36*(1), 12–19. https://eric.ed.gov/?id=EJ971753

Singh, A. K., & Singh, T. (2025). AI-tutors: Can AI replace human teachers. *International Journal of Statistics and Applied Mathematics*, *10*(6), 145–153. https://doi.org/10.22271/maths.2025.v10.i6b.2068

Trust, T., & Whalen, J. (2021). K-12 teachers' experiences and challenges with using technology for emergency remote teaching during the COVID-19 pandemic. *Italian Journal of Educational Technology*, *29*(2), 10-25. https://doi.org/10.17471/2499-4324/1192

Vygotsky, L. S. (1978). *Mind in society: Development of higher psychological processes* (M. Cole, V. John-Steiner, S. Scribner, & E. Souberman, Eds.). Harvard University Press. https://doi.org/10.2307/j.ctvjf9vz4

Wong, J., Baars, M., de Koning, B. B., & Paas, F. (2021). Examining the use of prompts to facilitate self-regulated learning in Massive Open Online Courses. *Computers in Human Behavior, 115*. Article 106596. https://doi.org/10.1016/j.chb.2020.106596

Zakir, S., Hoque, M. E., Susanto, P., Nisaa, V., Alam, M. K., Khatimah, H., & Mulyani, E. (2025). *Digital literacy and academic performance: The mediating roles of digital informal learning, self-efficacy, and students' digital competence. Frontiers in Education*, *10*, Article 1590274. https://doi.org/10.3389/feduc.2025.1590274

Zimmerman, B. J. (2002). Becoming a self-regulated learner: An overview. *Theory Into Practice*, *41*(2), 64–70. https://doi.org/10.1207/s15430421tip4102_2

PROFILING ENERGY LITERACY AMONG MALAYSIAN SECONDARY STUDENTS: INSIGHTS FROM QUESTIONNAIRE ANALYSIS

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ABSTRACT

Energy literacy is crucial in equipping young people with the knowledge, attitudes, and behaviours needed to make informed decisions about sustainable energy use and environmental responsibility. However, comprehensive assessments of students' energy literacy remain limited, particularly within Southeast Asian contexts. This study aimed to profile secondary school students' energy literacy by examining their knowledge, attitudes, and behaviours toward energy-related issues. A quantitative survey design was employed involving 62 Form Three students (aged 15) from several secondary schools in Bintulu, Sarawak. The validated 57-item questionnaire, adapted from DeWaters and Powers (2011), comprised three constructs: knowledge (30 items), attitudes (17 items), and behaviours (10 items). Descriptive statistics and item-level profiling were used to classify responses into high, moderate, and low tiers, enabling the identification of students' strengths, misconceptions, and learning gaps. The results revealed strong attitudinal support for energy conservation and energy education but moderate to low engagement in energy-saving behaviours, particularly those requiring collaboration, sustained effort, or lifestyle change. Students demonstrated sound understanding of fundamental concepts such as renewable energy and efficiency but showed weaker knowledge of Malaysia's energy systems, fossil fuel dependency, and policy-related issues. From an educational perspective, this profiling approach provides practical diagnostic information that can support teachers in identifying specific misconceptions and behavioural gaps, thereby informing targeted instructional strategies and context-based classroom activities. The findings highlight the need for contextualised, action-oriented energy education that embeds local and global sustainability challenges, enabling teachers to translate profiling results into meaningful classroom practices that foster critical thinking, agency, and real-world application. Strengthening such educational approaches can bridge the gap between knowledge and practice, cultivating energy-literate citizens capable of contributing to Malaysia's sustainable energy transition.

Keywords: Energy Literacy, Sustainability, Energy Education, Secondary Education, Questionnaire Analysis

1. Introduction

Energy literacy has emerged as a critical competency in the face of escalating global energy demand, environmental degradation, and the urgent call for sustainable development. It encompasses not only technical knowledge but also the attitudes and behaviours that drive informed energy-related decisions (DeWaters and Powers, 2011; Martins et al., 2020;

Ramachandran et al., 2023). Within formal education, cultivating energy literacy among students is vital to developing responsible energy consumers and future citizens capable of responding to environmental and economic challenges (Awolesi et al., 2024; Nik Aida Mastura et al., 2025b). Despite growing interest in the concept of energy literacy, relatively little research has examined energy literacy through detailed profiling of questionnaire responses. Such analysis enables educators to uncover nuanced patterns, misconceptions, and behavioural inconsistencies that might otherwise go unrecognized (Bahrami and Mohammadi, 2021; Hu and Yang, 2024). Profiling each item provides granularity necessary for diagnosing educational gaps and tailoring instructional design. Additionally, understanding how students perceive and act upon energy-related issues offers valuable direction for refining both curriculum content and pedagogical strategies (Kubsch, 2024; Nik Aida Mastura et al., 2025a).

This study aims to profile the energy literacy of secondary school students by analysing their responses to a 57-item instrument encompassing knowledge, attitudes, and behaviours. Specifically, it seeks to identify item-level performance trends, highlight areas of strength, and uncover gaps that may impede students' ability to participate effectively in a sustainable energy future. To guide this investigation, the following research questions were formulated:

1) What are the levels of energy knowledge, attitudes, and behaviours demonstrated by secondary school students based on their questionnaire responses?
2) Which specific items reflect high, moderate, or low performance across each construct?
3) What patterns emerge from the profiling analysis that can inform contextually relevant energy education practices?

3. Method

This study employed a quantitative survey design to examine students' energy literacy through structured, classroom-based data collection. The instrument was adapted from the well-established framework developed by DeWaters and Powers (2011), which has been extensively validated and applied in prior studies (Bahrami and Mohammadi, 2021; Ilmi et al., 2021; Lay et al., 2013; Öykün and Abbasoğlu, 2017). Demonstrating strong internal reliability (Cronbach's alpha = 0.828; Pallant, 2020), the questionnaire operationalized energy literacy across three core constructs namely knowledge, attitudes, and behaviours. Collectively, these dimensions provided an integrated measure of students' cognitive understanding, affective orientations, and behavioural engagement with energy-related issues. Participants comprised 62 secondary school students (aged 15) drawn from several schools in Bintulu, Sarawak. This East Malaysian region was purposefully selected due to its rich energy resources and strategic role in the national energy transition agenda (Ministry of Economy, 2023). In addition, participation was voluntary, and all ethical protocols and consent procedures were duly observed. Classroom-based administration provided a familiar environment that supported accurate and consistent responses. The instrument consisted of three components reflecting the main domains of energy literacy:

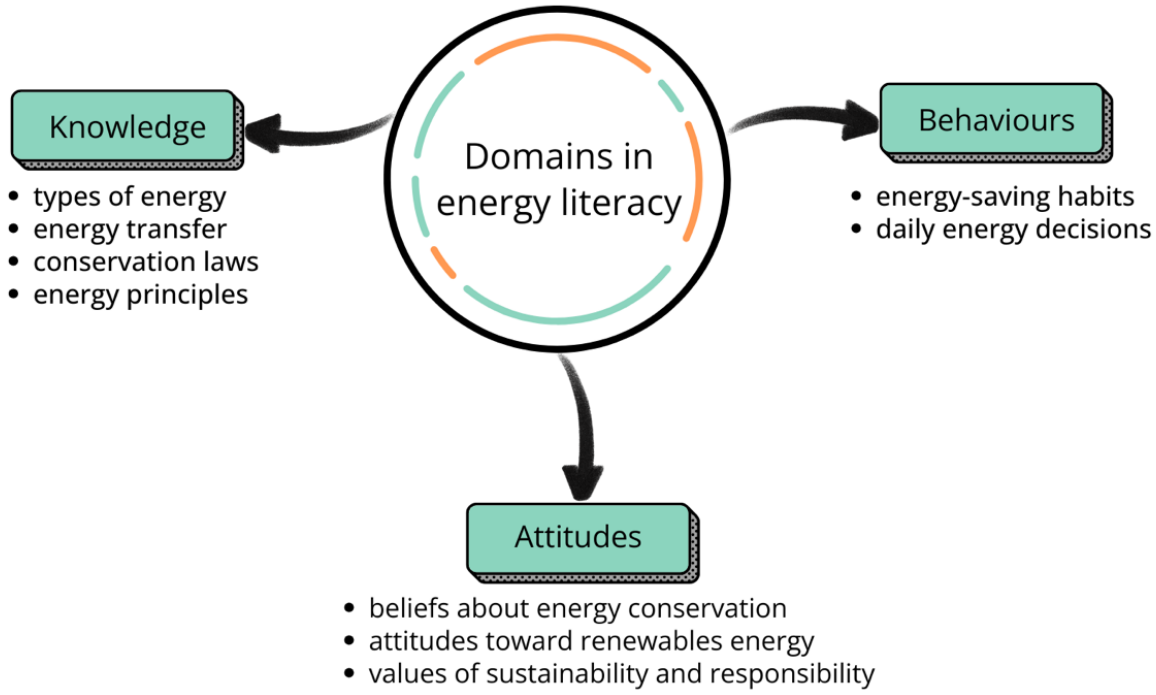
Knowledge: 30 multiple-choice items assessing students' understanding of energy sources, transformations, and applications in daily life, while identifying common misconceptions about energy systems and technologies (Adams et al., 2022; Mohd Yahya and Nor Asniza, 2024; Santillán and Cedano, 2023).

Attitudes: 17 Likert-scale items examining beliefs about energy conservation, support for renewable energy, and values related to environmental sustainability (Abdullahi et al., 2024; Tran and Vu, 2025).

Behaviours: 10 Likert-scale items measuring self-reported energy-saving practices in home and school contexts, such as reducing electricity use and promoting efficient energy habits (Appiah et al., 2023).

To illustrate the conceptual scope of these domains, Figure 1 presents the framework of energy literacy as operationalized in this study.

Figure 1: Domains and Key Components of Energy Literacy



Data were analysed using both descriptive and profiling techniques. Descriptive statistics (means and standard deviations) provided an overview of students' literacy levels, while item-level profiling categorized responses into high, moderate, or low performance tiers. For knowledge items, thresholds were based on the percentage of correct responses: high (> 60%), moderate (40–60%), and low (< 40%). For attitudes and behaviours, Likert mean scores were classified as high (> 4.00), moderate (3.00–4.00), and low (< 3.00), consistent with previous studies (DeWaters and Powers, 2013; Lee et al., 2015). This tiered analysis facilitated the identification of students' relative strengths, gaps, and areas for instructional improvement. Mapping these performance levels provided insights into learners' cognitive, motivational, and behavioural dimensions of energy literacy, enabling educators and policymakers to target interventions more effectively.

3. Result

3.1 Students' Level of Energy Knowledge, Attitudes, and Behaviours

Table 1 reports the percentage of correct responses for each of the 30 items in the knowledge subconstruct. Each item was scored as either correct or incorrect. The percentages reflect students' factual understanding of energy-related concepts.

Table 1: Items in the Knowledge Subconstruct

Item Number	Items in Questionnaire	Correct Response (%)	Performance Tier
K1	Each and every action on Earth involves ...	70.97	High
K2	The original source of energy for almost all living things on Earth is ...	74.19	High
K4	How do you know that a piece of wood has stored chemical potential energy?	66.13	High
K11	The term "renewable energy sources" means ...	62.90	High
K24	Which household item uses the most electricity per year?	62.90	High
K3	Energy is defined as ...?	56.45	Moderate
K8	When you turn on an incandescent light bulb, some of the energy is converted into light and the rest is converted into ...	53.23	Moderate
K9	What does it mean if an electric power plant is 35% efficient?	40.32	Moderate
K14	Most of the renewable energy used in Malaysia comes from ...	43.55	Moderate
K18	The best reason for buying appliances with energy efficiency labels is ...	48.39	Moderate
K19	Some people think that if we run out of fossil fuels, we can just switch over to electric cars. What is wrong with this idea?	43.55	Moderate
K20	If a person travelled alone to work 50 km every day and wanted to save gasoline, which one of the following options would save the most gasoline?	51.61	Moderate
K21	Which of the following always leads to energy savings?	45.16	Moderate
K22	Which uses the most energy in an average Malaysian home in one year?	50.00	Moderate
K28	Many scientists say Earth's average temperature is increasing. They say that one important cause of this change is ...	54.84	Moderate
K5	All of the following are forms of energy except ...	37.10	Low
K6	The amount of electrical energy (electricity) we use is measured in units called ...	58.06	Low
K7	Which two things determine the amount of electrical energy (electricity) an electrical device will consume?	25.81	Low
K10	It is impossible to ...	29.03	Low
K12	Which of the following energy resource is not renewable?	50.00	Low
K13	Which resource provides about 85% of the energy used in developed countries?	25.81	Low
K15	Compared to 2000, Malaysia's petroleum imports in 2020...	22.58	Low
K16	Scientists say the single fastest and most cost-effective way to address our energy needs is to ...	30.65	Low
K17	Which is the most abundant fossil fuel found in Malaysia?	25.81	Low
K23	Which uses the least energy in an average Malaysian home in one year?	14.52	Low
K25	Which source supplies most of Malaysia's annual energy?	20.97	Low
K26	Which one of the following sources generates the most electricity in Malaysia?	25.81	Low
K27	One advantage of using nuclear power instead of coal or petroleum for energy is that ...	37.10	Low
K29	Which of the following energy-related activities is least harmful to human health and the environment?	33.87	Low
K30	Which of the following choices is not a biofuel?	27.42	Low

As shown in Table 2, the mean and standard deviation for each of the 17 items in the attitudes subconstruct are presented to illustrate students' response trends. Responses were based on a 5-point Likert scale, with higher mean scores indicating stronger agreement with the statements related to energy conservation, personal responsibility, and support for renewable energy.

Table 2: Items in the Attitudes Subconstruct

Item Number	Items in Questionnaire	Mean	SD	Performance Tier
A1	Energy education should be an important part of every school's curriculum.	4.03	0.677	High
A2	I would do more to save energy if I knew how.	4.26	0.541	High
A3	Saving energy is important.	4.61	0.554	High
A8	All electrical devices should have a label	4.27	0.772	High
A5	I don't need to worry about turning the lights or computers off in the classroom, because the school pays for the electricity.	3.56	0.590	Moderate
A6	Malaysians should conserve more energy.	3.77	0.556	Moderate
A7	We don't have to worry about conserving energy, because new technologies will be developed in order to solve the energy problems for future generations.	3.74	0.441	Moderate
A9	The government should have stronger restrictions about the fuel mileage of new cars.	3.40	1.166	Moderate
A10	We should produce more of our electricity from renewable resources.	3.65	1.026	Moderate
A11	We should develop more ways of using renewable energy, even if it means that energy will cost more.	3.42	1.080	Moderate
A12	Efforts to develop renewable energy technologies are more important than efforts to find and develop new sources of fossil fuels.	3.77	0.965	Moderate
A13	Laws protecting the natural environment should be made less strict in order to allow more energy to be produced.	3.55	1.082	Moderate
A14	More solar farms should be built to generate electricity, even if the solar farms are located in farmlands.	3.47	0.970	Moderate
A15	More oil fields should be developed as they are discovered, even if they are located in areas protected by environmental laws.	3.42	0.879	Moderate
A16	I believe that I can contribute to solving the energy problems by making appropriate energy-related choices and actions.	3.71	0.818	Moderate
A17	I believe that I can contribute to solving energy problems by working with others.	3.74	0.904	Moderate
A4	The way I personally use energy does not really make a difference to the energy problems that our nation faces.	2.37	0.794	Low

Table 3 displays the mean and standard deviation for each of the 10 behavioural items. These items assess students' self-reported energy-saving practices at home and in everyday life, also using a 5-point Likert scale.

Table 3: Items in the Behaviours Subconstruct

Item number	Items in Questionnaire	Mean	SD	Performance Tier
B3	When I leave a room, I turn off the lights.	4.27	0.961	High
B4	I turn off the computer when it is not being used.	4.31	1.018	High

B1	I try to save water	3.87	0.983	Moderate
B5	Many of my everyday decisions are affected by my thoughts on energy use.	3.13	1.079	Moderate
B8	My family buys energy efficient compact fluorescent light bulbs.	3.47	1.082	Moderate
B9	I am willing to encourage my family to buy energy efficient compact fluorescent light bulbs.	3.34	1.101	Moderate
B2	I walk or ride bicycle to travel short distances, instead of asking for a ride in the car.	2.84	1.506	Low
B6	My family turns the heat down at night or the air conditioner temperature up when we are not home to save energy.	2.61	1.359	Low
B7	I am willing to encourage my family to turn the heat down at night or the air conditioner temperature up when we're not home to save energy	2.60	1.348	Low
B10	I am willing to buy fewer things in order to save energy.	2.89	1.147	Low

3.2 Item-Level Performance Across Constructs

3.2.1 Knowledge

Profiling of knowledge items showed that while students demonstrated strong understanding of basic energy concepts, performance declined on context-specific and applied items, particularly those related to Malaysia's energy landscape.

High-performing items (> 60%) reflected strong mastery of foundational principles. Students correctly identified the sun as the original energy source for living things (K2: 74.19%), recognized that all actions on Earth involve energy (K1: 70.97%), and understood that renewable sources are replenished by nature (K11: 62.90%). They also identified hydro as a major renewable source in Malaysia (K4: 66.13%) and refrigerators as the most electricity-consuming home appliance (K24: 62.90%). These results indicate clear conceptual understanding and practical awareness.

Moderate-performing items (40–60%) revealed partial comprehension of energy definitions and efficiency concepts. Students moderately understood that energy is the ability to do work (K3: 56.45%) and that incandescent bulbs release heat as a byproduct (K8: 53.23%). They showed limited but present awareness of energy-saving behaviours, including carpooling to save gasoline (K20: 51.61%) and identifying room cooling as the highest household energy use (K22: 50.00%). Similarly, knowledge of electricity billing (K6: 58.06%), unplugging chargers (K21: 45.16%), and energy-efficiency labeling (K18: 48.39%) was incomplete. Awareness of national energy systems was moderate, as reflected in partial understanding of natural gas as a key resource (K19: 43.55%), hydro dominance (K14: 43.55%), and the efficiency of power plants (K9: 40.32%).

Low-performing items (< 40%) exposed major misconceptions and contextual knowledge gaps. Students misidentified coal as a form of energy (K5: 37.10%) and showed weak awareness of fossil fuel reliance in developed nations (K13: 25.81%). Knowledge about Malaysia's energy profile was poor, including petroleum imports (K15: 22.58%), reliance on natural gas (K25: 20.97%), and electricity generation from coal (K26: 25.81%). The lowest-performing item, identifying lighting as the least energy-consuming activity in homes (K23: 14.52%), revealed widespread misunderstanding of everyday energy use. Other low-scoring items included recognizing benefits of energy conservation (K16: 30.65%), understanding nuclear power's environmental advantages (K27: 37.10%), and identifying non-biofuels (K30: 27.42%).

Overall, students displayed solid basic understanding but limited contextual and applied energy knowledge. Instructional efforts should therefore emphasize Malaysia's energy mix, sustainability issues, and practical efficiency concepts to strengthen energy literacy (Bussotti, 2023; Detken, 2023; Gladwin and Ellis, 2023).

3.2.2 Attitudes

Attitudinal profiling revealed strong foundational values but moderate ambivalence toward policy-oriented issues and limited sense of personal impact.

High-performing items (M > 4.00) reflected positive attitudes toward energy conservation and education. Students strongly agreed on the importance of saving energy (A3: M=4.61), knowing how to conserve it (A2: M=4.26), labelling appliances with energy and cost information (A8: M=4.27), and integrating energy education into school curricula (A1: M=4.03). These findings suggest established sustainability values and readiness for deeper engagement (Skarżyński and Wiśniewski, 2024).

Moderate-performing items (3.00 ≤ M < 4.00) represented uncertainty toward complex trade-offs. Twelve of the 17 items fell in this range, showing partial support for conservation (A6: M=3.77) and renewable energy (A10: M=3.65; A12: M=3.77). Students were ambivalent toward controversial measures such as building solar farms on agricultural land (A14: M=3.47), developing oil fields in protected areas (A15: M=3.42), or relaxing environmental protections for energy production (A13: M=3.55). They also showed moderate belief in technological optimism (A7: M=3.74) and modest confidence in individual or collective influence (A16: M=3.71; A17: M=3.74). These attitudes reflect partial understanding of systemic trade-offs and limited systems thinking (Biancardi et al., 2023).

Low-performing item (M < 3.00), A4 (M=2.37), indicated weak personal responsibility, as many students believed their own energy use had minimal national impact. This finding underscores the need for pedagogical approaches that strengthen energy citizenship and agency (Patel and Parkins, 2023).

In sum, students displayed generally positive but underdeveloped attitudes. Strengthening contextual understanding, moral responsibility, and efficacy beliefs can foster more informed and consistent pro-environmental engagement (Zhou and Traynor, 2022).

3.2.3 Behaviours

Behavioural profiling indicated strong adherence to simple personal habits but limited engagement in more demanding or socially influenced actions.

High-performing items (M ≥ 4.00) showed consistent practice of routine conservation habits, including turning off lights when leaving rooms (B3: M=4.27) and shutting down computers when not in use (B4: M=4.31). These low-effort actions appear well-internalised.

Moderate-performing items (3.00 ≤ M < 4.00) reflected partial engagement in sustainability practices. Students reported saving water (B1: M=3.87) but showed inconsistency in encouraging family members to buy energy-efficient bulbs (B9: M=3.34) or reflecting household practices (B8: M=3.47). Limited integration of energy considerations into daily decision-making (B5: M=3.13) suggests awareness not yet fully applied.

Low-performing items (M < 3.00) demonstrated low willingness to perform higher-effort actions such as walking or cycling short distances (B2: M=2.84), adjusting air-conditioning when away

(B6: M=2.61), motivating family behaviour change (B7: M=2.60), or reducing overall consumption (B10: M=2.89).

These findings show a gap between awareness and action, particularly for socially mediated or effortful behaviours. Effective interventions should therefore target behavioural confidence, family engagement, and social responsibility to transform knowledge and attitudes into consistent energy-saving practices (Aruta, 2023).

3.3 Emerging Patterns to Guide Contextual Energy Education

The profiling analysis offered valuable insights into the varying dimensions of energy literacy among secondary school students. A clear pattern emerged showing a disparity between students' conceptual knowledge and their ability to apply that knowledge to real-world, contextual scenarios. While students often demonstrated correct recall of basic facts, they struggled with items requiring application of that knowledge to Malaysia's national energy landscape or to ethical dilemmas involving sustainability trade-offs. Another recurring pattern involved the discrepancy between routine personal actions and more complex, socially mediated energy behaviours. Students showed high engagement with individual habits such as turning off lights but were less inclined to act in situations requiring family collaboration, lifestyle changes, or consumption adjustments. This suggests a tiered behavioural framework where low-effort actions are better internalised than those requiring deeper commitment or interpersonal influence.

The affective component of energy literacy revealed moderate performance in attitudinal items tied to systemic issues or long-term environmental trade-offs. While students acknowledged the importance of conservation, their support weakened when policy implications or environmental costs were introduced. This hesitancy suggests ambivalence when faced with competing values such as economic growth versus environmental protection. Finally, profiling also highlighted a need for curriculum content to better reflect the local context. Items related to Malaysia's energy profile such as dominant sources of electricity, fuel imports, and fossil fuel dependency were among the lowest-scoring. This underscores the importance of contextualising energy education, ensuring that students engage with material directly relevant to their own geographic and socio-political environment.

4. Discussion

The profiling of secondary students' energy literacy, covering attitudes, behaviours, and knowledge, reveals significant insights into both strengths and areas in need of intervention. While students exhibit strong positive attitudes toward energy conservation, their knowledge of energy concepts and behaviours related to energy-saving practices reflect notable gaps. This disconnect suggests that cognitive awareness alone is insufficient to foster active participation in sustainable practices. As Papadakis and Katsaprakakis (2023) highlight, transforming awareness into meaningful action requires integrated, targeted educational strategies that empower students as informed and responsible energy citizens.

High attitudinal scores on items related to energy education and conservation indicate students' receptiveness to sustainability issues when presented clearly and accessibly. However, their moderate agreement with more complex or trade-off-related issues such as cost implications of renewable energy or development in protected areas, reflects a limited understanding of systemic energy dilemmas. This ambivalence is further compounded by the low belief in personal efficacy (e.g., A4: "The way I personally use energy does not really make a difference"), indicating that students may perceive energy issues as beyond their individual influence. Embedding real-world dilemmas and ethical reasoning tasks into classroom

discourse, as proposed by Cummins (2024) and Radulescu (2022), may help strengthen students' sense of agency and nurture critical sustainability thinking.

Behavioural findings further expose a significant divergence between values and action. While routine, low-effort energy-saving behaviours (e.g., turning off lights or computers) are well internalised, students showed low engagement with socially mediated or high-effort practices, such as influencing family energy use or making consumption sacrifices. This aligns with findings by (Hamidi Razi et al., 2021), who underscore the importance of perceived behavioural control and supportive social environments in shaping sustainable actions. Therefore, energy education should extend beyond individual responsibility to include collaborative and community dimensions. Peer initiatives, school energy campaigns, and family-based outreach projects could serve as catalysts for developing sustained behavioural change (Paramati et al., 2022; Ye and Yue, 2023).

Regarding knowledge, students demonstrated proficiency on basic scientific concepts (e.g., energy definitions, energy sources), but struggled with advanced and context-specific topics, including Malaysia's energy landscape and global sustainability challenges. Items related to national energy production, fossil fuel dependencies, and systemic energy efficiency yielded consistently low performance. These gaps indicate a pressing need for localised, application-driven instruction that bridges theoretical content with everyday realities. Integrating case studies, energy audit exercises, and localised resource mapping can foster greater relevance and retention (Zakari et al., 2022; Brychkov et al., 2023). For instance, lessons that use Malaysia's actual energy data or encourage analysis of household electricity bills can make abstract ideas more tangible (Khafiso et al., 2025).

Importantly, this profiling analysis also highlights opportunities for refining the energy literacy instrument itself. The presence of consistently low-performing items suggests a need to review item phrasing for clarity and cognitive alignment. Revising these items could improve the diagnostic accuracy of future assessments and better support curriculum design. While the findings are constrained by the study's sample size and geographic scope, they provide valuable preliminary evidence to inform both research and practice. Future research could expand this work through longitudinal tracking and application in varied socio-geographic contexts to explore how energy literacy evolves over time and is influenced by cultural or infrastructural factors.

From a pedagogical perspective, the profiling results offer practical diagnostic value that can be directly applied in daily classroom practice. By examining item-level performance, teachers are able to identify specific misconceptions and behavioural gaps, particularly in relation to Malaysia's energy systems and everyday energy use. For instance, low performance on items related to household electricity consumption and national energy sources suggests the need for targeted instructional emphasis. Teachers may respond by integrating short, context-based learning activities, such as analysing actual household electricity bills, comparing energy consumption of common appliances, or discussing Sarawak's role in Malaysia's energy production. These strategies allow teachers to align instruction with students' identified learning needs without altering the existing curriculum structure, thereby bridging conceptual understanding with real-life energy decision-making.

5. Conclusion and Recommendations

This study presents a comprehensive profile of secondary school students' energy literacy across knowledge, attitudes, and behaviours. The findings reveal encouraging strengths in students' foundational understanding and positive energy attitudes, particularly in basic conservation practices. However, notable gaps remain in systems thinking, personal efficacy,

and contextual understanding of Malaysia's energy landscape. These disparities highlight the need for pedagogical strategies that move beyond awareness-raising toward cultivating critical reasoning, ethical judgment, and practical application of energy concepts.

To strengthen energy literacy holistically, instructional approaches should embed complex sustainability dilemmas, integrate local and global energy contexts, and promote collaborative action across classroom, household, and community domains. Embedding real-world energy scenarios such as national energy mix, policy trade-offs, and consumption challenges can deepen students' conceptual and contextual understanding while fostering active citizenship in energy transitions.

In the context of Bintulu, where energy-related industries and infrastructure play a significant economic and social role, the findings of this study also point to the potential for school–industry collaboration as a means of strengthening energy literacy. Schools may engage with local energy stakeholders, such as utility providers or private energy-related companies, through structured yet modest initiatives, including classroom talks, career exposure sessions, or contextual learning discussions led by industry practitioners. Such collaborations can help students connect classroom concepts with real-world energy systems, particularly in relation to electricity generation, energy efficiency, and sustainability challenges. At the classroom level, teachers can further encourage students to apply energy literacy through simple action-oriented tasks, such as guided home energy observations, small-group discussions involving family energy practices, or reflective activities on daily energy use. These approaches support the translation of knowledge and attitudes into more consistent energy-saving behaviours.

Future research should expand the sampling scope to include diverse regions, school types (urban–rural, public–private), and socio-cultural backgrounds to enhance generalisability and enable cross-regional comparisons. Methodologically, a mixed-methods design is recommended. While quantitative approaches establish reliable benchmarks, qualitative insights from interviews, focus groups, or classroom observations can uncover deeper cognitive and socio-cultural dynamics underlying students' energy perceptions and behaviours.

Continuous refinement of assessment tools is also essential. Future studies should undertake localised validation through expert consultation, pilot testing, and iterative user feedback to ensure cultural and curricular alignment. Pedagogically, findings support the integration of energy literacy within interdisciplinary and experiential learning models such as digital simulations, home energy audits, and community-based sustainability projects to bridge conceptual knowledge with authentic practice.

Finally, sustained collaboration among educators, curriculum developers, and policymakers is crucial to institutionalise energy literacy within Malaysia's educational strategy. Embedding it as a core competency will not only enhance scientific understanding but also cultivate informed, responsible, and empowered citizens capable of contributing meaningfully to sustainable energy transitions.

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References

Abdullahi, A. M., Hussein, H. A., Ahmed, M. Y., Hussein, O. A., & Warsame, A. A. (2024). The impact of education for sustainable development on university students' sustainability behavior: a case study from undergraduate students in Somalia. *Frontiers in Education*, *9*. https://doi.org/10.3389/feduc.2024.1413687

Adams, J., Kenner, A., Leone, B., Rosenthal, A., Sarao, M., & Boi-Doku, T. (2022). What is energy literacy? Responding to vulnerability in Philadelphia's energy ecologies. *Energy Research and Social Science*, *91,* 102718. https://doi.org/10.1016/j.erss.2022.102718

Appiah, M. K., Gyening, E. K., Teye, P. K., Frimpong, C., & Nsowah, A. (2023). The implications of energy literacy on energy savings behavior: A model of contingent effects of energy value and attitude. *Energy Reports*, *10*, 72–85. https://doi.org/10.1016/j.egyr.2023.06.008

Aruta, J. J. B. R. (2023). Science literacy promotes energy conservation behaviors in Filipino youth via climate change knowledge efficacy: Evidence from PISA 2018. *Australian Journal of Environmental Education*, *39*(1), 55–66. https://doi.org/10.1017/aee.2022.10

Awolesi, O., Salter, C. A., & Reams, M. (2024). A systematic review on the path to inclusive and sustainable energy transitions. *Energies*, *17*(14). https://doi.org/10.3390/en17143512

Bahrami, S., & Mohammadi, Y. (2021). Assessing energy literacy of Iranian ninth-grade students. *Journal of Turkish Science Education*, *18*(4), 707–731. https://doi.org/10.36681/tused.2021.99

Biancardi, A., Colasante, A., D'Adamo, I., Daraio, C., Gastaldi, M., & Uricchio, A. F. (2023). Strategies for developing sustainable communities in higher education institutions. *Scientific Reports, 13*(1), 1–19. https://doi.org/10.1038/s41598-023-48021-8

Brychkov, D., Goggins, G., Doherty, E., Romero, N., Roudil, N., Di Trani, A., Singh, A., Smit, S., McLoughlin, E., de Castro Rodrigues Lima, R., Günbay, S. M., Delmonte, B. A., Hill, A., Domegan, C., & Clifford, E. (2023). A systemic framework of energy efficiency in schools: experiences from six European countries. *Energy Efficiency*, *16*(4). https://doi.org/10.1007/s12053-023-10099-4

Bussotti, P. (2023). Introducing the concept of energy: Educational and conceptual considerations based on the history of physics. *Proceedings of the 5th International Baltic Symposium on Science and Technology Education* (pp. 38–57). https://doi.org/10.33225/BalticSTE/2023.38

Cummins, S. (2024). Building "Glocal" Literacy to Develop Global Citizens. In *Communication and Education: Promoting Peace and Democracy in Times of Crisis and Conflict* (pp. 257–268). John Wiley & Sons, Inc. https://doi.org/10.1002/9781119985280.ch15

Detken, F. (2023). Young children's ideas of energy compared with the scientific energy concept: Results of a video study with interviews about children's own drawings. *Frontiers in Education*, *8*. https://doi.org/10.3389/feduc.2023.1035066

DeWaters, J. E., & Powers, S. E. (2011). Energy literacy of secondary students in New York State (USA): A measure of knowledge, affect, and behavior. *Energy Policy*, *39*(3), 1699–1710. https://doi.org/10.1016/j.enpol.2010.12.049

DeWaters, J., & Powers, S. (2013). Establishing measurement criteria for an energy literacy questionnaire. *Journal of Environmental Education*, *44*(1), 38–55. https://doi.org/10.1080/00958964.2012.711378

Gladwin, D., & Ellis, N. (2023). Energy literacy: towards a conceptual framework for energy transition. *Environmental Education Research*, *29*(10), 1515–1529. https://doi.org/10.1080/13504622.2023.2175794

Hamidi Razi, D., Ranjpour, R., & Motafakker Azad, M. A. (2021). Energy literacy and energy-related financial literacy in Iran: Case of Northwestern Academic Community. *Environmental Energy and Economic Research*, *5*(3), 17–31. https://doi.org/10.22097/eeer.2021.277525.1189

Hu, J.-L., & Yang, P.-S. (2024). Interactive Cycles between Energy Education and Energy Preferences: A Literature Review on Empirical Evidence. *Energies*, *17*(20). https://doi.org/10.3390/en17205092

Ilmi, N., Sanjaya, L. A., Budi, A. S., Astra, I. M., Puspa, R. W., Dinata, F. A., Putri, R. A., Winarko, H. B., Pertiwi, W. A., & Rasmi, D. P. (2021). Project based learning: Model electric power plants MaS WaWi (biomass, sun, water, and wind) to improve student energy literacy. *AIP Conference Proceedings*, *2320*. https://doi.org/10.1063/5.0037528

Ministry of Economy. (2023). *National Energy Transition Roadmap*. https://ekonomi.gov.my/sites/default/files/2022-09/Dasar_Tenaga_Negara_2022-2040.pdf

Khafiso, T., Adekunle, S. A., & Aigbavboa, C. (2025). Assessment of energy-saving strategies mitigating high energy usage in residential buildings. *Property Management, 43*(4), 540–561. https://doi.org/10.1108/PM-12-2024-0126

Kubsch, M. (2024). What affects the continued learning about energy? Evidence from a 4-year longitudinal study. *Journal of Research in Science Teaching*, *61*(5), 975–997. https://doi.org/10.1002/tea.21931

Lay, Y.-F., Khoo, C.-H., Treagust, D. F., & Chandrasegaran, A. L. (2013). Assessing secondary school students' understanding of the relevance of energy in their daily lives. *International Journal of Environmental & Science Education*, *8*(1), 199–215. https://www.researchgate.net/publication/255703966_Assessing_secondary_school_students'_understanding_of_the_relevance_of_energy_in_their_daily_lives

Lee, L.-S., Lee, Y.-F., Altschuld, J. W., & Pan, Y.-J. (2015). Energy literacy: Evaluating knowledge, affect, and behavior of students in Taiwan. *Energy Policy*, *76*, 98–106. https://doi.org/10.1016/j.enpol.2014.11.012

Martins, A., Madaleno, M., & Ferreira Dias, M. (2020). Energy literacy: Does age matters? In *Proceedings of the ACM International Conference* (pp. 546–551). https://doi.org/10.1145/3434780.3436653

Mohd Yahya, F. J., & Nor Asniza, I. (2024). A bibliometric study on energy literacy and education: Mapping trends, focus areas and research gaps. *Journal of Contemporary Social Science and Education Studies*, *4*(2), 71–83. https://doi.org/10.5281/zenodo.13370480

Nik Aida Mastura, N. A. M., Kamisah, O., & Tan, S. Y. (2025a). Energy education: adapting to learning preferences and pedagogical strategies. *Journal of Education and Learning*, *19*(4), 2332–2341. https://doi.org/10.11591/edulearn.v19i4.23031

Nik Aida Mastura, N. A. M., Kamisah, O., & Tan, S. Y. (2025b). Integrating energy literacy into science education: a comprehensive systematic review. *International Journal of Evaluation and Research in Education*, *14*(2), 1253–1263. https://doi.org/10.11591/ijere.v14i2.31873

Öykün, T., & Abbasoğlu, S. (2017). Energy literacy survey at high school in Northern Cyprus. *International Journal of New Trends in Arts*, *6*(2). www.ijtase.net

Pallant, J. (2020). *SPSS Survival Manual* (7th ed.). Routledge. https://doi.org/10.4324/9781003117452

Papadakis, N., & Katsaprakakis, D. Al. (2023). A review of energy efficiency interventions in public buildings. *Energies*, *16*(17), 6329. https://doi.org/10.3390/en16176329

Paramati, S. R., Shahzad, U., & Doğan, B. (2022). The role of environmental technology for energy demand and energy efficiency: Evidence from OECD countries. *Renewable and Sustainable Energy Reviews*, *153,* 111735. https://doi.org/10.1016/j.rser.2021.111735

Patel, S., & Parkins, J. R. (2023). Assessing motivations and barriers to renewable energy development: Insights from a survey of municipal decision-makers in Alberta, Canada. *Energy Reports*, *9*, 5788–5798. https://doi.org/10.1016/j.egyr.2023.05.027

Radulescu, V. (2022). New requirements for all levels of education in energy management in the current context of global crisis. *Revista Romaneasca Pentru Educatie Multidimensionala*, *14*(4), 155–170. https://doi.org/10.18662/rrem/14.4sup1/664

Ramachandran, A., Ellis, N., & Gladwin, D. (2023). Energy literacy: A review in education. *Journal of Environmental Education*, *55*(3), 191–202. https://doi.org/10.1080/00958964.2023.2283694

Santillán, O. S., & Cedano, K. G. (2023). Energy literacy: A systematic review of the scientific literature. *Energies*, *16*(21), 7235. https://doi.org/10.3390/en16217235

Skarżyński, K., & Wiśniewski, A. (2024). The reflections on energy costs and efficacy problems of modern LED lamps. *Energy Reports*, *12*, 4926–4937. https://doi.org/10.1016/j.egyr.2024.10.038

Tran, T. H. H., & Vu, T. D. (2025). Enhancing renewable energy product consumption of young customers through sustainable development goals knowledge: An application of the theory of planned behavior. *Sustainability*, *17*(9), 3784. https://doi.org/10.3390/SU17093784

Ye, X., & Yue, P. (2023). Financial literacy and household energy efficiency: An analysis of credit market and supply chain. *Finance Research Letters*, *52*, 103563. https://doi.org/10.1016/j.frl.2022.103563

Zakari, A., Khan, I., Tan, D., Alvarado, R., & Dagar, V. (2022). Energy efficiency and sustainable development goals (SDGs). *Energy, 239*, 122365. https://doi.org/10.1016/j.energy.2021.122365

Zhou, S., & Traynor, A. (2022). Measuring students' learning progressions in energy using cognitive diagnostic models. *Frontiers in Psychology*, *13*, 892884. https://doi.org/10.3389/fpsyg.2022.892884

EFFECT OF GEOGEBRA ON THE MATHEMATICS ACHIEVEMENT OF STEM LEARNERS

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ABSTRACT

This study investigated the impact of GeoGebra, a dynamic mathematics software, on the mathematics achievement of 60 Filipino Grade 11 STEM learners regarding conic sections. Utilising a quasi-experimental, non-equivalent control group design, the research compared a GeoGebra-assisted approach with traditional instruction through a teacher-made, MELCs-aligned pre-test and post-test. Pre-intervention analysis confirmed that both groups started with equivalent and unsatisfactory achievement levels. However, post-test results revealed that while both groups improved significantly, the experimental group achieved a higher mean score compared to the control group. The resulting t-value of -4.76 ($p < 0.05$) and a large effect size (Hedges' g = 1.21) suggest that GeoGebra intervention was effective in improving conceptual understanding and visual engagement. Though the findings are bounded by certain limitations, including a short intervention period and reliance on a teacher-made assessment rather than standardised national tests, the results suggest that GeoGebra serves as a valuable pedagogical supplement for bridging instructional gaps in complex mathematical topics. Future research should explore the long-term retention of these gains and the scalability of technology integration across diverse educational settings.

Keywords: GeoGebra, Mathematics Achievement, Conic Sections, STEM Learners, Quasi-experimental Design, Technology Integration

1. Introduction

In many classrooms today, math is still taught through traditional lectures. Unfortunately, the traditional chalk-and-talk lecture has been the standard, yet this method often leads to a lack of interest among students and makes it difficult for them to picture abstract math concepts (Anario et al., 2023; Padernal and Diego, 2020).This is a serious problem in math education, and many experts believe that digital tools are the key to helping students explore math in real-time (Anario et al., 2023).

The need for a change is urgent when looking at how Filipino students are performing. According to the 2022 PISA results, the Philippines scored only 355 in Mathematics which is far below the international average of 472. It was even more alarming when only 16% of our students reached a basic level of math literacy (OECD, 2023). This low performance is also seen in our National Achievement Tests (NAT) and was made worse by the disruptions of the COVID-19 pandemic (Behiga, 2022). At Valencia National High School (VNHS), where the researcher is teaching, this struggle is a daily reality. In the conducted school Learning Action Cell (LAC) sessions and in the submitted progress reports, there showed a consistently downward trend when it comes to students' academic achievement in mathematics.

A major reason for this low math performance is that students simply cannot visualise the abstract concepts since they are only used to memorising or solving formulas but not on how those formulas work in a physical space (Anario et al., 2023). This is where GeoGebra comes

in. Unlike a basic graphing calculator, GeoGebra combines algebra and geometry into one interactive screen allowing students to move points around and see how equations change instantly (Bautista, 2023). However, despite its proven effectiveness, GeoGebra is rarely used in Philippine schools because teachers have not been trained on facilitating it in the classroom, and somehow, they feel hesitant in moving away from familiar teaching routines (Wassie and Zergaw, 2019).

Currently, there is a major gap in research where there is surprisingly little data on how it performs within a rural Philippine Senior High School STEM classroom. Most existing research focuses on big cities or schools that already have advanced technology. There is a clear need for evidence focusing on rural settings like VNHS, especially for complex subjects like Conic Sections in Pre-Calculus which is incredibly difficult to learn without high-quality visual aids. Furthermore, there is a gap in providing teachers with ready-to-use materials. This study uniquely addresses these issues by not only measuring student success in a GeoGebra-assisted instruction but also developing a contextualised learning package. This package is designed to help teachers overcome the technical barriers found in local schools and offers a practical way to move from traditional methods to interactive learning as promoted by the Department of Education (DepEd).

To put simply, this research aims to investigate the potential of GeoGebra to enhance the mathematical achievement of Grade 11 STEM students at VNHS in learning conic sections and to develop a contextualised learning package in integrating technology into the classroom. This work intends to help bridge the gap between low national test scores and the 21st-century skills needed for our Filipino students to succeed.

2. Literature Review

2.1 Theoretical Foundation

STEM (Science, Technology, Engineering, and Mathematics) fields are essential for global progress. While the practical applications of science, engineering, and technology might be more immediately recognisable, mathematics acts as the underlying code that unites all STEM disciplines (Just and Siller, 2022). Despite this critical role, the optimal methods for integrating mathematics effectively into STEM classrooms remain an ongoing area of research. In addition, engaging students in mathematics and demonstrating its real-world value remains a constant challenge in education. Traditional mathematics instruction, often characterised by teacher-centred lectures and static visuals, promotes rote memorisation, and fails to connect abstract concepts to practical applications (Alabdulaziz et al., 2021). This limitation clashes with the visual-oriented learning styles of 21st-century students, leading to disengagement (Schaver, 2019; Attard et al., 2021).

Dynamic Mathematics Software (DMS), which includes GeoGebra, is a response to this challenge. It facilitates a transition from teacher-focused to learner-focused instruction promoting active learning, visualisation, and manipulation of mathematical objects (Çekmez, 2020; Simons, 2019). This approach aligns strongly with Constructivist Learning Theory, where students actively construct knowledge through exploration and engagement rather than passively receiving information (Mosese and Ogbonnaya, 2021; Dahal et al., 2019). Furthermore, GeoGebra's effectiveness is also framed by Vygotsky's Sociocultural Theory, specifically the Zone of Proximal Development (ZPD) and scaffolding (Bwalya, 2019).

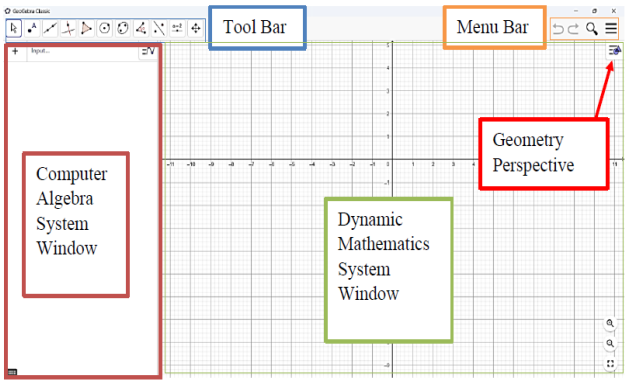
GeoGebra acts as a technological tool that, when integrated with collaborative learning, provides the necessary scaffolding to help students progress to advanced concepts. Its dynamic nature supports four key benefits of technology in math education, which are aiding

proofs, linking representations, supporting reasoning, and functioning as a simulated learner (Cullen et al., 2020)

2.2 GeoGebra's Empirical Benefits and Challenges

2.2.1 Benefit of GeoGebra

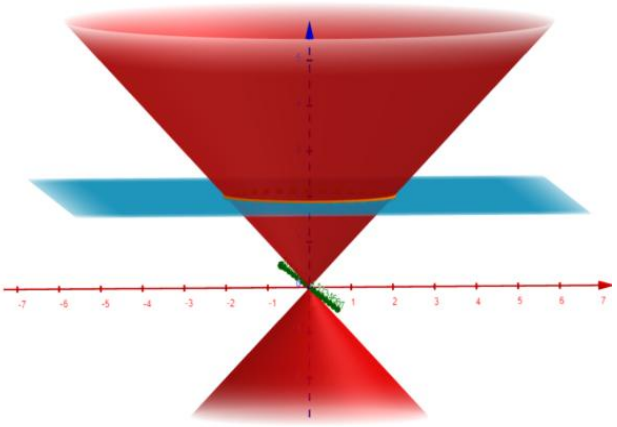
Figure 1: Features of GeoGebra



GeoGebra, as shown in Figure 1, is a leading DMS, distinguished by its free, open-source nature and its unique integration of Dynamic Geometry and Computer Algebra Systems (CAS) (Hohenwarter et al., 2008). Research consistently points to three main ways how this software helps students. First, it leads to better grades. Many studies show that students using GeoGebra get much higher scores in algebra and geometry than those taught with traditional methods (Picaza, 2023; Bloron et al., 2022; Mukamba and Makamure, 2020). Second, the software helps students think more critically. It strengthens their ability to analyse complex graphs and understand abstract ideas (Zulnaidi et al., 2020). Finally, the interactive nature of the tool makes math more fun. This boost in motivation often leads to better problem-solving skills and more creativity in the classroom (Selvy et al., 2020; Hidayat et al., 2023). Collectively, these studies show that GeoGebra is more than just a digital calculator but a powerful tool that improves both student performance and their attitude toward math. This research builds on these findings by assessing if these same benefits apply to complex topics like Conic Sections within the specific local context of Valencia National High School.

2.2.2 GeoGebra in Learning Conic Sections

Figure 2: 3D Graphics View of a Double Right Circular Cone Cut by a Plane using GeoGebra



One of the hardest parts of Pre-Calculus is trying to visualise and explain how a flat plane cuts through a cone to create different shapes, as illustrated in Figure 2. Studies by Poudel (2023) and Ulson (2024) found that Grade 11 STEM students find this much easier when they use GeoGebra instead of looking at static pictures in a textbook. Even though some research shows that a student's positive attitude toward the tool does not always guarantee a perfect test score, the improvement in their ability to draw and move these figures is a clear sign that the software works as a learning aid of these concepts (Ulson, 2024). Some teachers even combine GeoGebra with physical 3D models. Sudihartinih et al. (2020) explored this combined approach for teaching the concept of eccentricity in conic sections. The use of manipulatives offered a tangible, sensory way to interact with the abstract concepts, while GeoGebra provided dynamic visualisations and precise measurements. These methods facilitated a deeper and more accurate understanding of the mathematical properties of conics. Additionally, GeoGebra's features, such as the

sliders and animation, are useful in transforming a static 2D drawing into a dynamic 3D experience bridging the gap between algebra and geometry. Hence, given these proven roadmaps for using dynamic mathematics tools, this study can focus on using GeoGebra specifically to help students overcome the visualisation hurdles that usually make conic sections so difficult to master.

2.2.3 GeoGebra in Learning Conic Sections

Even with all the benefits, employing GeoGebra in every classroom is not always easy. Researchers usually group these challenges into two categories called first-order and second-order barriers (Mokotjo and Mokhele, 2021). The first group involves external problems that are outside of the teacher's control. These include factors like slow internet, limited access to computers, and poor connectivity in rural schools (Wassie and Zergaw, 2019). The second group consists of internal issues that stem from the teachers themselves. This often relates to their personal beliefs, a lack of specialised training, or a simple hesitation to move away from conventional teaching methods (Munyaruhengeri et al., 2023). Beyond these technical and personal hurdles, there is also a pedagogical risk to consider. Some experts worry that students might rely too much on the software to find quick answers without understanding the mathematical logic behind them (Cirneanu and Moldoveanu, 2024). While GeoGebra is a proven way to help students learn, it is still not being used enough in the Philippines because of these specific barriers. This situation creates a research gap that this study intends to fill. This research moves beyond just proving that the software works. Instead, it focuses on finding a practical way to make technology-enhanced learning a reality even in schools with very limited resources

3. Research Methodology

3.1 Research Design

The study utilised a quasi-experimental, non-equivalent control group design based on the positivism paradigm. This design was selected due to the impracticality of random assignment in an educational setting. The study employed two pre-determined groups, specifically, the experimental group, which received instruction enhanced by GeoGebra software alongside traditional teaching, and the control group, which received traditional instruction alone. In determining the result of GeoGebra intervention, both groups were administered a pretest and a post-test on conic sections. This structure allows for the comparison of achievement changes between non-randomised groups, providing evidence of the instructional method's effectiveness.

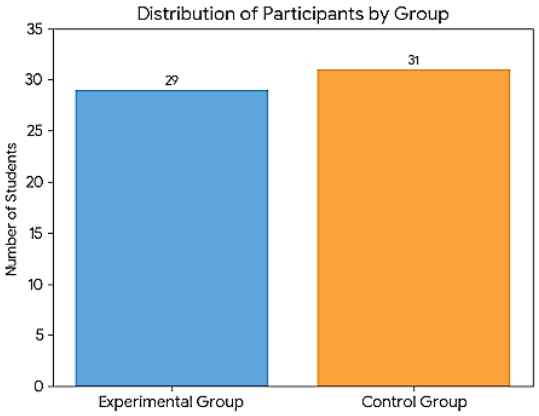
3.2 Research Environment and Participants

The research was conducted at Valencia National High School in Ormoc City, Leyte, Philippines, a school offering the STEM track. The intervention took place in a dedicated computer laboratory equipped with 40 computer units, ensuring a 1:1 student-to-computer ratio and each unit was installed with GeoGebra Classic 6. Moreover, both the experimental and control groups utilised the same laboratory which included a projector and chalkboard. All sessions were held under consistent instructional time and resource conditions to minimise external variables.

Figure 3: Grade 11 STEM Students at Valencia National High School during a GeoGebra-Assisted Mathematics Session

Source: Photos captured by the researcher dated from August to October 2024 (1st Quarter of School Year 2024-2025)

Figure 4: Distribution of Participants by Group



Based on data from Figure 4, there were 29 students in the experimental group and 31 students in the control group. A total of 60 Grade 11 STEM students enrolled for the school year 2024-2025 were selected using convenience sampling. This method was chosen because of its practicality and the ease of access to the participants within the school. However, using convenience sampling introduces specific threats to external validity. Because the participants were not selected randomly from the entire population of STEM students in the Philippines, the findings may be influenced by the unique characteristics of this specific school and its students (Creswell, 2009). This means the results might not be fully generalisable to other schools or different geographical regions where student backgrounds and technological access might differ. To improve the reliability of the results, the researcher took steps to ensure the groups were comparable in their prior mathematics performance before the study began.

3.3 Research Instrument

A teacher-designed test was developed and used as both the pretest and post-test to assess students' mathematics achievement consistently and accurately, aligning with the approach of Bloron et al. (2022). The test focused on the Precalculus curriculum's conic sections content and comprised 40 multiple-choice questions structured to evaluate a range of cognitive skills, from recall to advanced critical thinking.

The test was developed using a Table of Specifications (TOS) to ensure it aligned with the Most Essential Learning Competencies (MELCs) set by the Department of Education. To ensure the test was high quality, it underwent a three-stage validation process by a Master Teacher, a Research Adviser, and a Research Method Specialist. Following validation, a pilot test was conducted which demonstrated excellent internal consistency, yielding a Cronbach's

alpha reliability coefficient of 0.903. Necessary revisions were made based on pilot results and expert recommendations, and the final 40-item test was reviewed again before implementation to further guarantee it was a reliable and valid measure of mathematics achievement.

3.4 Data Gathering Procedure

The following figures present the GeoGebra-assisted activities included in the structured learning package designed by the researcher and were used to discuss conic sections. This series of figures encourages an active discovery process where students engage directly with the geometric formation of each conic section.

Figure 5 and Figure 6 establish the foundational origin of a conic by showing how a cutting plane interacts with a double right circular cone. During the lesson, the discussion focused on how students can manipulate the plane's tilt in GeoGebra to observe and explain the precise moment a circle stretches into an ellipse or snaps into a parabola or hyperbola. This hands-on manipulation allows for a real-time debate on the boundaries between different sections.

Figure 5: The Double Right Circular Cone Centred at (x,y,z) = (0,0,0)

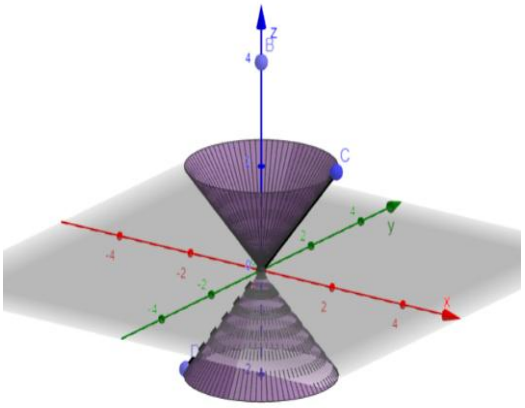


Figure 5 above is a double right circular cone centred at (x,y,z) = (0,0,0) in 3D graphics view using GeoGebra. With this figure, students can illustrate the formation of a double right circular cone.

Figure 6: 3D Visualisation of the Intersection Between a Plane and a Cone

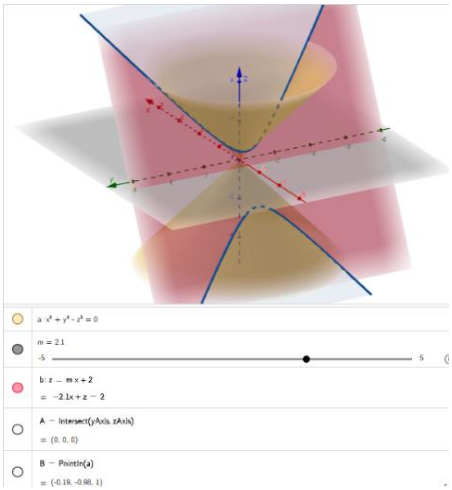


Figure 6 shows how GeoGebra was used to visualise the intersection of a cutting plane and the cone and identify the resulting conic section.

The next figures shift the discussion to specific locus properties through student-led construction. Figure 7 allows students to verify the constant radius of a circle, while Figure 8 enables them to drag a point along the parabola to confirm it remains equidistant from the focus and directrix. Meanwhile, Figures 9 and 10 use a dual-foci approach, letting students define the ellipse and hyperbola through the constant sum and constant difference of distances, respectively. Students were engaged in constructing these figures themselves and the class discussion evolved from memorising formulas to a dynamic understanding of how varying parameters, such as the distance between foci or the position of the directrix, physically alters the geometry of the curve.

Figure 7: Circle with Centre A and a Point B on the Circle

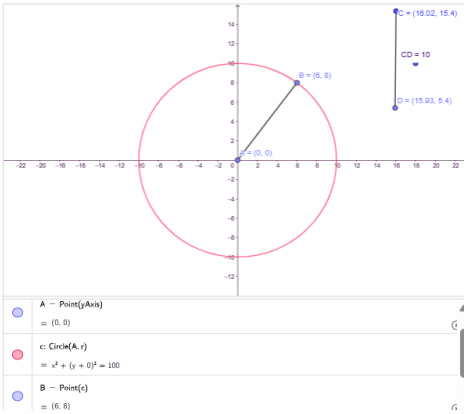


Figure 7 shows how to draw a circle and demonstrates how changing the radius affects the circle while keeping the centre fixed.

Figure 8: Parabola with its Focus and Directrix

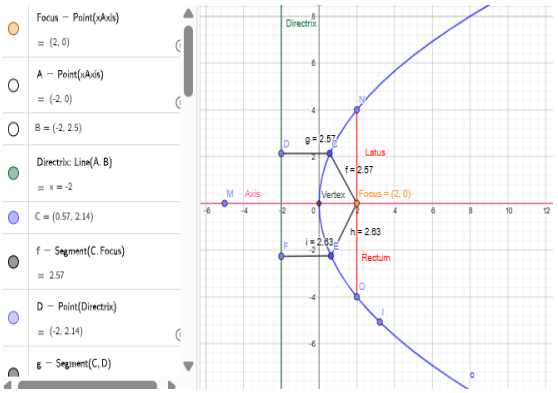


Figure 8 shows how to define a parabola using its fixed point called the focus and its fixed line called the directrix.

Figure 9: Ellipse with Its Properties

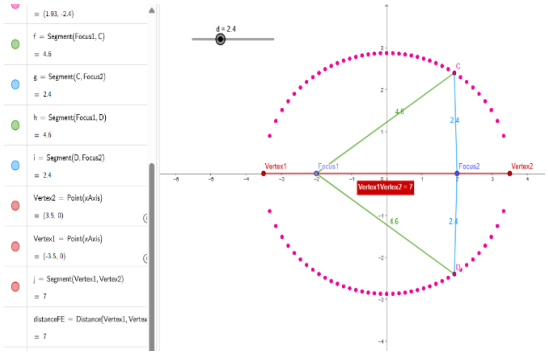


Figure 9 shows how to construct and define an ellipse using the foci and two circles.

Figure 10: Hyperbola with Its Foci

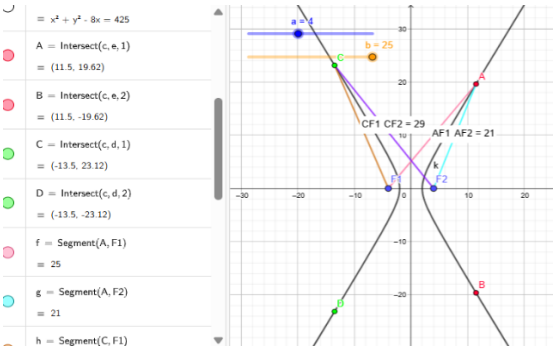


Figure 10 shows how to construct and define a hyperbola with its two fixed points.

The study was implemented over the entire first quarter of the school year to comprehensively cover all elements of conic sections aligning with the natural progression of the Precalculus curriculum and allowing for the examination of longer-term effects. The procedure began with the administration of the pretest to establish a baseline understanding for both the control and experimental groups. Subsequently, both groups received instruction on the same content. The control group were lectured traditionally, while the experimental group experienced instruction enhanced by GeoGebra software for interactive exploration. Following the instructional phase, the post-test was administered to both groups to evaluate their final mathematics achievement.

Ethical protocols were strictly followed to protect the participants. Formal approval to conduct the study was granted by the School Principal and the Department of Education (DepEd) local authorities. Before starting, students and their parents were informed about the nature of the research, and signed informed consent was obtained. Furthermore, participants were assured that their data would remain anonymous and confidential. To minimise performance pressure, students were informed that their test results would be used for research purposes only and would not affect their official grades for the subject.

4. Results

4.1 Mathematics Achievement of Control and Experimental Groups

Table 1: Mathematics Achievement of Control and Experimental Groups Before and After the Intervention

Group	N	Test	Mean	SD	Mean Difference	Verbal Interpretation
Control	31	Pre-test	15.97	2.77	12.87	Unsatisfactory
		Post-test	28.84	2.76		Good
Experimental	29	Pre-test	16.59	2.60	15.67	Unsatisfactory
		Post-test	32.28	2.83		Very Good

Note: Verbal interpretations are based on criteria established by Brookhart (2013).

Table 1 presents the baseline and post-intervention mathematics achievement scores for the Control (n = 31) and Experimental (n = 29) groups, measured using a 40-item test. At the baseline, both groups performed at an unsatisfactory level according to the criteria from Brookhart (2013), with the Control Group recording a mean of 15.97 (SD = 2.77) and the Experimental Group achieving a slightly higher mean of 16.59 (SD = 2.60). Following the intervention, the Experimental Group achieved a "Very Good" verbal interpretation with a mean score of 32.28 (SD = 2.83), while the Control Group reached a "Good" interpretation with a mean of 28.84 (SD = 2.76). Both groups demonstrated significant progress, but the Experimental Group showed a more substantial 94.57% increase in mean scores compared to the 80.59% growth in the Control Group. This trend suggests that while traditional methods are effective, GeoGebra-enhanced instruction accelerates learning at a higher rate. Furthermore, the standard deviation remained stable for both groups, indicating that the intervention benefited students across the board rather than just a few high performers. Although both groups showed progress, the post-test mean difference of 3.44 points suggests the comparative effectiveness of the GeoGebra-enhanced approach, which requires further confirmation through an independent-samples t-test.

4.2 Normality Tests

To ensure the validity of the comparison, normality tests using the Kolmogorov-Smirnov and Shapiro-Wilk tests, presented in Table 2, were conducted to evaluate the distribution of pre-test and post-test results for each group. The results below showed that all p-values exceeded 0.05, indicating that the data was normally distributed. Given that the assumption of normality was met, parametric tests were used for further analysis.

Table 2: Normality Tests of Pre-Test and Post-Test Data of the Two Groups

Group	Tests	Kolmogorov-Smirnov[a]			Shapiro-Wilk		
		Statistic	df	p-value	Statistic	df	p-value
Control	Pre-Test	.152	31	.064	.958	31	.251
	Post-Test	.158	31	.057	.929	31	.051
Experimental	Pre-Test	.141	29	.147	.964	29	.413
	Post-Test	.140	29	.155	.972	29	.604

4.3. Test of Difference

Table 3: Comparison of Pre-Test Scores between the Two Groups

Groups	N	Mean	SD	t	Mean Difference	p - value
Control	31	15.97	2.77	-0.89	-0.62	0.377
Experimental	29	16.59	2.60			

Note: Tested at 0.05 Significance interval, if $p < 0.05$, then reject H_o.

Before the intervention, an independent sample t-test was conducted to determine if the two groups started with the same mathematical levels. Table 3 summarises these baseline results which showed no significant difference in the initial mean difference of -0.62 between the Control Group (M = 15.97) and the Experimental Group (M = 16.59). With a t-statistic of -0.89 and a p-value of 0.377, the result clearly exceeds the 0.05 significance threshold. Because the p-value is greater than 0.05, the null hypothesis cannot be rejected. This statistical trend confirms that both groups possessed a comparable level of understanding regarding conic sections at the start of the study and provides a solid foundation for measuring the impact of the GeoGebra intervention.

Table 4: Comparison of Pre-test and Post-test Scores Within Each Group

Groups	Paired t-test	N	Mean Difference	SD	t	df	p - value
Control	Pre-Post	31	-12.87	2.57	-27.93	30	.000
Experimental	Pre-Post	29	-15.69	2.49	-33.87	28	.000

Note: Tested at 0.05 Significance interval, if $p < 0.05$, then reject H_o.

Table 4 presents the test of difference in mathematics achievement within the control and experimental groups prior and after the intervention. For both the Control and Experimental groups, the p-value is .000. Since this is much lower than the standard alpha level of .05, the null hypothesis is rejected. This indicates that both groups experienced a statistically significant increase in their mathematics achievement scores from pre-test to post-test. The Mean Difference is negative for both groups (-12.87 for Control and -15.69 for Experimental). In the context of a "Pre - Post" calculation, a negative value signifies that the Post-test scores were higher than the Pre-test scores, showing improvement in both groups. Moreover, while both groups improved, the Experimental group showed a larger mean increase (15.69 points) compared to the Control group (12.87 points). The Experimental group also produced a higher t-value (-33.87 vs. -27.93), suggesting that the effect of the intervention in the experimental group was slightly more pronounced or consistent than the standard method used in the control group. Meanwhile, the Standard Deviation (SD) of the differences is relatively low and similar for both (2.57 and 2.49), which suggests that the amount of improvement was consistent across individual students within each group. The results suggest that while traditional methods led to significant learning gains, the GeoGebra-assisted instruction applied to the Experimental group resulted in a numerically higher average improvement in mathematics achievement.

Table 5: Comparison of Post-Test Scores between the Two Groups

Groups	N	Mean	SD	Hedges' G	t	Mean Difference	p-value
Control	31	28.84	2.83	1.21	-4.76	-3.44	.000
Experimental	29	32.28	2.76				

Note: Tested at 0.05 Significance interval, if $p < 0.05$, then reject H_o; Effect Size: Small – 0.2; Medium – 0.5; Large – 0.8

Table 5 presents the comparison of mathematics achievement between the two groups using the post-test scores. The statistical analysis reveals that the Experimental group (M = 32.28, SD = 2.76) performed significantly better than the Control group (M = 28.84, SD = 2.83) in mathematics achievement. With a t-value of -4.76 and a p-value of .000, the difference between the two groups is statistically significant at the .05 level, confirming that the performance gap is not due to chance. The observed mean difference of -3.44 highlights a consistent pattern of higher achievement in the Experimental group, further supported by a Hedges' G value of 1.21. This indicates a large effect size, suggesting that the specific intervention or instructional strategy used for the Experimental group was highly effective in a practical, real-world classroom setting. The implication of these findings is that the GeoGebra implemented in the Experimental Group provides a more robust framework for mathematics instruction than the traditional approach used for the Control group, as it not only raised average scores but did so with a level of consistency, as reflected in the similar standard deviations signifying it is effective across a diverse range of learners.

5. Discussion

The pre-intervention analysis established that both the Control and Experimental groups began the study with statistically equivalent mathematics achievement, both performing at an unsatisfactory verbal level. The subsequent independent-samples t-test confirming no significant difference (p = 0.377) assures the internal validity of the study, which means any post-test disparities can be confidently attributed to the use of GeoGebra as an intervention and not on pre-existing group differences. Additionally, post-test results showed that both instructional approaches were effective, as both groups revealed statistically significant improvements (p = .000). However, the Experimental group demonstrated a greater mean difference in improvement (-15.69) and achieved a higher post-test mean (M = 32.28, "Very Good") compared to the Control group (M = 28.84, "Good"). The formal comparison of post-test scores yielded a statistically significant disparity (t(58) = -4.76, p = .000), and the calculated large effect size (g = 1.21) provides evidence of the practical significance of the GeoGebra intervention. These results reinforce studies by Poudel (2023) and Zulnaidi et al. (2020), suggesting that dynamic software facilitates better conceptual visualisation and deeper understanding.

Despite these positive outcomes, there are a few reasons to be careful about the findings. First, the study was relatively short, which took only one academic quarter of the school year. This may suggest that students might have performed well simply because the new software was stimulating and may not guarantee they will remember the material in the long run. Second, the "teacher-effect" suggests that the success could have been influenced by the teacher's specific enthusiasm or skill. Third, because the test questionnaire was created by the teacher, though it was curriculum-aligned, rather than being a standardised national test, it is harder to prove the results would be the same in every school.

With the statistically significant results and acknowledged limitations, this study underscores that while traditional teaching still plays an essential role in enhancing mathematical abilities, technology-based tools like GeoGebra serve as a highly effective supplement for bridging instructional gaps in complex topics like conic sections.

6. Conclusion

In conclusion, this study suggests that the GeoGebra intervention resulted in a significant improvement in mathematics achievement within the specific context of conic sections. The interactive and engaging visual learning experience of GeoGebra helped bridge the initial learning gaps identified by the unsatisfactory baseline scores of both groups. Fortunately, though both instructional approaches led to progress, the Experimental group demonstrated a statistically significant advantage, suggesting that technology-enhanced learning can be more effective than conventional methods for this particular topic. These results reinforce the potential value of incorporating interactive tools to support conceptual understanding in mathematics education.

With regards to the recommendations of this study, it is suggested that educators consider integrating GeoGebra into mathematics lessons where visualisation is key to help students grasp complex concepts and utilising its features for real-time formative assessments. To support this, institutions are encouraged to provide comprehensive teacher training and prioritise equipping classrooms with necessary technology to ensure equitable access. Curriculum designers are also encouraged to establish guidelines that recommend technology integration for topics that benefit most from visual representation. Finally, future research should be dedicated to exploring GeoGebra's long-term impact on advanced mathematics, investigating variables such as student demographics and learning styles, and analysing the scalability of its widespread adoption.

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References

Alabdulaziz, M. S., Aldossary, S. M., Alyahya, S. A., & Althubiti, H. M. (2021). The effectiveness of the GeoGebra Programme in the development of academic achievement and survival of the learning impact of mathematics among secondary stage students. *Education and Information Technologies, 26*, 2685–2713. https://doi.org/10.1007/s10639-020-10371-5

Anario, K. J. A., Quimpo, M. L., & Bais, N. M. R. (2023). Mathematical software GeoGebra: Its effect on students' competency in mathematics. *Industry and Academic Research Review, 1*(1), 344–351. https://iiari.org/conference_article/mathematical-software-geogebra-its-effect-on-students-competency-in-mathematics/

Attard, C., Berger, N., & Mackenzie, E. (2021). The positive influence of inquiry-based learning teacher professional learning and industry partnerships on student engagement with stem. *Frontiers in Education*, *6*. https://doi.org/10.3389/feduc.2021.693221

Bautista, G. (2023, January). *GeoGebra and function arts workshop 1.* In GeoGebra and Arts Workshop. https://doi.org/10.13140/RG.2.2.29129.01129

Behiga, R. C. (2022, June 11). Issues with National Achievement Test (NAT) in the Philippines [Unpublished manuscript]. ResearchGate. https://www.researchgate.net/publication/361229592_ISSUES_WITH_NATIONAL_ACHIEVEMENT_TEST_NAT_IN_THE_PHILIPPINES

Bloron, R. J. A., Belleza, A. P., Capuyan, R. S., Ramada, J. C., & Apurado, S. A. (2022). Effectiveness of Geo Gebra in teaching theorems and postulates in geometry. *Mathematical Statistician and Engineering Applications, 71*(4), 9297–9303. https://doi.org/10.17762/msea.v71i4.1726

Brookhart, S. M. (2013). *How to create and use rubrics for formative assessment and grading*. ASCD. https://share.google/xLO8asxjoacgXrgYr

Bwalya, D. (2019). Influence of GeoGebra on students' achievement in geometric transformations and attitude towards learning mathematics with technology. *Journal of Education and Practice, 10*(13), 25–36. https://doi.org/10.7176/JEP/10-13-04

Çekmez, E. (2020). Using dynamic mathematics software to model a real-world phenomenon in the classroom. *Interactive Learning Environments*, *28*(4), 526–538. https://doi.org/10.1080/10494820.2019.1674882

Cirneanu, A.-L., & Moldoveanu, C.-E. (2024). Use of digital technology in integrated mathematics education. *Applied System Innovation, 7*(4), 66. https://doi.org/10.3390/asi7040066

Creswell, J. W. (2009). *Research design: Qualitative, quantitative, and mixed methods approaches* (3th ed.). SAGE Publications. https://www.ucg.ac.me/skladiste/blog_609332/objava_105202/fajlovi/Creswell.pdf

Cullen, C. J., Hertel, J. T., & Nickels, M. (2020). *The roles of technology in mathematics education. Educational Forum, 84*(2), 166–178. https://doi.org/10.1080/00131725.2020.1698683

Dahal, N., Shrestha, D., & Pant, B. P. (2019). Integration of GeoGebra in teaching and learning geometric transformation. *Journal of Mathematics and Statistical Science, 5*, 323–332. https://www.ss-pub.org/jmss/integration-of-geogebra-in-teaching-and-learning-geometric-transformation/

Hidayat, R., Kamarazan, N. A., Nasir, N., & Ayub, A. F. M. (2023). The effect of GeoGebra software on achievement and engagement among secondary school students. *Malaysian Journal of Mathematical Sciences, 17*(4), 611–627. https://doi.org/10.47836/mjms.17.4.06

Hohenwarter, M., Hohenwarter, J., Kreis, Y., & Lavicza, Z. (2008, July). *Teaching and learning calculus with free dynamic mathematics software GeoGebra.* In *Proceedings of the 11th International Congress on Mathematical Education (ICME 11)*, Topic Study Group 16: Research and Development in the Teaching and Learning of Calculus, Monterrey, Mexico. https://www.researchgate.net/publication/228869636_Teaching_and_Learning_Calculus_with_Free_Dynamic_Mathematics_Software_GeoGebra

Just, J., & Siller, H.-S. (2022). The role of mathematics in STEM secondary classrooms: A Systematic literature review. *Education Sciences*, *12*(9), 629. https://doi.org/10.3390/educsci1209062

Mokotjo, L. G., & Mokhele, M. L. (2021). Challenges of integrating GeoGebra in the teaching of mathematics in South African high schools. *Universal Journal of Educational Research, 9*(5), 963–973. https://doi.org/10.13189/ujer.2021.090509

Mosese, N., & Ogbonnaya, U. I. (2021). GeoGebra and students' learning achievement in trigonometric functions graphs representations and interpretations. *Cypriot Journal of Educational Sciences, 16*(2), 827–846. https://eric.ed.gov/?id=EJ1296808

Mukamba, E. & Makamure, C. (2020). Integration of GeoGebra in teaching and learning geometric transformations at ordinary level in Zimbabwe. *Contemporary Mathematics and Science Education, 1*(1), ep20001. https://doi.org/10.30935/conmaths/8431.

Munyaruhengeri, J. P. A., Umugiraneza, O., Ndagijimana, J. B., & Hakizimana, T. (2023). Potentials and limitations of GeoGebra in teaching and learning limits and continuity of functions at selected senior four Rwandan secondary schools. *Cogent Education, 10*(2), 2238469. https://doi.org/10.1080/2331186X.2023.2238469

OECD. (2023). *PISA 2022 results (Volume I and II) – Country notes: Philippines*. OECD Publishing. https://www.oecd.org/en/publications/pisa-2022-results-volume-i-and-ii-country-notes_ed6fbcc5-en/philippines_a0882a2d-en.html

Padernal, R. E., & Diego, C. V. (2020). Academic performance of senior high school students in pre-calculus. *Philippine Social Science Journal*, 3(2), 69-70. https://doi.org/10.52006/main.v3i2.185

Picaza, R. R. (2023). Geogebra application for trigonometry subject: A quasi-experimental research. *East Asian Journal of Multidisciplinary Research*, *2*(5), 2145–2164. https://doi.org/10.55927/eajmr.v2i5.4152

Poudel, G. (2023). Use of ICT in teaching conic section. *The Journal of Aadikavi, 12*(1), 16–26. https://doi.org/10.3126/joaa.v12i1.65810

Schaver, Z. (2019). *The effects of GeoGebra on student achievements, critical thinking/problem-solving skills, and engagement/motivation in high school mathematics* (Master's capstone project, Northwestern College, Orange City, IA). NWCommons Institutional Repository. https://nwcommons.nwciowa.edu/education_masters/147/

Selvy, Y., Ikhsan, M., Johar, R., & Saminan. (2020). Improving students' mathematical creative thinking and motivation through GeoGebra-assisted problem-based learning. *Journal of Physics: Conference Series, 1460*, Article 012004. https://doi.org/10.1088/1742-6596/1460/1/012004

Simons, E. (2019). *The effectiveness of dynamic mathematical software in the instruction of the unit circle* [Master's thesis, California State University, San Bernardino]. ScholarWorks. https://scholarworks.lib.csusb.edu/etd/959/

Sudihartinih, E., Purniati, T., & Rohayati, A. (2020). Using GeoGebra and manipulatives on conics as a learning tool for students. *EduMa: Mathematics Education Learning and Teaching, 9(*1), 21–33. https://doi.org/10.24235/eduma.v9i1.6268

Ulson, K. C. (2024). Using graphing application in illustrating the conic sections: Its effect on student's performance. *International Journal of Humanities and Education Development (IJHED), 6*(3), 1-7. https://doi.org/10.22161/jhed.6.3.1

Wassie, Y. A., & Zergaw, G. A. (2019). Some of the potential affordances, challenges and limitations of using GeoGebra in mathematics education. *Eurasia Journal of Mathematics Science and Technology Education*, *15*(8). https://doi.org/10.29333/ejmste/108436

Zulnaidi, H., Oktavika, E., & Hidayat, R. (2020). Effect of use of GeoGebra on achievement of high school mathematics students. *Education and Information Technologies*, *25*(1), 51–72. https://doi.org/10.1007/s10639-019-09899-y

EFFECTS OF EXPERIMENTAL STOMATA MEASUREMENT ACTIVITIES ON HIGH SCHOOL STEM LEARNING OUTCOMES IN CAMBODIA

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ABSTRACT

Experimental learning serves as the pedagogical cornerstone of STEM education, bridging the gap between theoretical knowledge and classroom application. By engaging in direct experimentation, students transition from passive learners to active investigators capable of solving complex, real-world problems. This study aims to implement classroom activities on how to handle the size and calculate the plant stomata density to enhance student learning outcomes at high school. A quasi-experimental design was employed with a sample of 38 students, divided into a control group and a treatment group. The control group was defined as a traditional teaching classroom, while the treatment group was defined as an inquiry-based learning classroom. The results indicated that the score of the control group was significantly lower than the score of the treatment group (p-value<0.05). This result confirmed that it is valuable for pedagogy teaching at the high school level.

Keywords: STEM Learning, Experimental Class, Students' Achievement

1. Introduction

The vision of education reform is to ensure that Cambodia develops human capital by 2050, towards the country becoming a manufacturing country ((Ministry of Education, Youth and Sport, 2019; Royal Government of Cambodia, 2023). The Ministry of Education has developed a series of strategic plans to equip young people with 21st-century knowledge and skills, leading to full-fledged, creative, and productive citizens in society (Ministry of Education, Youth and Sport, 2019; Ministry of Education, Youth and Sport, 2025)

Traditional teaching methods, in the form of the transfer of knowledge from teacher to student and recitation, lead to students being inactive, lacking in deep thinking and analysis, and obstructing creative productivity. The inquiry-based learning through practical, experimental activities, and STEM learning hands-on could be conducted so that students develop problem-solving skills and innovative ideas (Gizaw and Sota, 2023; Korthagen et al., 2006; López-Belmonte et al., 2022). Experimental activities are the foundation of STEM education, including observing real-world phenomena, testing the evidence based on data collection and analysis, and then drawing conclusions independently. In addition, experiments help learners expand their knowledge, solve problems, and provide opportunities for students to gain hands-on experience in the laboratory and use technology (Jamil et al., 2024; National Research Council, 2006).

The biology textbook includes experiments in each lesson but does not clearly explain the methods for conducting experiments and hands-on classroom activities (Mam et al., 2020; Ministry of Education, Youth and Sport, 2025). Most biology teachers are traditional performance teachers rather than conducting comprehensive experiments for the students. Thus, this research gap comes from the lack of STEM pedagogy in teaching methodology by transforming the tradition into an inquiry-based approach through plant stomata measuring and graphing.

This research aims to achieve effective student outcomes through hands-on classroom activities by measuring the plant stomata of grade 10 students in Cambodia. To reach the research objective, the research question was formed as How does the integration of a STEM hands-on classroom influence the Grade 10 students' learning outcomes?

2. Research Methodology

2.1 Research Design

This study employed a quasi-experimental design using pre-test and post-test measures to evaluate the efficacy of STEM experimental practice compared to traditional instruction (Creswell and Creswell, 2017). This design allows for the comparison of learning outcomes between a treatment group and a control group under controlled conditions. Through the teacher serving as a facilitator, the treatment group's instructional emphasis shifted from passive learning to an active scientific inquiry process that included fundamental concepts, experimental and technical instructions on scientific procedures, and hands-on activities that strengthened understanding.

2.2 Participants

A total of 38 students participated in the study. The participants were randomly selected from the target population and divided into two groups, each consisting of 19 students. One group served as the Treatment Group and participated in a practical, experiment-based instructional approach. The second group was the traditional teacher-led instruction, serving as the baseline for the study, called the “Control Group”.

2.3 Research Instrument

To measure student learning outcomes, a pre-test and a post-test were administered. The pre-test was used to assess participants’ prior knowledge before the instructional intervention, while the post-test measured learning outcomes after the lesson. The same test format was used for both groups to ensure consistent results. The assessment was designed to be divided into two parts, each with 25 scores, to evaluate the students' knowledge before and after classroom instruction. Part 1 aims to reach an understanding of the theoretical concepts and scientific principles in the lesson. Part 2 evaluates students' learning outcomes through practical and hands-on experiments. These outcomes were measured by the students' proficiency in scientific inquiry, specifically their ability to calibrate microscopes and use ocular/objective micrometres independently. The teacher acted as a facilitator, guiding the technical process, while the primary outcome was the students' success in calculating the size and density of stomata with mathematical precision. Additionally, following the intervention, the treatment group completed a survey to assess their engagement in STEM activities. This instrument consisted of six items measured on a 4-point Likert scale (ranging from 1-Strongly Disagree to 4-Strongly Agree), adapted from Chang (1994) and Madriaga and Siobal (2022).

To ensure instrument quality, the survey was validated by two experts and the research advisors.

2.4 Experiment Procedure

2.4.1 Plant Stomata Sampling

This study used twelve species of aquatic and terrestrial plants for stomata measurement, of which six species are in the monocotyledon, and the other six species are in the dicotyledon. This selection provided a basis for the stomata measurement activities.

2.4.2 Plant Stomata Measuring Procedure

The students in the treatment group obtained a hand-on STEM activity by measuring stomata and calculating stomata density. The stomata are measured through the optical microscope with a 10x ocular and a 40x objective magnification, attached ocular and objective micrometre in 10µm.

Phase 1: Stomata size measuring technique

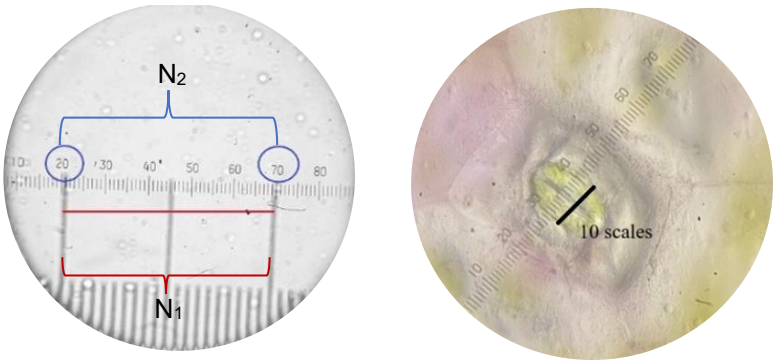
Students used ocular and objective micrometres to calibrate their equipment, following the methodology established by Dy et al. (2007). This process required students to apply the calibration using the formula:

$$X = \frac{D\ x\ N_1}{N_2}$$

X: The length/width of the ocular micrometre.
D: The distance of a single division on a stage micrometre, known as 10µm.
N_1 and N_2: The number of overlapping scales between the objective and ocular lenses.

Students calculated the ratio, then converted the unit scales seen in the microscope into actual micrometres

Figure 1: Stomata's Size Measuring Technique.



(a) (b)

(a) The overlap between the objective (N1) and ocular (N2) micrometer,
(b) The stomata size viewed in width

Phase 2: Calculating the stomata's density technique

Students calculated the stomata's density using a three-step computational process, following Koenig (2020), Marlene (2024) and Renne (2023).

1) Field of View (FoV) determination by dividing the eyepiece field number (18mm) by the objective magnification value (40x).
2) The total visible area (area of FoV) was determined using the formula:

$$A = \pi r^2$$

3) Stomata's density computation by applying the density formula:

$$stomata\ density = \frac{number\ of\ stomata}{area\ of\ FoV\ (A)}$$

2.5 Classroom Application Design

To ensure the internal validity of the study, both the treatment group and the control group were taught by the same teacher. The instructional period for both groups was two hours with a lesson plan, instructional slides, and scientific figures. The instructor prepared the lesson plan, teaching materials, experimental equipment, workbook, and test sheet before class started. To determine the influence of the STEM-based practical activities, all students were administered a pre-test before the instructional intervention. Following that, two hours of training on plant stomata, encompassing fundamental scientific concepts and monocot/dicot traits, were given to both groups. The control group received traditional teacher-led instruction focusing on theoretical concepts through lecture in the textbook. The treatment group participated in an extra-class experimental session where they applied the two phases, including the processing of stomata density and size measurement. Then, following the instructions, both groups took the post-test to measure learning outcomes. In addition to the post-test, the treatment group was requested to complete a six-item survey to assess their engagement levels during the STEM-integrated activities.

2.6 Data Analysis

All statistical analyses were performed using the Statistical Package for the Social Sciences (SPSS version 21.0.0.0 32-bit edition) software. A one-way Analysis of Covariance (ANCOVA) was used to examine whether there was a significant difference between pre-test and post-test scores between the treatment and control groups. The score of student engagement (Likert-scale, 1-Strongly disagree, 2-Disagree, 3-Agree, 4-Strongly agree) was analysed using descriptive statistics. The scale was calculated with a 0.75-interval (Table 1).

Table 1: The 4 points of the Likert scale

Mean Score Range	Interpretation
1.00-1.75	Strongly disagree
1.76-2.50	Disagree
2.51-3.25	Agree
3.26-4.00	Strongly agree

3. Results and Discussion

3.1 Research Finding

Table 2 shows pre-test and post-test scores from both treatment and control groups, including mean and standard deviation (SD). The mean difference refers to the mean score between before and after classroom activities. The mean score of the control increased from 16.76 to 19.39 (2.63 score difference), while the mean score of the treatment increased from 17.73 in the pre-test to 41.02 in the post-test (23.29 score difference). The performances of both groups have positively improved, but the treatment group showed greater improvement.

Table 2: Mean and standard deviation of student scores between the control and treatment groups

Groups	n	Pre-Test		Post-Test		Mean of Difference
		Mean	SD	Mean	SD	
Control	19	16.76	4.32	19.39	3.57	2.63
Treatment	19	17.73	5.69	41.02	4.85	23.29

Table 3 shows that the ANCOVA test determines if there are significant differences between student groups while controlling for their initial knowledge (Pre-test scores). There was a significant difference between the groups, $F(1, 35) = 266.945$, $p<0.001$, indicating that the treatment group had a profound positive impact on student scores. The significant difference between groups ($p<0.001$) suggests that the experimental approach was highly effective compared to traditional learning. The improvement of the classroom through experimental learning helps increase student engagement, provides opportunities for learning through the use of hands-on materials and the implementation of experimental processes, encourages students to think critically, collaborate in groups (giving, sharing, and accepting reasonable ideas in groups), and be independent and take ownership of group and individual learning, as well as fulfilling students' learning interests (Mom et al., 2024; Heng and Shimizu, 2019; Yaki, 2022).

Table 3: The results of ANCOVA test

	SS	DF	MS	F-value	Pr(>F)
Pre-test	93.269	1	93.269	5.821	0.021
Groups	4276.899	1	4276.899	266.945	<0.001
Residuals	560.758	35	16.022		

The result of students' engagement is shown in Table 4. The descriptive statistics for student satisfaction and understanding were measured on a 4-point Likert scale ranging from 1 (Strongly Disagree) to 4 (Strongly Agree). The overall mean of 3.33 illustrates a highly positive score through teaching, incorporating STEM activities, and the benefits of STEM learning. Students clearly see the value of STEM. They believe it is important for their future jobs and think it should be part of their school subjects. The highest-rated item was the importance of including STEM subjects into classroom activities (Mean=3.52), followed closely by the perceived importance of STEM for future careers (Mean=3.47). Students strongly agreed that experiments enhanced their understanding of theoretical concepts (Mean=3.32) and reported high levels of enjoyment during practical sessions (Mean=3.36). Students recognised the practical application of their studies, noting a strong connection between STEM subjects and real-life scenarios (Mean=3.37). Interestingly, the lowest mean (Mean=2.94) was for "More experimental class in the next section" While still positive, it is particularly lower than other

scores. Despite this being the only item to fall below a 3.0 mean, the minimum score of 2 suggests that no students "Strongly Disagreed" with this sentiment. This aligns with the findings of De Loof et al. (2022) and López-Belmonte et al. (2022), who argued that integrated STEM education bridges the gap between theoretical knowledge and practical application better than traditional instruction.

Table 4: The ratings of student satisfaction and understanding

Question Items	Mean	Min	Max	SD
1. I enjoy practicing the experiment.	3.36	2	4	0.59
2. More experimental class in the next section.	2.94	2	4	0.62
3. The experiments make me understand the lesson clearly.	3.32	3	4	0.48
4. It's important to integrate STEM subjects into classroom activities.	3.52	3	4	0.51
5. STEM subjects are important for my future career.	3.47	2	4	0.61
6. STEM subjects are connected to real-life.	3.37	3	4	0.5
Overall mean	3.33			

3.2 Discussion

The findings of this study provide evidence for the efficacy of STEM-based experimental practices at the high school level. For the students, the hands-on learning approach converted theoretical scientific ideas into reality. A critical factor in this transition was the role of the teacher as a facilitator, who guided students through the technical complexities of using microscopes and ocular/objective micrometres. By engaging in the two-phase computational process established by Dy et al. (2007), Koenig (2020), Marlene (2024) and Renne (2023), students were able to bridge the gap between theoretical principles and practical application. Specifically, the teacher's instruction on calculating the size and density of stomata provided students with specialised skills and measurable technical outcomes that go beyond traditional textbook learning. This finding aligns with the work of Mom et al. (2024) and Yaki (2022) regarding the benefits of independent and collaborative learning. Furthermore, the survey data reveal that students not only enjoyed the experimental process but also recognised its long-term value, specifically regarding the integration of STEM into the curriculum and its relevance to their future careers. Interestingly, while students were highly positive about the current lesson's clarity, the slightly lower score for wanting more experimental classes in the future may reflect the intensive cognitive demand of STEM activities. This demand is often associated with the high-level student outcomes required in technical measurements and precision calculations. Nevertheless, the overall results support the conclusion of De Loof et al. (2022), suggesting that integrated STEM education effectively bridges the divide between classroom theory and real-world scenarios, thereby fostering a more profound and lasting understanding of the subject matter.

3.3 Limitations

This research study was applied to 10th-grade students of Chea Sim Boeung Keng Kang High School, Cambodia. Two groups of students were randomly selected; each group contains 19 students (N =38), which is considered a small sample size. Therefore, the results may not be fully generalisable to all high school students across Cambodia.

4. Conclusion and Recommendations

4.1 Conclusion

The findings of this study have significant implications for education, particularly in enhancing student learning outcomes through the integration of STEM-based classroom activities. A key finding of this research is that the role of the teacher as a facilitator is essential in bridging the gap between theory and practice. Students demonstrated a significant increase in essential scientific inquiry skills, in microscopic calibration and the technical measurement of stomata size and density, such as microscopic calibration and data recording. Furthermore, the hands-on nature of the task, supported by teacher-led instruction on the use of ocular and objective micrometres, bridged the gap between abstract biological concepts and real-world observation. This structured guidance led to higher levels of student motivation and technical proficiency compared to traditional, passive learning environments.

4.2 Recommendations

The findings of this study provide a model for transitioning from traditional instruction toward inquiry-based STEM pedagogy at the high school level. To build upon the success of this activity and address the research questions further, the following actions are recommended:

- For Curriculum Developers: Integrate standardised micro-measurement protocols into plant physiology modules and prioritise the provision of ocular and objective micrometres to school laboratories.
- For Educators: Transition toward inquiry-based leadership by fostering student-centred experimentation and STEM-based activities.
- For Policy Makers: Support professional development programmes focused on STEM pedagogical integration for teachers' professional development.
- Future studies should address comparative research focusing on the disparity in experimental proficiency between urban and rural student populations to ensure equitable scientific literacy.

References

Chang, L. (1994). A psychometric evaluation of 4-point and 6-point Likert-type scales in relation to reliability and validity. *Applied psychological measurement*, *18*(3), 205-215. https://doi.org/10.1177/014662169401800302

Creswell, J. W., & Creswell, J. D. (2017). *Research design: Qualitative, quantitative, and mixed methods approaches* (5th ed.). SAGE Publications. https://books.google.com.kh/books?id=335ZDwAAQBAJ

De Loof, H., Boeve-de Pauw, J., & Van Petegem, P. (2022). Integrated STEM education: The effects of a long-term intervention on students' cognitive performance. *European Journal of STEM Education,* 7(1), Article 13. https://doi.org/10.20897/ejsteme/12738

Dy, B., Em, S., & Hul, T. (2007). *Supporting book for biology student.* National of Education, Cambodia.

Gizaw, G. G., & Sota, S. S. (2023). Improving science process skills of students: A review of literature. *Science Education International*, *34*(3), 216-224. https://doi.org/10.33828/sei.v34.i3.5

Jamil, M., Mehmood, W., & Saleem, A. (2024). *Biology textbook Grade X (2020): Analysis for the development of higher order thinking skills among secondary school science students*. *Global Regional Review, 9*(1), 29–35. https://doi.org/10.31703/grr.2024(IX-I).03

Koenig, F. (2020, November 20). *Microscope magnification – Pushing the limits*. Microscope International. Retrieved January 4, 2024, from https://microscopeinternational.com/microscope-magnification/

Korthagen, F., Loughran, J., & Russell, T. (2006). Developing fundamental principles for teacher education programs and practices. *Teaching and teacher education*, *22*(8), 1020-1041. https://doi.org/10.1016/j.tate.2006.04.022

López-Belmonte, J., Segura-Robles, A., Moreno-Guerrero, A.-J., & Parra-González, M. E. (2022). Comparative analysis between a STEM-based learning process and traditional teaching. *South African Journal of Education*, *42*(1). https://doi.org/10.15700/saje.v42ns1a2057

Madriaga, A. G., & Siobal, R. A. (2022, May 13). *Factors affecting senior high school students to choose STEM as their strand* [Paper presentation]. *DLSU Senior High School Research Congress*, De La Salle University, Manila, Philippines. https://animorepository.dlsu.edu.ph/conf_shsrescon/2022/paper_cli/6/

Mam, C., Noda, Y., Funai, H., Iwayama, T., & Kato, J. (2020, April 13). *Methods for teaching light wavelength dependencies on seed germination and seedling elongation applicable for high school experimental class in developing countries (Studies in Subject Development, No. 8)*. Graduate School of Education, Aichi University of Education & Shizuoka University. https://shizuoka.repo.nii.ac.jp/record/12325/files/8-0105.pdf

Marlene. (2024, December 17). *Determining stomatal density: Skills (DP IB Biology)*. Save My Exams. https://www.savemyexams.com/dp/biology/ib/23/hl/revision-notes/form-and-function/gas-exchange/determining-stomatal-density-skills/

Ministry of Education, Youth and Sport. (2019). *Cambodia's Education 2030 roadmap sustainable development.* https://planipolis.iiep.unesco.org/sites/default/files/ressources/cambodia_education_2030_roadmap_sustainable_development.pdf

Ministry of Education, Youth and Sport. (2025, March 5). *Education Congress: The education, youth and sport performance in the academic year 2023–2024 and goals for the academic year 2024–2025.* https://nepcambodia.org/documents/education-congress-the-education-youth-and-sport-performance-in-the-academic-year-2023-2024-and-goal-for-the-academic-year-2024-2025/

Mom, P., Mom, S., Phann, S., Srieng, K., & Kong, S. O. (2024). Implementing STEM project to improve student's creativity and learning outcomes in the concept of circulatory system. *Insecta: Integrative Science Education and Teaching Activity Journal, 5*(1), 121-129. https://jurnal.iainponorogo.ac.id/index.php/insecta/article/view/8270

National Research Council. (2006). *America's lab report: Investigations in high school science*. The National Academies Press. https://www.nationalacademies.org/read/11311/chapter/1

Renne, S. L. (2023). How to measure your microscope's HPF. A critical guide for residents. *Pathologica*, *115*(6), 302-307. https://doi.org/10.32074/1591-951X-900

Royal Government of Cambodia. (2023, August 24). *Pentagonal Strategy–Phase I: For growth, employment, equity, efficiency, and sustainability — Building the foundation towards realizing the Cambodia Vision 2050* (Strategy document). Council for the Development of Cambodia.http://cdc-crdb.gov.kh/en/strategy/documents/Pentagonal-Strategy-Phase-I__English__24.08.2023.pdf

Heng, T., & Shimizu, K. (2019). The development of biology experiment for improving pre-service teachers' science process skills at teacher training institutions in Cambodia. In *Proceedings of the 43rd Annual Meeting of the Japan Society of Science Education* (p. 604 - 607). Japan Society of Science Education. https://www.jstage.jst.go.jp/article/jssep/43/0/43_604/_pdf/-char/ja

Yaki, A. A. (2022). Fostering critical thinking skills using integrated STEM approach among secondary school biology students. *European Journal of STEM Education*, *7*(1), Article 6. https://doi.org/10.20897/ejsteme/12481

STUDENT

SECTION

COMMUNITY-BASED STEM ENGINEERING DESIGN OF FUNCTIONAL FOODS FROM BLACK GLUTINOUS RICE AND 'NAM DOK MAI' MANGO TO PROMOTE MENTAL WELL-BEING: A MIXED-METHODS STUDY

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ABSTRACT

Community-based STEM education that foregrounds student agency can generate significant learning gains and community benefits. This mixed-methods study examined a 7-week engineering design process (EDP) unit in which Third-year high school students co-defined, co-developed, and co-facilitated the creation of functional foods from local black glutinous rice and Nam Dok Mai mango. Three student co-researchers led instrument development, user-testing coordination, data curation, and preliminary analysis. Participants comprised 42 students and 56 community members. Quantitative measures included an analytic EDP rubric (0–24), a STEM literacy test (0–100), a STEM attitudes scale (1–5), a teamwork/ communication rubric (1-4), and the DASS-21 to assess community well-being. Paired-samples t-tests and Cohen's dz effect sizes were calculated; qualitative reflections, observations, and focus groups were thematically analysed. Students demonstrated large gains in EDP competence (dz = 1.20), STEM literacy (dz = 0.78), attitudes (dz = 0.60), and teamwork/communication (dz = 0.74). Community members exhibited small but significant reductions in stress (dz = 0.30), anxiety (dz = 0.28), and depression (dz = 0.27). Three qualitative themes—local relevance, feedback-driven iteration, and student-led data stewardship—illuminated mechanisms of impact. Aligned with the need for contextually grounded STEM research in the Global South, the findings underscore the value of student co-researcher roles and community partnerships for equitable STEM learning.

Keywords: Community-based STEM, Engineering Design Process, Student Agency, Functional Foods, Mental Well-being

1. Introduction

1.1 Background and Rationale

Integrated STEM education situates the engineering design process (EDP) as a vehicle for applying disciplinary knowledge to real-world challenges, promoting problem solving, collaboration, and motivation (National Research Council, 2012; NGSS Lead States, 2013; Dym et al., 2005; National Academy of Engineering and National Research Council, 2014). In resource-constrained, agriculture-adjacent contexts common in Thailand, community-based projects tapping local crops can heighten relevance and transfer (Basu and Barton, 2007; Krajcik and Blumenfeld, 2005). Functional foods derived from local bioactives afford interdisciplinary integration—food chemistry, nutrition, prototyping, sensory testing, and optimisation—within authentic design constraints (Khoo, Azlan, Tang, and Lim, 2017; Masibo and He, 2009). Despite the promise of community-based STEM, few studies report both

validated assessments and community outcomes, nor foreground student co-researchers' agency. Student participation in research roles can enhance data quality, peer leadership, and authenticity. This study addresses these gaps by examining a co-designed EDP unit led in part by student co-researchers, employing rigorous validity and reliability evidence, and assessing complementary community well-being outcomes via DASS-21 (Psychology Foundation, n.d.; Oei et al., 2013).

2. Objectives and Research Questions

2.1 Objectives

1. Evaluate effects of a community-based EDP unit on secondary students' EDP competence, STEM literacy, STEM attitudes, and teamwork/ communication.
2. Identify design features and mechanisms, including student co-researcher roles, that support engagement and learning.
3. Examine changes in community well-being (DASS-21) following participation in integrated tasting and micro well-being activities.

2.2 Research Questions

RQ1: To what extent does the EDP unit improve students' EDP competence, STEM literacy, STEM attitudes, and teamwork/communication?

RQ2: Which design features—local relevance, structured iteration, or student-led facilitation—explain patterns of engagement and learning?

RQ3: What pre–post changes occur in DASS-21 domains among community members, and how should these be interpreted given the one-group design?

3. Method

3.1 Research Design

A mixed-methods one-group pre-post design was used for student outcomes, with a complementary one-group pre-post for community well-being. Qualitative data contextualised the mechanisms (Braun and Clarke, 2006).

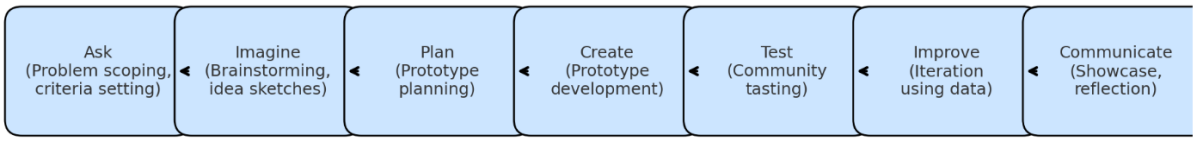
3.2 Participants and Setting

The study involved 42 third-year secondary school students and 56 community members in Ban Haed Municipality, Khon Kaen, Thailand. Community participants were aged 15-50 years. Three volunteer students—Itthipat Meephet, Naphatchon Bunphiw, and Ploypradab Khamthong—acted as co-researchers, supporting instrument development, data collection coordination, and preliminary analysis. Inclusion criteria for students included assent/parental consent and full enrolment in the 7-week unit; community inclusion required attendance at both tasting/well-being events and informed consent.

3.3 Intervention

The 7-week unit followed EDP phases (ask-imagine-plan-create-test-improve-communicate), anchored in the challenge: How might we co-design culturally acceptable, nutrient-dense functional foods using local rice and mango to support community well-being? Integration mapped to science (bioactives, nutrition), technology (spreadsheets, QR feedback), engineering (prototyping, safety), and mathematics (ratios, statistics, optimisation). Student co-researchers drafted consent scripts, piloted and refined surveys, trained peers for sensory protocols, curated digital logs, and co-facilitated focus groups. As shown in Figure 1.

Figure 1: The Seven-Phase Engineering Design Process (EDP) Cycle Implemented in the 7-week Unit.



3.4 Measures

EDP competence: An analytic rubric (0-24) across six criteria—scoping, ideation, planning, prototyping/testing, iteration, and communication (Dym et al., 2005). Content validity via experts (IOC .67-1.00; M = .83); inter-rater reliability ICC(2,k) = .84. STEM literacy: 30-item test (20 multiple-choice, 10 constructed-response); blueprint-aligned to the NRC Framework (difficulty .35-.80; discrimination .25–.62; KR-20 = .82). STEM attitudes: 1–5 Likert scale with subscales interest, utility, self-efficacy; α = .88. Teamwork/communication: Analytic rubric (1–4) for collaboration, role responsibility, evidence-based argumentation, audience-appropriate communication; α = .86. Two raters independently scored a stratified sample of artifacts; discrepancies were resolved through consensus. Community DASS-21: Depression Anxiety Stress Scales-21 Thai version; total α = .91; subscale αs = .84-.88 (Psychology Foundation, n.d.; Oei et al., 2013). Subscale scores were computed as the sum of seven items multiplied by 2, per standard guidelines (higher scores indicate greater symptom severity).

3.5 Procedures

Administrative permission for the study was granted by Ban Haed Municipality School; no formal institutional review board number was issued. All adult participants provided written informed consent, and parents/guardians of minors provided consent alongside student assent. Participant identities were anonymised in all datasets and reporting, in accordance with SEAMEO STEM-ED ethical guidelines. Week 0: consent/assent, pre-tests. Weeks 1–2: problem scoping, literature, criteria definition. Weeks 3–4: formulation, prototyping (e.g., rice-mango gel bites), safety. Weeks 5–6: 9-point hedonic testing, community tasting 1, feedback analysis, iteration. Week 7: community showcase with mindful tasting and brief breathing exercises; post-tests. Fidelity was monitored via an observation checklist (M adherence = 87%, SD = 8%).

3.6 Data Analysis

Paired-samples t-tests assessed pre–post changes. Effect sizes are reported as Cohen's dz for paired designs (Cohen, 1988), with 95% confidence intervals for mean differences; p values are unadjusted for multiplicity. Assumptions (normality, outliers) were screened; missing data < 5% were handled listwise. Qualitative data underwent thematic analysis (Braun and Clarke, 2006) with dual coding and intercoder agreement κ = .79. Joint displays integrated quantitative and qualitative findings.

3.7 Results

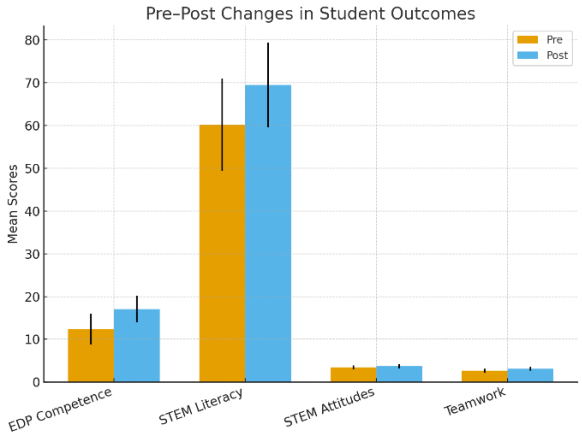
3.7.1 Student Outcomes EDP Competence

Figure 2 visualises gains across the four student outcome domains. The most substantial improvement occurred in EDP competence, with students advancing nearly 4.7 points (approximately 38% increase from baseline). visualises these gains across the four student outcome domains. The most substantial improvement occurred in EDP competence, with students advancing nearly 4.7 points (approximately 38% increase from baseline). This large effect size (dz = 1.20) reflects deep gains in problem scoping, ideation generation, prototyping decisions, and iterative design thinking. STEM literacy showed robust gains of 9.3 percentage points with a moderate-to-large effect size (dz = 0.78), indicating meaningful improvement in science and engineering content knowledge. STEM attitudes and teamwork/communication demonstrated consistent, positive shifts (dz = 0.60 and 0.74, respectively), suggesting that the authentic, community-grounded design process fostered motivation and collaborative capacity. Collectively, these multi-domain gains underscore the value of the EDP unit as an integrated learning experience. As shown in Table 1 and Figure 2

Table 1: Pre-Post Changes in 42 Third-Year Secondary School Students' EDP Competence, STEM Literacy, STEM Attitudes, and Teamwork/Communication (N = 42).

Outcome	Mean (pre-test) ± SD	Mean (post-test) ± SD)	t(41)	p-value	dz	95% CI for Δ
EDP Competence	*12.4 (3.6)*	*17.1 (3.1)*	*7.78*	*<.001*	*1.20*	*[3.48, 5.92]*
STEM Literacy	*60.2 (10.8)*	*69.5 (9.9)*	*5.05*	*<.001*	*0.78*	*[5.58, 13.02]*
STEM Attitudes	*3.41 (0.52)*	*3.72 (0.49)*	*3.89*	*<.001*	*0.60*	*[0.15, 0.47]*
Teamwork/Communication	*2.66 (0.48)*	*3.10 (0.44)*	*4.79*	*<.001*	*0.74*	*[0.25, 0.63]*

Figure 2: Pre–Post Comparisons of Student Outcomes with Error Bars (±1 SD).



3.7.2 Community Well-Being

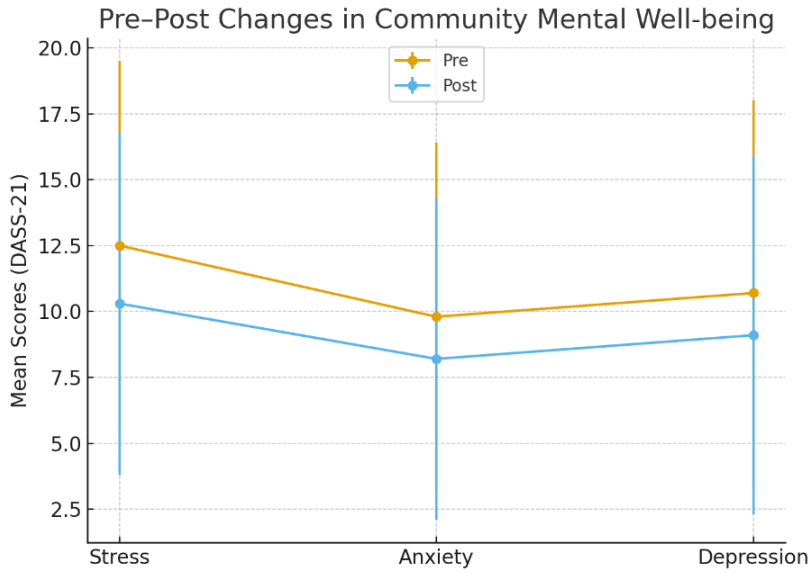
Figure 3 presents pre-post changes in the three DASS-21 domains for community members. Although the absolute reductions were modest—stress decreased by 2.2 points. presents pre-post changes in the three DASS-21 domains for community members. Although the absolute reductions were modest-stress decreased by 2.2 points (from 12.5 to 10.3), anxiety by 1.6 points (from 9.8 to 8.2), and depression by 1.6 points (from 10.7 to 9.1) -the effect sizes were consistent and statistically significant across all three domains (dz ≈ 0.27-0.30). This pattern suggests that even a short, community-anchored engagement that integrated sensory experience, mindful practice, and social connection generated measurable reductions in psychological symptom severity. The consistency across domains indicates that the

intervention's effects were not confined to a single well-being dimension but rather reflected broad, albeit modest, improvements in community mental health. As shown in Table 2 and Figure 3.

Table 3: Pre-Post Changes in Community Members' Stress, Anxiety, and Depression Scores on the DASS-21 (N = 56).

Domain	Mean (pre-test) ± SD	Mean (post-test) ± SD)	t(55)	p-value	dz	95% CI for Δ
Stress	*12.5 (7.0)*	*10.3 (6.5)*	*2.24*	*.029*	*0.30*	*[0.22, 4.18]*
Anxiety	*9.8 (6.6)*	*8.2 (6.1)*	*2.09*	*.041*	*0.28*	*[0.05, 3.15]*
Depression	*10.7 (7.3)*	*9.1 (6.8)*	*2.02*	*.048*	*0.27*	*[0.02, 3.18]*

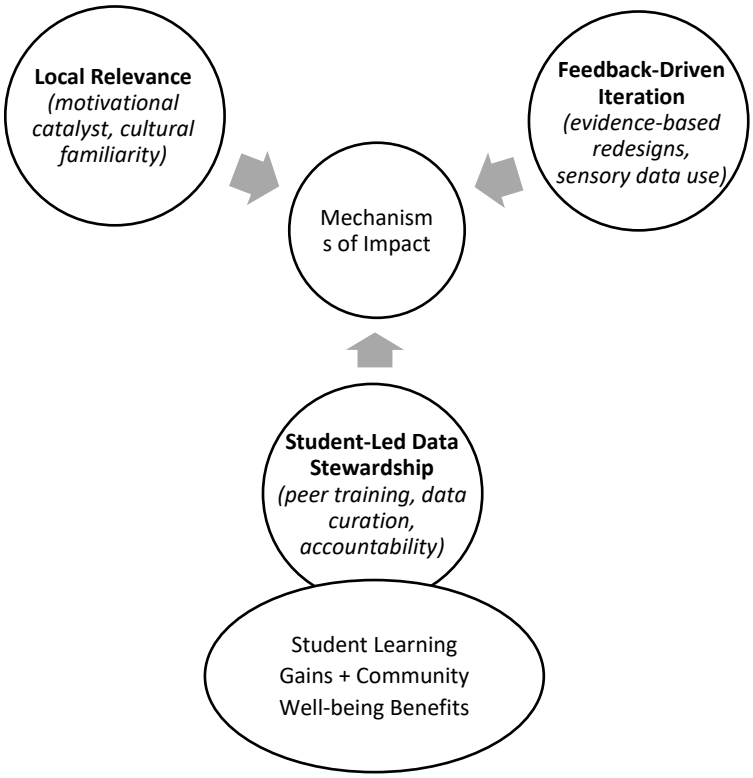
Figure 3: Pre-Post Changes in Community Well-Being Outcomes (DASS-21 Domains).



3.7.3 Qualitative Themes

1. Local relevance as motivational catalyst: Student reflections emphasised pride and persistence through prototyping failures when working with culturally familiar ingredients (Basu and Barton, 2007).
2. User feedback-driven iteration: Community sensory data-sweetness, texture, labeling preferences-prompted evidence-based modifications in EDP cycles (Dym et al., 2005).
3. Student-led data stewardship: Co-researchers' training of peers in sensory protocols and management of digital logs enhanced communication and data integrity (Krajcik and Blumenfeld, 2005). As shown in Figure 4.

Figure 4: Conceptual Map of Three Qualitative Themes Explaining Mechanisms of Impact.



4. Discussion

4.1 Summary of Principal Findings

This study examined a 7-week, community-anchored EDP unit and found substantial gains in students' EDP competence (dz = 1.20), STEM literacy (dz = 0.78), STEM attitudes (dz = 0.60), and teamwork/communication (dz = 0.74). Community members who engaged in tasting and micro well-being activities reported small but statistically significant reductions in stress, anxiety, and depression (dz ≈ 0.27–0.30). Qualitative analyses converged on three mechanisms—local relevance, feedback-driven iteration, and student-led data stewardship—that plausibly underpin these effects. Together, the findings indicate that a contextually grounded, participatory STEM model can yield educationally meaningful student outcomes with complementary community benefits.

4.2 Interpretation and Mechanisms of Impact

Two design features appear central. First, the anchoring of EDP in culturally familiar food systems provided authenticity, meaningful constraints, and clear success criteria. This local relevance likely increased persistence through prototyping failures and supported transfer from disciplinary knowledge to design choices (e.g., adjusting ratios and textures based on sensory data). Second, formalised feedback loops operationalised the EDP as evidence-based iteration rather than a single build-and-present cycle. Students gathered user data (hedonic ratings, comments), rapidly analysed patterns, and enacted redesigns; this positioned evidence as the driver of iteration and deepened conceptual reasoning.

A third feature—the presence of student co-researchers—appears to have amplified both engagement and data quality. By leading instrument piloting, protocol training, and data curation, these students fostered peer accountability, improved adherence to procedures, and modelled evidence-centred discourse. The combination of authenticity (local problem),

structured iteration (data-to-decision cycles), and distributed leadership (co-researchers) offers a coherent explanation for the multi-domain gains observed. For community outcomes, the small effect sizes are consistent with short, non-clinical engagements; benefits likely reflect social connectedness, mindful focus during tasting, and perceived contribution rather than treatment-level change.

4.3 Comparison with Prior Literature

The pattern and magnitude of student gains align with established evidence that integrated, design-based STEM improves problem solving, motivation, and collaboration (e.g., Dym et al., 2005; National Academy of Engineering and National Research Council, 2014; Kelley and Knowles, 2016; NGSS Lead States, 2013). This study extends prior work in three ways. First, it employs validated, blueprint-aligned assessments with acceptable reliability and inter-rater checks, strengthening claims beyond anecdotal reports of engagement. Second, it integrates community well-being measures, illustrating complementary outcomes for participants beyond the classroom. Third, it foregrounds student co-researchers as a practical mechanism to enhance data integrity and peer leadership underreported but scalable strategy in resource-constrained settings. The observed community well-being changes converge with scholarship on service learning and school-community partnerships that report modest psychosocial benefits from purposeful, relational activities.

4.4 Implications for Practice and Policy

For educators in resource-constrained contexts, three design moves are actionable

1) Anchor projects in locally meaningful challenges. Leveraging community assets (e.g., local crops) increases relevance and makes design constraints tangible.
2) Make iteration visible and evidence-based. Build structured feedback cycles (e.g., hedonic testing, quick-turn analyses) and require students to justify redesigns using data.
3) Institutionalise student co-researcher roles. Train selected students to co-lead instrument development, protocol adherence, and data stewardship to build assessment capacity and a culture of evidence use.

At the system level, curriculum and assessment policies should recognize analytic rubrics, reliability checks, and effect-size reporting as routine in classroom inquiry. Providing lightweight tools (e.g., shared rubrics, open-source analysis templates) can help schools normalise rigorous, equity-oriented STEM practices aligned with Global South realities.

4.5 Methodological Considerations and Validity

Several features enhance confidence in the findings: alignment of instruments to a test blueprint, acceptable internal consistency (e.g., KR-20/$\alpha \approx .80$ or higher), inter-rater reliability for performance rubrics, and treatment fidelity monitoring. Triangulation across quantitative gains and qualitative themes strengthens interpretive validity. Nevertheless, internal validity remains limited by the one-group pre–post design, which is vulnerable to maturation and testing effects. For community outcomes, the small pre–post reductions on DASS-21 should be interpreted cautiously; without a comparison group, alternative explanations (e.g., event novelty, short-term mood variation) cannot be ruled out. Missing data were minimal, but listwise deletion may still introduce minor bias.

4.6 Limitations and Directions for Future Research

Three limitations constrain inference. First, the absence of a control or comparison group prevents strong causal claims. Quasi-experimental or randomised designs with delayed post-

tests would better estimate durability and rule out rivals. Second, the 7-week duration may underestimate longer-term impacts on STEM identity or career interest; longitudinal follow-ups and transfer tasks are warranted. Third, the study's context—a single school-community partnership—may limit generalisability. Future work should (a) test scalability across diverse communities and crops; (b) isolate mechanisms via factorial designs that vary feedback intensity and co-researcher involvement; (c) examine measurement invariance and rater drift in performance assessments; and (d) include cost and feasibility analyses to inform adoption at scale. Given the small but significant community effects, mixed-methods studies that trace specific pathways (e.g., social connectedness, perceived contribution, mindful engagement) could clarify how educational interventions yield complementary well-being benefits.

5. Conclusion

Community-anchored, feedback-rich EDP projects that leverage student co-researchers can produce sizable, multi-domain learning gains and modest community well-being benefits. This model offers a feasible and rigorous pathway for equitable STEM education in resource-constrained settings and merits further testing through comparative and longitudinal designs.

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References

Basu, S. J., & Barton, A. C. (2007). Developing a sustained interest in science among urban minority youth. *Journal of Research in Science Teaching, 44*(3), 466–489. https://doi.org/10.1002/tea.20143

Braun, V., & Clarke, V. (2006). Using thematic analysis in psychology. *Qualitative Research in Psychology, 3(*2), 77–101. https://doi.org/10.1191/1478088706qp063oa

Cohen, J. (1988). *Statistical power analysis for the behavioral sciences* (2nd ed.). Routledge. https://doi.org/10.4324/9780203771587

Dym, C. L., Agogino, A. M., Eris, O., Frey, D. D., & Leifer, L. J. (2005). *Engineering design thinking, teaching, and learning. Journal of Engineering Education, 94*(1), 103–120. https://doi.org/10.1002/j.2168-9830.2005.tb00832.x

National Academy of Engineering and National Research Council. (2014). *STEM integration in K–12 education: Status, prospects, and an agenda for research*. The National Academies Press. https://doi.org/10.17226/18612

Kelley, T. R., & Knowles, J. G. (2016). A conceptual framework for integrated STEM education. *International Journal of STEM Education, 3*, 11. https://doi.org/10.1186/s40594-016-0046-z

Khoo, H. E., Azlan, A., Tang, S. T., & Lim, S. M. (2017). Anthocyanidins and anthocyanins: Colored pigments as food, pharmaceutical ingredients, and the potential health benefits. *Food & Nutrition Research, 61*, 1305193. https://foodandnutritionresearch.net/index.php/fnr/article/view/1257

Krajcik, J. S., & Blumenfeld, P. C. (2005). Project-based learning. In R. K. Sawyer (Ed.), *The Cambridge handbook of the learning sciences* (pp. 317–334). Cambridge University Press. https://doi.org/10.1017/CBO9780511816833.020

Psychology Foundation. (n.d.). *Depression Anxiety Stress Scales (DASS)*. University of New South Wales. https://www2.psy.unsw.edu.au/dass/

Masibo, M., & He, Q. (2009). Mango bioactive compounds and related nutraceutical properties: A review. *Food Reviews International*, 25(*4*), 346–370. https://doi.org/10.1080/87559120903153524

National Research Council. (2012). *A framework for K–12 science education: Practices, crosscutting concepts, and core ideas*. The National Academies Press. https://doi.org/10.17226/13165

NGSS Lead States. (2013). *Next Generation Science Standards: For states, by states*. The National Academies Press. https://doi.org/10.17226/18290

Oei, T. P. S., Sawang, S., Goh, Y. W., & Mukhtar, F. (2013). Using the Depression Anxiety Stress Scale 21 (DASS-21) across cultures**.** *International Journal of Psychology, 48*(6), 1018–1029. https://doi.org/10.1080/00207594.2012.755535

SOLAR-POWERED BIMODULAR HYDRAGRIC ANTHROSOL PHYSICOCHEMICAL MONITORING SYSTEM FOR INNOVATIVE FARMING DIAGNOSTICS

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ABSTRACT

Integrating innovative approaches to soil monitoring is significant as it enhances sustainability, optimises resource use, and improves farming diagnostics. The development of the system, along with its sustainable development goals, comprises four organised phases: Material Collection, Electronic System Calibration, Device Fabrication, and Performance and Testing Validation. Results indicate that the AGRONEX devices were successfully designed and fabricated by ensuring all the methods were strictly followed during development. The recorded transmission rate was 8 bits per second, which can be considered slow, yet the system remains reliable since the Master device reads ten times per minute and calculates its mean for accurate readings. The maximum operational range is measured at 54 metres, thereby making it suitable and highly functional for controlled agricultural setups. The calculated mean absolute percentage error between AGRONEX and the commercial soil analyser recorded that pHydrogen has 2.6%, indicating slightly lower precision, but achieved 0% error for moisture, showing complete accuracy, and only 0.5% error for temperature, reflecting near-accurate performance. The mean and standard deviation difference, along with the effect size, indicate that AGRONEX systematically reports higher values than the commercial soil analyser. Overall, the performance of AGRONEX has proven to be a reliable and efficient soil monitoring device, essential for soil management.

Keywords: Soil, Monitoring System, pHydrogen, Moisture, Temperature

1. Introduction

Rice production trends across the Philippines by region from 2013 to 2023, showing that overall rice output has stagnated despite slight increases in area and yields. The Bicol Region generally produces thousands of metric tons of palay (unmilled rice) annually, with yields around 3.7–4.7 t/ha. Camarines Norte's rice output has fluctuated, with significant quarterly declines reported in late 2024. Despite these outputs, agricultural diagnostics remain limited because advanced soil monitoring technologies are not widely available to farmers in Bicol or Camarines Norte to guide real-time nutrient and moisture management for improved yields (Bartelet et al., 2025).

Previous studies confirm that real-time, sensor-based soil monitoring improves agricultural decision-making by providing accurate analysis of key soil parameters. The integration of NPK sensors with machine learning supports precise soil diagnosis and crop recommendations, leading to increased agricultural productivity (Aniyan et al., 2024). IoT-enabled systems that monitor NPK, moisture, pH, and temperature promote healthier crop growth while reducing

excessive fertilizer and water use (Aliparo et al., 2022; Jenath et al., 2024). Furthermore, replacing laboratory-based soil testing with real-time IoT analysis enables efficient fertiliser and irrigation management (Madhumathi et al., 2020).

In accordance with the Sustainable Development Goals, this study aims to develop a solar-powered bimodular monitoring system, named AGRONEX, designed to detect soil physicochemical properties for innovative farming diagnostics. Specifically, it seeks to design and fabricate the AGRONEX System, assess the transmission rate of calculated data from the AGRONEX Master device to the Slave device in monitoring soil parameters across varying operational ranges, measure its maximum operational range in detecting soil parameters, determine its percentage error compared to a commercial soil analyser, and calculate its accuracy rate through the mean absolute percentage error.

2. Method

2.1 Material Collection

All materials were sourced from online platforms and local hardware stores with expert guidance to ensure quality and reliability. The Master device utilises an Arduino Uno, Bluetooth module, Li-ion battery, and soil multiparameter sensor to acquire and transmit soil data, while the Slave device employs an Arduino Mega, Bluetooth module, and TFT display to process and visualise results in real time. At the system level, renewable power is provided by a monocrystalline solar panel and an MPPT solar charge controller, supported by a battery for energy storage, with protection ensured through a DC breaker and surge protective device. Structural components such as a GI pipe and flat sheet strengthen the system's durability for outdoor agricultural deployment.

Table 1: Materials Specification and Cost Analysis

Materials	Quantity	Specification	Cost (Php)
Monocrystalline Solar Panel	2	30 Watts / unit	1260 (630/unit)
MPPT Solar Charge Controller	1	12 Volts, 30Ah	400
Battery	1	12 Volts, 5000mAh	430
DC Breaker	2	FPV-63 C16	900 (450/unit)
Surge Protective Device	1	FSP-D40	930
Arduino	1	Uno	550
Arduino	1	Mega	1,150
Bluetooth Module	2	HC-05	400 (200/unit)
Soil Multiparameter Sensor	1	-	3,240
Li-ion Battery	1	11.1 Volts	740
TFT Display	1	4 Inches	890
G-I Pipe	1	2", 20 Ft	1,375
Flat Sheet	1	1.1 Mm	1,035
Total			**13,300**

2.2 Electronic Software Calibration

2.2.1 Master Device

Figure 1: Schematic Diagram of Master Device

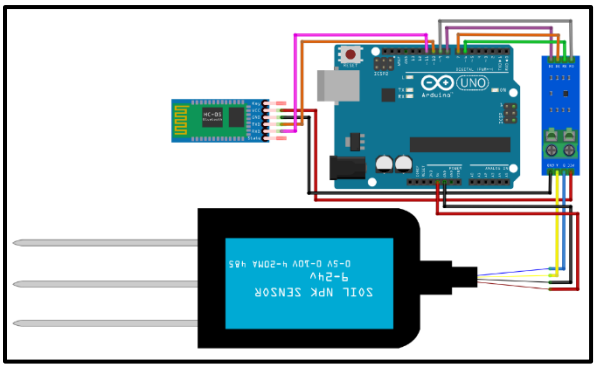

Figure 2: Abstract Design of Master Device

Figure 1 shows the Master device setup, which uses an Arduino Uno, an HC-05 Bluetooth Module, a Soil Sensor, and an RS-485 to TTL Module. Figure 2 shows the Master device enclosed by a 3D model casing.

The Arduino Uno acts as the master microcontroller, collecting data from the soil sensor through the RS-485 module and transmitting it to a Slave device via the HC-05 Bluetooth module. The soil sensor provides soil parameters such as N-P-K, pHydrogen, moisture, and temperature, processed by Arduino and then sent wirelessly to a receiving device for display. The Master Device is programmed to collect sensor data ten times per minute and calculate its mean before transmitting it via Bluetooth, ensuring accurate readings while providing stable and efficient communication.

2.2.2 Slave Device

Figure 3: Schematic Diagram of Slave Device

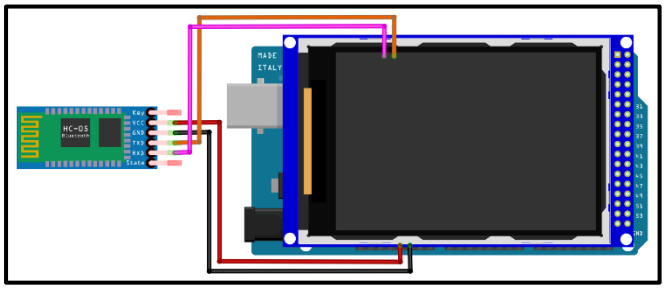

Figure 4: Abstract Design of Slave Device

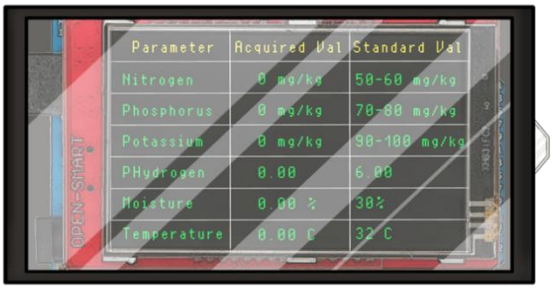

Figure 3 shows the Slave device setup, which uses an Arduino Mega 2560, an HC-05 Bluetooth Module, and a 4-inch TFT LCD Display. Figure 4 shows the Slave device enclosed by a 3D model casing.

The Arduino Mega functions as the slave microcontroller, receiving data from a Master device via Bluetooth and displaying it on the TFT screen. The HC-05 Bluetooth module, configured in slave mode, establishes a wireless connection with the Master device, which sends data commands. Upon receiving the data, the Arduino processes it and updates the TFT LCD display accordingly. The Slave Device is programmed to receive the transmitted data and display it on the 4" TFT LCD, providing users with a user-friendly interface for monitoring soil conditions.

2.3 Device Fabrication

Figure 5: Circuit Diagram of AGRONEX

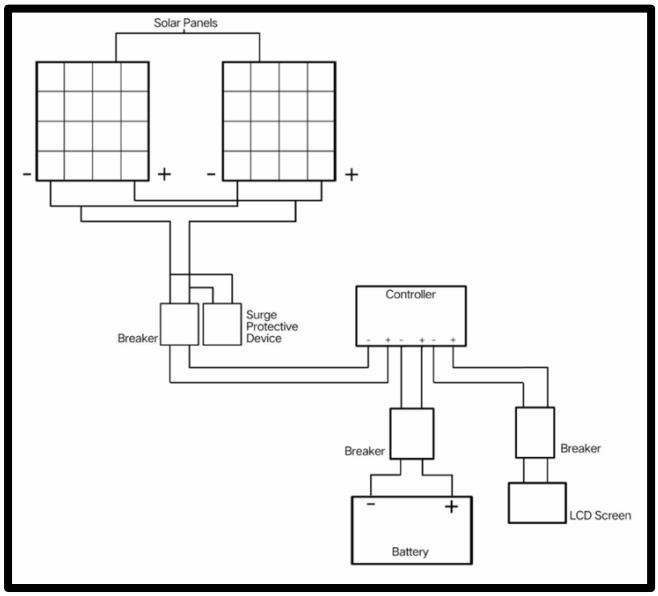

Figure 6: Abstract Design of AGRONEX

Figure 5 shows the Circuit Diagram of AGRONEX, which includes a Monocrystalline Solar Panel, an MPPT Solar Charge Controller, a Battery, a DC Breaker, and a Surge Protective Device, connected by electrical wires. Figure 6 shows a complete AGRONEX Device, supported by a T-shaped tube and mounted in a recycled tire.

The development of AGRONEX began with constructing a 2.6-meter metal pole and an aluminium frame measuring 11×16×10 inches, which served as the structure for the control box. A T-shaped tube was installed inside the control box to support and connect the solar panels mounted at each end. The base, made from a recycled tire filled with cement, provided stability for the entire setup. Inside the control box, the researchers integrated the battery, charge controller, and breakers connected to the solar panels to establish the power system. Finally, the Slave device was mounted at the centre of the pole as the monitoring unit, completing the assembly of the AGRONEX system. This configuration ensured a stable, self-sustaining, and centrally managed system capable of continuous field operation and real-time monitoring.

2.4 Performance and Testing Validation

The researchers conducted field testing of the AGRONEX system in an open paddy-field in Labo, Camarines Norte, to comprehensively evaluate its effectiveness and usability. During testing, a tape measure was used to identify the operational ranges across three trials, with the maximum operational range determined at the final point of disconnection between the Master and Slave devices. Using the Arduino IDE software, the researchers monitored data size and transmission time to calculate the transmission rate and assess communication efficiency. The accuracy of AGRONEX was then validated by comparing its readings of pH, moisture, and temperature with those from a commercial soil analyser, and a statistical tool was employed to compute the overall accuracy rate of the system.

2.5 Statistical Treatment

Data Transfer Rate Formula. The transmission rate between the AGRONEX Master and Slave devices was determined by dividing the data size (in bits) by the transmission time (in seconds).

Eq. 1

$$Transmission\ Rate = \frac{Data\ Size\ (in\ bits)}{Transmission\ Time\ (in\ seconds)}$$

Percentage Error. It is about calculating the differences between an observed value and a theoretical value as a percentage of that value. In this case, the readings of AGRONEX were subtracted from the readings of the commercial soil analyser and divided by the exact readings of the commercial soil analyser, then multiplied by 100 to compute the percentage error.

Eq. 2

$$Percentage\ Error = \left(\frac{AGRONEX\ reading - Commercial\ analyser\ reading}{Commercial\ analyser}\right) \times 100$$

Mean absolute percentage error. Measures the average magnitude of error produced by a model, or how far off predictions are on average. To calculate the mean absolute percentage error, first calculate the absolute value of each residual. Once the absolute value of a residual is calculated, divide this value by the original data point and multiply by 100. Add all these percentages up and divide by the total number of data points to get our mean absolute percentage error.

Eq. 3

$$Mean\ Absolute\ Percentage\ Error = \frac{\sum \left(\frac{|A - F|}{A}\right) \times 100}{N}$$

3. Results and Discussion

3.1 Design and Fabrication

All the devices of this study, including the Master device, Slave device, and the AGRONEX system, were successfully designed and fabricated by ensuring all schematic diagrams, material requirements, and procedures were strictly followed during the development. Furthermore, the overall design and functional outcomes affirm the system's capability to meet the intended research objectives and operational standards in terms of usability, efficiency, and reliability.

Figure 7: Actual Fabricated Master Device

Figure 8: Actual Fabricated Slave Device

Figure 9: Actual Fabricated AGRONEX

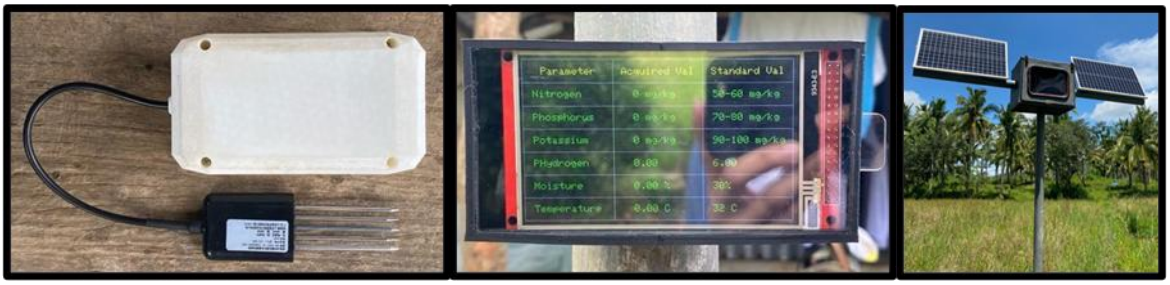

Figure 7 shows the actual fabricated Master Device enclosed by a 3D model casing with the soil sensor probe used for data acquisition. Figure 8 shows the actual fabricated Slave Device enclosed by a 3D model casing displaying the monitoring interface that presents real-time soil parameters. Figure 9 shows the actual fabricated AGRONEX system installed in the field, featuring the solar-powered structure with a mounted control box and monitoring unit.

3.2 Transmission Rate

Table 2: Recorded Transmission Rate of AGRONEX Master and Slave Devices

	Trial 1	Trial 2	Trial 3
Data Size (Bits)	48	48	48
Transmission Time (Seconds)	6	6	6
Transmission Rate (Bits per Second)	**8**	**8**	**8**

In Table 2, the transmission performance of the AGRONEX Master and Slave devices is presented. Across all three trials, a consistent data size of 48 bits was recorded. The corresponding transmission time for each trial was measured at 6 seconds, resulting in a uniform transmission rate of 8 bits per second, as determined using the standard transmission rate formula. This consistency across trials indicates stable communication between the devices, reinforcing the system's reliability in handling data exchange. Although the recorded transmission rate of 8 bits per second may be considered slow, it does not compromise the efficiency of the device. Instead, the system ensures reliability by consistently detecting soil parameters six times per minute, providing farmers with more accurate and updated information that supports better field management decisions.

3.3 Operational Ranges

Table 3: Recorded Operational Ranges of AGRONEX

	Trial 1	Trial 2	Trial 3
Operational Range (Metres)	**18**	**36**	**54**

In Table 3, the recorded operational ranges of the AGRONEX system are presented. Based on the data gathered, the short range for trial 1 is 18 metres. In trial 2, the medium range is 36 metres. In trial 3, the long range is 54 metres. Using the given data, the researchers were able to determine that the maximum operational range of the AGRONEX is 54 metres. These findings indicate that the system's wireless communication capability performs efficiently within typical farm-scale distances, demonstrating reliability in data transmission across varying operational ranges.

3.4 Comparison of Data

Table 4: Computed Percentage Error of pHydrogen

	Trial 1	Trial 2	Trial 3
AGRONEX	5.7	4.6	5.1
Commercial Soil Analyser	5.5	4.5	5.0
Percentage Error	**3.6%**	**2.2%**	**2%**

In Table 4, the comparison of the readings of AGRONEX and a commercial soil analyser for pHydrogen is presented. Based on the gathered data for trial 1, the reading of AGRONEX is 5.7, while the reading of the commercial soil analyser is 5.5. In trial 2, the reading of AGRONEX is 4.6, while the reading of the commercial soil analyser is 4.5. In trial 3, the reading of AGRONEX is 5.1, while the reading of the commercial soil analyser is 5.0. For the percentage error for trial 1 in terms of pHydrogen, the percentage error is 3.6%. In trial 2, the percentage error is 2.2%. In trial 3, the percentage error is 2%.

Table 5: Mean, SD, and Effect Size of pHydrogen

	Mean	Standard Deviation	Effect Size
AGRONEX	**5.3**	**0.55**	
Commercial Soil Analyser	**5**	**0.50**	
	d = 0.13	d = 0.06	**d = 0.79**

In Table 5, the mean, standard deviation, and effect size of the readings of AGRONEX and a commercial soil analyser for pHydrogen are presented. Results indicate that AGRONEX produced a higher mean value (M = 5.13) than the commercial soil analyser (M = 5.00), suggesting a tendency for AGRONEX to report elevated pHydrogen readings. The standard deviations for AGRONEX (SD = 0.55) and the commercial soil analyser (SD = 0.50) indicate slightly greater variability in AGRONEX measurements, while the commercial soil analyser demonstrates marginally more consistent readings. The small mean difference (0.13) and standard deviation difference (0.06) suggest minimal discrepancies in measurement performance between the two devices. However, the large effect size (d = 0.79) indicates practical significance, implying a meaningful difference in pHydrogen measurements and supporting the conclusion that AGRONEX systematically reports higher pHydrogen values than the commercial soil analyser.

Table 6: Computed Percentage Error of Moisture

	Trial 1	Trial 2	Trial 3
AGRONEX	99%	99%	99%
Commercial Soil Analyser	99%	99%	99%
Percentage Error	**0%**	**0%**	**0%**

In Table 6, the comparison of the readings of AGRONEX and a commercial soil analyser for moisture is presented. Based on the gathered data for trial 1, the reading of AGRONEX is 99%, while the reading of the commercial soil analyser is 99%. In trial 2, the reading of AGRONEX is 99%, while the reading of the commercial soil analyser is 99%. In trial 3, the reading of AGRONEX is 99%, while the reading of the commercial soil analyser is 99%. For the percentage error for trial 1 in terms of moisture, the percentage error is 0%. In trial 2, the percentage error is 0%. In trial 3, the percentage error is 0%.

Table 7: Mean, SD, and Effect Size of Moisture

	Mean	Standard Deviation	Effect Size
AGRONEX	**0**	**0**	
Commercial Soil Analyser	**0**	**0**	
	d = 0	d = 0	**d = 0**

In Table 7, the mean, standard deviation, and effect size in terms of comparison of the readings of AGRONEX and a commercial soil analyser for moisture are presented. Results show perfect agreement between AGRONEX and the commercial soil analyser across all trials. Identical readings resulted in a mean difference (M=0), standard deviation (SD=0), and effect size of (d=0). These values indicate the complete absence of variability between paired measurements and confirm that no statistically or practically meaningful difference exists between the instruments. Overall, the findings provide strong evidence that AGRONEX delivers moisture measurements that are equivalent in both accuracy and consistency to those produced by the commercial soil analyser.

Table 8: Computed Percentage Error of Temperature

	Trial 1	Trial 2	Trial 3
AGRONEX	99%	99%	99%
Commercial Soil Analyser	99%	99%	99%
Percentage Error	**0%**	**0%**	**0%**

In Table 8, the comparison of the readings of AGRONEX and a commercial soil analyser. The temperatures are presented. Based on the gathered data for trial 1, the reading of AGRONEX is 28.5°C, while the reading of the commercial soil analyser is 28.3°C. In trial 2, the reading of AGRONEX is 28.4°C, while the reading of the commercial soil analyser is 28.3°C. In trial 3, the reading of AGRONEX is 27.5°C, while the reading of the commercial soil analyser is 27.3°C. For the percentage error for trial 1 in terms of pHydrogen, the percentage error is 0.7%. In trial 2, the percentage error is 0.3%. In trial 3, the percentage error is 0.7%.

Table 9: Mean, SD, and Effect Size of Temperature

	Mean	Standard Deviation	Effect Size
AGRONEX	**28.13**	**0.55**	
Commercial Soil Analyser	**27.97**	**0.57**	
	d = 0.17	d = 0.06	**d = 0.79**

In Table 9, the mean, standard deviation, and effect size in terms of comparison of the readings of AGRONEX and a commercial soil analyser for temperature are presented. Results indicate that AGRONEX recorded a slightly higher mean value (M = 28.13) than the commercial soil analyser (M = 27.97), suggesting a tendency toward higher temperature readings. AGRONEX also exhibited marginally lower variability (SD = 0.55) compared to the commercial device (SD = 0.57), indicating more consistent measurements. The small mean difference (0.17) and standard deviation difference (0.06) imply minimal discrepancies in measurement performance between the two analysers. However, the large effect size (d = 0.79) denotes practical significance, indicating a meaningful difference and supporting the conclusion that AGRONEX systematically reports higher temperature values than the commercial analyser.

3.5 Accuracy Rate

Table 10: Computed Mean Absolute Percentage Error of Soil Parameters

Soil Parameters	Trial 1	Trial 2	Trial 3	MAPE
pHydrogen	3.6%	2.2%	2%	**2.6%**
Moisture	0%	0%	0%	**0%**
Temperature	0.7%	0.3%	0.7%	**0.5%**

In Table 10, the computed mean absolute percentage error of soil parameters, specifically for pHydrogen, moisture, and temperature, is presented. The calculated mean absolute percentage error is based on the summation of the percentage error of each trial in Table 4-6. The researchers found that the mean absolute percentage error in terms of pHydrogen is 2.6%, indicating a less accurate result. In terms of moisture, the mean absolute percentage error is 0%, showcasing an accurate result. In terms of temperature, the mean absolute percentage error is 0.5%, showing a near-accurate result. These findings confirm AGRONEX's reliable performance, showing consistent precision across most soil parameters when compared to a commercial analyser. The device remains effective in monitoring essential soil data for accurate farming diagnostics and informed agricultural decision-making.

4. Conclusion

The overall findings confirm that the AGRONEX system, along with its Master and Slave devices, was successfully designed and fabricated according to the established procedures and specifications, resulting in effective functionality and stable performance. The system demonstrated consistent data transmission at a rate of 8 bits per second and maintained reliable communication up to a maximum range of 54 metres, indicating its suitability for typical agricultural environments. Accuracy evaluations further validated its precision, showing minimal deviations from the commercial soil analyser, particularly in soil moisture and temperature detection. The mean difference and standard deviation difference, along with the effect size, indicate that AGRONEX systematically reports higher pHydrogen and temperature values than the commercial soil analyser. The findings from the field testing may be generalised to small- to medium-sized rice fields with similar soil conditions and management practices. However, such generalisation should be made with caution, as system performance may differ across varying soil types. Collectively, these results affirm AGRONEX's reliability, efficiency, and potential as a practical tool for farming diagnostics.

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References

Aniyan, N., Vincent, B., Philip, F., Anil, A., & John, J. E. (2024). Soil category classification using machine vision and automated NPK content estimation. *Proceedings of the 1st International Conference on Innovative Sustainable Technologies for Energy, Mechatronics, and Smart Systems (ISTEMS 2024)* (pp. 1–6). IEEE. https://doi.org/10.1109/ISTEMS60181.2024.10560085

Aliparo, J., Delos Santos, C., Sese, C. M., Trinidad, J. V., Beaño, M. G., & Capuno, M. E. A. (2022). IoT-based assessment and monitoring of NPK content and fertility condition of soil. *TENCON 2022 - 2022 IEEE Region 10 Conference (TENCON)*, 1–6. https://doi.org/10.1109/tencon55691.2022.9978040

Bartelet, H. A., Prodigalidad, A. J. D., Dy, J. S., & Manzano, J. G. N. (2025). Understanding rice production stagnation in the Philippines: Regional evidence and development implications. *PLoS ONE*, *20*(10), e0335344. https://doi.org/10.1371/journal.pone.0335344

Jenath, M., Sinnur, R., Bhogavelli, V. K., & Jagadish, B. (2024). Terrestrial moisture sensor using IoT and neutralizing pH value of the soil. *Proceedings of the 10th International Conference on Communication and Signal Processing (ICCSP 2024)* (pp. 842–847). IEEE. https://doi.org/10.1109/ICCSP60870.2024.10543808

Madhumathi, R., Arumuganathan, T., & Shruthi, R. (2020). Soil NPK and moisture analysis using wireless sensor networks. *Proceedings of the 11th International Conference on Computing, Communication and Networking Technologies (ICCCNT 2020)* (pp. 1–6). IEEE. https://doi.org/10.1109/ICCCNT49239.2020.9225547

Roberts, A. (2023, February 8). *Mean absolute percentage error (MAPE): What you need to know.* Arize AI. https://arize.com/blog-course/mean-absolute-percentage-error-mape-what-you-need-to-know/

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