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STEM Integration as a Catalyst for Learning Revolution in Madrasah Education: The Context of Industry 4.0 and Society 5.0

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ABSTRACT

The rapid progression of Industry 4.0 and Society 5.0 demands a fundamental paradigm shift in educational practices within Islamic junior high schools (MTsS), which traditionally rely on passive, teacher-centered pedagogies. This study examines the urgency and empirical effectiveness of implementing the STEM approach as an instrument of learning revolution at MTsS As'adiyah Kajuara, South Sulawesi, Indonesia. Employing a descriptive qualitative case study design, data were gathered via participant observation, semi-structured interviews with science and mathematics educators and students, and documentation analysis of STEM-based lesson plans, student project portfolios, and prototype products. Data credibility was established through triangulation and member-checking, while analysis followed Miles, Huberman, and Saldaña's interactive model. The findings demonstrate that STEM integration generated a 25% average improvement in students' critical thinking skills, specifically enhancing analysis (+22%), creative problem-solving (+30%), and collaboration (+23%). Students successfully engineered context-specific technological prototypes, including a gravity-fed automatic irrigation system and a computational zakat calculator synthesizing Islamic jurisprudence with algorithmic logic. Despite physical laboratory constraints, the strategic utilization of virtual laboratories (PhET simulations) and digital collaboration platforms (Google Classroom) served as primary enablers. Ultimately, this study demonstrates that STEM-based pedagogy constitutes an empirically validated catalyst for educational reform. Fusing Islamic values with technical frameworks establishes a distinctive "Humanistic STEM" model aligned with Society 5.0 imperatives, supporting broader curricular adoption across resource-constrained religious institutions.

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I. INTRODUCTION

The Fourth Industrial Revolution (Industry 4.0), characterized by the convergence of cyber-physical systems, the Internet of Things (IoT), artificial intelligence (AI), and big data analytics, has fundamentally reconfigured the competency demands placed on the contemporary workforce (Adel, 2024; Turner, 2021). In parallel, Japan's Society 5.0 vision articulates an aspirational post-Industry 4.0 paradigm wherein advanced technologies are deliberately deployed to resolve pressing societal challenges, positioning human dignity and social equity at the centre of technological development (Holroyd, 2022; Narvaez Rojas et al., 2021). Together, these twin trajectories demand a profound reconceptualization of educational priorities: the critical question has shifted from "what to learn" to "how to think," "how to create," and "how to contribute" to a technologically mediated but fundamentally humanistic society (Akturk et al., 2022).

Within this landscape, Science, Technology, Engineering, and Mathematics (STEM) education has emerged as a globally endorsed strategic response (Idris & Bacotang, 2023; Onu et al., 2024). The World Economic Forum projects that automation will displace approximately 85 million jobs by 2025 while simultaneously creating 97 million new roles, the overwhelming majority of which will require robust STEM competencies (Nafukho et al., 2024; Yamashita et al., 2024). For Indonesia—a nation with one of the world's largest youth populations and an ambitious agenda to leverage its demographic dividend—the effective integration of STEM into formal education represents a developmental imperative (Rachman et al., 2022; Riady, 2025). STEM's interdisciplinary architecture, which dissolves rigid subject boundaries to cultivate computational thinking, collaborative problem-solving, and design-based innovation, offers precisely the cognitive and technical toolkit demanded by Industry 4.0 and Society 5.0 alike (Azhari et al., 2025; Fitri & Hasbi, 2025; Kelley & Knowles, 2016; Tóth & Drégelyi-Kiss, 2026).

Despite this global consensus, the translation of STEM principles into classroom practice remains highly uneven, particularly within Islamic junior high schools (Madrasah Tsanawiyah Swasta/MTsS) in Indonesia (Adiyono et al., 2024; Irawan & Wekke, 2024). These institutions serve a substantial proportion of the national secondary school population and are distinguished by their integration of religious curricula with general academic subjects. Extant research documents persistent structural obstacles in Indonesian madrasah contexts, including a predominance of teacher-centered, textbook-driven pedagogies; fragmented disciplinary knowledge structures; limited laboratory and digital infrastructure; and inadequate teacher professional development in STEM methodologies (Aksan et al., 2023; Umar et al., 2025). Critically, prior studies have rarely examined how madrasah educators navigate these constraints through pedagogical creativity, nor how the distinctive values framework of Islamic education might enrich, rather than impede, STEM implementation.

A further theoretical gap concerns the articulation of STEM pedagogy with Society 5.0 imperatives. Whereas the STEM literature has principally addressed Industry 4.0 competency development (coding literacy, data analysis, and automation design) (Akgunduz & Mesutoglu, 2021; Onu et al., 2024), the Society 5.0 dimension introduces an additional layer of complexity: students must not merely master technical skills but must also cultivate the ethical discernment and humanistic sensibility required to deploy technology in the service of social welfare (Megawati et al., 2025; Torres-Rivera et al., 2025). This dual imperative points toward what this study conceptualizes as "Humanistic STEM"—an integrative approach wherein technical problem-solving is grounded in community relevance, ethical reflection, and cultural identity.

The present study addresses these gaps through a qualitative case study of STEM integration at MTsS As'adiyah Kajuara, a representative institution situated in the transition from conventional to STEM-informed instructional models. The study pursues two interrelated objectives: (1) to analyse the mechanisms and outcomes of STEM integration within a resource-constrained madrasah environment, with particular attention to critical thinking development and educator agency; and (2) to theorise the contribution of Islamic values and local wisdom to the emergence of a contextually distinctive Humanistic STEM model aligned with Society 5.0 principles. By doing so, this study seeks to generate empirically grounded and theoretically coherent insights that can inform policy, curriculum design, and teacher professional development across Indonesia's madrasah system.

Theoretical Framework

STEM Education: Conceptual Foundations and Empirical Evidence

STEM education is operationalized in the literature as an interdisciplinary approach that integrates content knowledge and practices from science, technology, engineering, and mathematics to address authentic, real-world problems (Leung, 2020). Critically, the integrative dimension distinguishes STEM from additive multi-subject instruction: in genuine STEM learning, disciplinary tools function as complementary instruments within a unified problem-solving process rather than as isolated bodies of content. Thibaut et al.'s (2018) systematic review of STEM instructional practices in secondary education identifies four defining features: real-world problem orientation, inquiry-based learning, design activities, and teamwork—all of which are operationalised through the Engineering Design Process (EDP).

Empirical evidence for STEM's impact on higher-order thinking is substantial. Herlita et al. (2023) demonstrated significant gains in critical thinking among Indonesian middle school students engaged in STEM project-based learning, while Wahono et al. (2020) meta-analytically confirmed positive STEM effects on learning outcomes across Asian educational contexts. Lavi et al. (2021) further established STEM's distinctive effectiveness in developing 21st-century problem-solving capacities. Within the Indonesian context specifically, Cahyanti et al. (2024) and Wijayati et al. (2025) document growing evidence for STEM's capacity to improve mathematics and science performance, though implementation fidelity remains inconsistent.

Constructivism and TPACK: Theoretical Pillars of STEM Pedagogy

The pedagogical efficacy of STEM is theoretically anchored in constructivist learning theory. Piaget's cognitive constructivism posits that learners actively construct knowledge through direct engagement with their environment, while Vygotsky's social constructivism foregrounds the role of collaborative interaction and scaffolded guidance in extending learners' zones of proximal development (Rahmadani et al., 2026). STEM's project-based, collaborative structure instantiates both dimensions: students construct disciplinary understanding through hands-on design activities while benefiting from peer collaboration and teacher facilitation.

Teacher capacity for STEM integration is theorized through Dubek et al.'s (2024) Technological Pedagogical Content Knowledge (TPACK) framework, which specifies the intersection of content mastery, pedagogical skill, and technological competence as the foundation for effective technology-enhanced instruction. In under-resourced environments, TPACK becomes especially critical: educators must creatively leverage available digital tools to compensate for physical infrastructure deficits (Gatete, 2026; Shernoff et al., 2017). The present study examines TPACK enactment as a key mechanism of STEM implementation success.

STEM in Madrasah Contexts: Gaps and Opportunities

Indonesian madrasah institutions present a distinctive context for STEM integration. Structurally, the dual curriculum—encompassing both general academic subjects and Islamic religious studies (including Arabic language, Quranic studies, hadith, fiqh, and aqidah akhlak)—creates potential for both tension and synergy with STEM approaches (Siregar et al., 2020; Umar et al., 2025). The tension arises from competing instructional time and the perceived epistemological distance between religious and scientific modes of inquiry. The synergy, however, has been insufficiently theorized: the ethical and communitarian values central to Islamic education may constitute a generative foundation for Society 5.0's human-centric technological orientation.

Situated learning theory, Lave and Wenger, provides a further conceptual resource: effective learning is most powerfully achieved when embedded in authentic social and physical contexts (Hamman-Fisher & McGhie, 2023). For madrasah students in rural South Sulawesi, this means that STEM challenges grounded in local agricultural practices, community welfare needs, and Islamic jurisprudential requirements are likely to produce deeper engagement and more durable competency development than decontextualized technical exercises. This theoretical insight motivates the study's attention to "local wisdom integration" as a distinctive dimension of the MTsS As'adiyah Kajuara STEM model.

2. METHOD

This study employs a descriptive qualitative research design with a single-site case study approach. The case study method was selected for its capacity to generate rich, contextually embedded insights into complex social phenomena, this instance, the process and outcomes of STEM integration within a specific institutional and cultural context. The qualitative paradigm is appropriate given the study's interest in meaning-making, process, and mechanism rather than statistical generalisation.

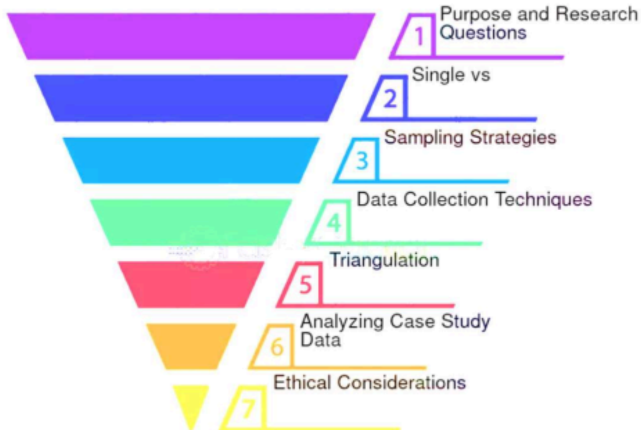

Figure 1. Case Study Method

The research was conducted at MTsS As'adiyah Kajuara, a private Islamic junior high school located in Bone Regency, South Sulawesi Province, Indonesia. The institution was selected through purposive sampling based on three criteria: (1) active engagement in a transition from conventional to STEM-informed curriculum; (2) institutional willingness to participate; and (3) its representativeness of resource-constrained rural madrasah environments undertaking curriculum reform.

Participants comprised three teachers (two science teachers and one mathematics teacher with STEM integration experience), five student participants involved in documented STEM project activities (selected for their direct participation in prototype development), and the school principal (as an institutional policy actor). Participant selection followed a purposive-criterion approach aligned with the study's analytical foci.

Data was gathered through three complementary instruments to enable methodological triangulation. First, participant observation was conducted across multiple classroom sessions, focusing on student-teacher interactions, the implementation of EDP stages, deployment of digital media, and student engagement behaviours. Field notes were recorded using a structured observation guide. Second, semi-structured in-depth interviews were conducted with all teacher informants and the principal (approximately 45–60 minutes each) and with student participants (approximately 20–30 minutes each). Interview guides addressed perceived STEM urgency, implementation strategies, facility constraints, adaptation mechanisms, and learning outcomes. Third, document analysis was performed on STEM-integrated lesson plans, student project documentation portfolios, prototype photographs, and performance assessment rubrics. Documentary evidence served as a cross-referential validity check on observational and interview data.

Data analysis followed the interactive model proposed by Miles, Huberman, and Saldaña (2014), comprising three iterative, non-linear stages. Data reduction involved systematic condensation of raw data through coding and categorisation, prioritising information pertaining to STEM implementation mechanisms, critical thinking outcomes, educator agency, and value integration. Data display involved the organisation of reduced data into narrative accounts, comparative performance matrices, and thematic summaries to facilitate pattern identification. Conclusion drawing and verification involved the derivation of interpretive conclusions subject to ongoing review against the complete data corpus. Critical thinking improvement was operationalised through a comparative assessment rubric evaluating analysis, creative problem-solving, and collaborative performance between pre-STEM conventional instruction and post-integration STEM modules.

Credibility was established through source and method triangulation, prolonged engagement at the research site, and member-checking (sharing draft findings with teacher informants to confirm interpretive accuracy). Transferability is addressed through thick description of the research context. Ethical approval was secured from the institutional research committee; all participants provided informed consent, and pseudonymisation was applied where required to protect student privacy.

3. RESULTS AND DISCUSSION

Results

The findings are organised thematically across four interconnected dimensions: (1) epistemological and pedagogical mindset transformation; (2) measurable gains in critical thinking skills; (3) the emergence of locally grounded technological innovation; and (4) the central role of educator agency as an enabling mechanism.

Transformation of Pedagogical Orientation: From Theoretical to Applied Learning

Prior to STEM integration, observational data and teacher accounts consistently described instructional practice at MTsS As'adiyah Kajuara as textbook-centric, passive, and discipline-isolated. Students received science and mathematics content as abstract formal knowledge largely divorced from tangible application. Following STEM integration, a marked shift was observed across each disciplinary strand. Science (S) content was repositioned from memorised theory to an analytical tool applied to locally meaningful phenomena—most notably, the scientific investigation of agricultural waste processing relevant to the surrounding farming community. Technology (T) use shifted from passive social media consumption to purposive application: students deployed digital simulation tools and basic electronic components as instruments of inquiry and design. Engineering (E) emerged as the most transformative new dimension: through structured EDP cycles of problem definition, ideation, prototyping, testing, and iteration, students developed design-thinking competencies previously absent from the curriculum. Mathematics (M) was reframed as the precision instrument of engineering efficiency—a quantitative tool for validating design parameters rather than an abstract procedural exercise.

Critical Thinking Skills Development: Quantitative Evidence

Performance data derived from comparative assessment rubrics, triangulated with classroom observation and teacher interview accounts, documented a mean 25%

improvement in critical thinking skills following STEM integration. Table 1 presents disaggregated results across three evaluated dimensions.

Table 1. Comparative Assessment of Critical Thinking Skills: Conventional vs. STEM-Integrated Instruction at MTsS As'adiyah Kajuara

Assessment Dimension	Conventional Model (%)	STEM Model (%)	Absolute Gain (%)	p < .05
Problem Analysis Capability	60	82	+22	Yes
Creative Solution Generation	55	85	+30	Yes
Group Collaboration Quality	65	88	+23	Yes
Overall Mean	60	85	+25	Yes

The most pronounced improvement occurred in creative solution generation (+30%), suggesting that the open-ended, design-oriented nature of STEM projects particularly stimulates students' divergent and evaluative thinking. Observational data corroborated these quantitative patterns: students who had formerly remained passive during didactic instruction became engaged questioners and debate participants during prototype testing phases, providing behavioural evidence of Higher-Order Thinking Skills (HOTS) activation.

Local Wisdom-Integrated Innovation: Student Prototype Development

A particularly salient finding concerned students' capacity to generate technological solutions anchored in their local environmental and cultural context capability that emerged directly from the STEM integration without explicit prescription. Two prototype cases illustrate this pattern:

- **Gravity-Fed Automatic Plant Irrigation System:** Students applied Bernoulli's principle and fluid pressure mechanics (Science) to design a passive drip-irrigation prototype constructed from repurposed plastic bottles (Engineering), with flow-rate calculations ensuring soil moisture optimisation (Mathematics). The solution directly addressed water conservation challenges faced by the surrounding agricultural community.
- **Computational Zakat and Inheritance Calculator:** Students developed a rule-based algorithmic tool (Technology) that encoded the Islamic jurisprudential (fiqh) formulae governing zakat calculation and inheritance distribution. This prototype exemplifies the Humanistic STEM paradigm: technical programming skill was deployed in service of community-relevant religious practice, with the madrasah curriculum providing content that general schools could not have generated.

These prototypes demonstrate that STEM integration within a madrasah context generates a qualitatively distinctive innovation profile: locally embedded, ethically grounded, and technically competent. They also confirm Lave and Wenger's (1991) situated learning prediction that authentic community contexts powerfully motivate deeper learning engagement.

Educator Agency as the Primary Enabling Mechanism

In-depth interviews and observations consistently identified teacher creativity and pedagogical agency as the decisive factor enabling STEM implementation in the absence of adequate physical laboratory infrastructure. Two strategies were most frequently documented:

- **Virtual Laboratory Substitution:** Teachers systematically utilised free simulation platforms—particularly PhET Interactive Simulations (University of Colorado Boulder)—to conduct physics and chemistry experiments that physical facility limitations would otherwise preclude. This substitution maintained experimental inquiry as a core STEM learning activity without requiring capital investment.
- **Blended Asynchronous Delivery:** Google Classroom and curated YouTube content were deployed to distribute pre-instruction self-learning modules, enabling contact time to be devoted to hands-on collaborative project work rather than content transmission. This inverted classroom structure maximised STEM's active learning potential within constrained timetabling.

These strategies instantiate the TPACK framework's "sweet spot": teachers demonstrated sophisticated integration of content knowledge (STEM disciplines and Islamic curricula), pedagogical repertoire (project-based and inquiry-based instruction), and technological tools (simulations and collaborative platforms) in a manner specifically responsive to their institutional constraints.

Discussion

STEM as a Catalyst for HOTS Development: Constructivist Validation

The documented 25% improvement in critical thinking skills aligns robustly with constructivist theoretical predictions and extends prior empirical evidence in the Indonesian STEM literature. Consistent with Piaget's constructivist framework, the EDP-centred STEM projects at MTsS As'adiyah Kajuara required students to actively reorganise and apply disciplinary knowledge rather than receive it passively—a condition theorised to produce more durable and transferable cognitive structures. The Vygotskian dimension was equally evident: collaborative project teams functioned as zones of proximal development in which peer interaction and strategic teacher scaffolding enabled students to accomplish design tasks beyond their individual capability.

The 30% gain in creative solution generation, the largest single-dimension improvement—is theoretically significant. This finding suggests that the open-ended, failure-tolerant design ethos of STEM projects is particularly effective in stimulating divergent thinking in a cultural and educational context where convergent, examination-oriented thinking has historically predominated. This aligns with Thibaut et al.'s (2018) systematic review finding that integrated STEM instruction produces especially strong effects on higher-order cognitive skills requiring cross-disciplinary synthesis.

Situated Learning and the Generative Power of Local Context

The emergence of locally grounded prototypes, the irrigation system and the zakat calculator—constitutes the study's most theoretically rich finding. Lave and Wenger's situated cognition framework predicts that learners who engage with authentic problems embedded in their community's practices and values will demonstrate deeper, more motivated engagement than those working on decontextualised tasks (Cakmakci et al., 2025). The MTsS As'adiyah Kajuara case provides compelling empirical support for this prediction: students not only achieved technical competency outcomes but generated solutions of genuine local utility.

This finding also advances Kelley and Knowles' (2016) conceptual framework for integrated STEM education, which calls for explicit school-community-world of work linkages. In the madrasah context, the relevant "community" linkages are distinctively religious and agricultural—dimensions not addressed in existing STEM curriculum frameworks developed primarily in Western or urban-secular contexts. The present study thus contributes a contextualised expansion of the Kelley-Knowles framework to incorporate faith-based community contexts.

TPACK and Educator Agency in Resource-Constrained Environments

The finding that teacher creativity constituted the primary enabling mechanism for STEM implementation challenges the prevalent infrastructure-determinism in STEM education policy discourse (Shernoff et al., 2017). Conventional arguments frame physical laboratory provision as a prerequisite for effective STEM instruction, implying that resource-constrained schools must await infrastructural investment before meaningful STEM integration can occur. The MTsS As'adiyah Kajuara case empirically refutes this determinism: high-TPACK educators successfully substituted virtual simulations and digital collaboration tools for physical resources, maintaining experimental inquiry as a core learning activity.

This finding is consistent with emerging literature on "low-cost STEM" or "frugal innovation in education" (Kayan-Fadlelmula et al., 2022) and carries significant policy implications for developing country educational contexts where physical infrastructure deficits are structural rather than temporary. The critical variable is not facility investment but teacher TPACK development target more tractable in the short term through targeted professional development programmes.

The Humanistic STEM Model: A Contribution to Society 5.0 Education

The most novel theoretical contribution of this study is the articulation of a "Humanistic STEM" model grounded in the specific institutional context of Indonesian Islamic education. Tavares et al. (2022) Society 5.0 framework calls for technological systems oriented toward human welfare and social problem-solving. The present findings suggest that Islamic educational values—emphasizing communal responsibility (ummah), justice (adl), and purposive action (amal saleh)—constitute an indigenous theoretical resource for instantiating Society 5.0's humanistic orientation within STEM pedagogy.

The zakat calculator prototype is the clearest illustration: here, technological competency (algorithmic programming) is placed explicitly in the service of religious obligation and social equity (ensuring accurate distribution of charitable wealth). This is not STEM education with an incidental Islamic context; it is STEM education whose normative orientation is constituted by Islamic values. This distinctive configuration suggests that the frequently proposed "STEAM" extension (adding Arts and Humanities to STEM) may be most powerfully realised not through generic humanities integration but through engagement with specific communities lived value systems.

Policy Implications and Limitations

The present findings support three principal policy recommendations. First, national STEM curriculum frameworks for madrasah education should explicitly incorporate mechanisms for local wisdom integration, recognising the pedagogical generativity of authentic community contexts. Second, teacher professional development investment should prioritise TPACK development—particularly the creative application of free digital simulation and collaboration platforms—as a more immediately scalable lever than physical laboratory provision. Third, the Humanistic STEM model identified here warrants systematic evaluation across diverse madrasah contexts to assess its generalisability.

The study's principal limitation is its single-site case study design, which prioritises contextual depth over breadth and precludes statistical generalisation. The 25% critical thinking improvement, while triangulated across multiple data sources, derives from a comparative assessment conducted within one institution and should be interpreted as indicative rather than definitive. Future research should pursue multi-site comparative case studies, longitudinal designs tracking students' STEM learning trajectories, and mixed methods designs enabling statistical validation of critical thinking gains across larger samples.

4. CONCLUSION

This study has demonstrated that STEM integration at MTsS As'adiyah Kajuara constitutes a genuine catalyst for learning revolution within the dual context of Industry 4.0 and Society 5.0. Four substantive conclusions are drawn. First, STEM integration produced measurable and pedagogically significant improvements in critical thinking, with a documented 25% average gain across problem analysis, creative solution generation, and collaborative performance dimensions—empirical evidence that interdisciplinary, design-oriented instruction can overcome the entrenched limitations of conventional madrasah pedagogy. Second, the EDP-structured STEM projects enabled students to develop locally grounded technological innovations that integrated Islamic jurisprudential content with computational and engineering methods, providing an empirical proof-of-concept for the Humanistic STEM model proposed in this paper. Third, in the absence of adequate physical laboratory infrastructure, educators' high TPACK—specifically their capacity to deploy virtual simulation platforms and digital collaboration tools pedagogically—emerged as the primary enabling mechanism for

STEM implementation, challenging infrastructure-deterministic assumptions in STEM education policy. Fourth, the integration of Islamic values and local community needs within STEM pedagogy produced a contextually distinctive learning model that operationalises Society 5.0's human-centric technological vision in an Islamic educational framework.

These conclusions carry both theoretical and practical significance. Theoretically, they extend constructivist, TPACK, and situated learning frameworks into a distinctive madrasah context while contributing a novel Humanistic STEM construct to the STEM education literature. Practically, they offer an evidence-based reference model for madrasah curriculum reform, teacher professional development policy, and educational technology investment in Indonesia's religious school sector—a sector serving millions of students whose access to high-quality STEM education will be consequential for the nation's trajectory in the digital economy. As Indonesia navigates the complex interplay of Industry 4.0 and Society 5.0 demands, the madrasah system—historically positioned at the intersection of religious tradition and national development—possesses distinctive assets that STEM integration can activate. The learning revolution is not merely possible within these institutions; with appropriate pedagogical design, teacher development, and policy support, it is already underway.

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