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An Empirical Framework for Interdisciplinary Science Project Implementation in Indonesian Vocational Schools

Devy Lestari

devylestari@mail.unnes.ac.id

Universitas Negeri Semarang

Sri Kadarwati

Universitas Negeri Semarang

Muhamad Imaduddin

University of Bremen

Litasari Aldila Aribowo

Universitas Negeri Semarang

Siti Ekowati Rusdini

Universitas Negeri Semarang

Ariyatun Ariyatun

Universitas Negeri Jakarta

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Abstract

Interdisciplinary science projects are increasingly important in vocational education, yet empirical evidence remains limited on how interdisciplinary integration is enacted across different school contexts. This study addresses this gap by developing a multisite empirical framework that captures variations and developmental patterns of interdisciplinary project implementation in Indonesian vocational schools. A qualitative-dominant multisite study was conducted across 20 vocational schools in Semarang, Indonesia, using teacher survey responses, project documents, assessment evidence, and field clarification notes. Data were analyzed through thematic coding, rubric-based scoring, cross-case comparison, typology construction, and framework development. The findings revealed substantial variation in implementation, forming a four-level developmental continuum: technical-administrative, multidisciplinary, vocational-contextual interdisciplinary, and systemic-integrative. The overall implementation score was 2.82 out of 4.00, indicating that most schools were transitioning from multidisciplinary practices toward more coherent interdisciplinary enactment. Project design structure emerged as the strongest dimension, whereas epistemic integration was the weakest. Qualitative evidence showed that although project activities were generally well organized, scientific concepts, social and environmental issues, and vocational knowledge were frequently connected only at the activity or thematic level rather than through explicit conceptual integration. Assessment similarly tended to prioritize products, participation, reports, and presentations over interdisciplinary reasoning. More advanced implementation occurred when vocational contexts served as epistemic bridges connecting scientific knowledge with authentic problems and when teacher collaboration, school leadership, facilities, time allocation, and coordination provided systemic support. The resulting framework offers an empirically grounded model for diagnosing and advancing interdisciplinary project-based learning in vocational education.

1. Introduction

Vocational education is increasingly positioned beyond preparing students for immediate occupational tasks. It is expected to develop students' capacity to interpret, connect, and apply knowledge in complex workplace and societal contexts (Baartman & Bruijn, 2011; Wheelahan et al., 2025). Contemporary vocational problems are rarely technical in isolation; they require scientific reasoning, social understanding, environmental awareness, economic judgment, collaboration, and context-sensitive decision-making (López & López, 2020; Mcgrath et al., 2020). Therefore, learning designs should bridge conceptual knowledge and practical action, enabling students to understand both how occupational practices are performed and why they matter in broader professional, social, and environmental contexts (Wheelahan, 2015; Karaca-Atik et al., 2023). Vocational education should not be reduced to narrow skills training because students need conceptual, theoretical, and transferable knowledge to critically understand work practices and participate in occupational and societal debates (Wheelahan et al., 2025). Recent literature also emphasizes transversal competences, social participation, and knowledge-based capability as essential for vocational learning amid changing labour markets and complex forms of work (Xu, Zhang, Philbin, & Guo, 2022). Thus, vocational schools should serve as learning spaces that

meaningfully connect technical competence, disciplinary knowledge, social awareness, transversal skills, and workplace relevance.

Project-based learning (PjBL) has been widely discussed as a pedagogical approach that can connect conceptual knowledge, vocational practice, workplace relevance, and real-world problem solving. In vocational education, this connection is important because students are expected not only to produce technical outputs, but also to understand the scientific, social, environmental, and economic considerations underlying vocational practices. PjBL is commonly characterized by student autonomy, constructive investigation, goal setting, collaboration, communication, reflection, and engagement with real-world practices (Kokotsaki, Menzies, & Wiggins, 2016). Reviews and meta-analyses have reported that PjBL can improve academic achievement, engagement, higher-order thinking, and meaningful learning when projects are structured around authentic problems, inquiry processes, and clear learning goals (C. Chen & Yang, 2019; Guo, Saab, Post, & Admiraal, 2020; Sánchez-garcía & Reyes-de-cózar, 2025). However, the effectiveness of PjBL did not depend merely on the existence of project activities. PjBL research has strongly focused on outcomes and measurement, while less attention has been given to the structural and contextual conditions that shape implementation (Boon, Orozco, & Sivakumar, 2022; Sukack et al., 2022). This gap is particularly important in vocational education because project quality depends on the alignment among disciplinary knowledge, vocational relevance, assessment practices, teacher collaboration, and school-level support. Therefore, examining how interdisciplinary science projects are designed, integrated, assessed, and institutionally supported is necessary for understanding the quality of their implementation in vocational schools.

The main research problem addressed in this study arises from the gap between the promise of interdisciplinary project-based learning and the complexity of implementing it in vocational schools. Real-world problems require students to integrate knowledge from different domains, yet school-based projects may remain fragmented, activity-oriented, or limited to product completion. Interdisciplinary learning requires the integration of concepts, methods, and perspectives from multiple fields to construct a more comprehensive understanding of complex phenomena (Klein, 2008; Spelt, Biemans, Tobi, Luning, & Mulder, 2009). In science education, this discourse has been strongly developed through integrated STEM education. A framework linking scientific inquiry, engineering design, technological literacy, and mathematical thinking has been proposed to strengthen instructional integration (Kelley & Knowles, 2016). Such integration requires a coherent instructional design rather than the mere aggregation of separate subject areas (English, 2016). Nevertheless, most integration studies still focus on STEM, while the integration of natural sciences and social sciences in vocational project-based learning remains less systematically examined.

A general solution to this problem is to examine project implementation not only as a teaching method, but also as a process of curriculum enactment. Curriculum reform does not automatically translate into classroom practice. Written curriculum is interpreted, adapted, and negotiated by teachers within particular institutional, material, and cultural conditions (Remillard & Heck, 2014). Teacher agency, leadership support, facilities, time allocation, collaboration patterns, assessment systems, and school

culture influence how curricular ideas are enacted in practice. Recent work on teacher agency also reinforces that teachers' capacity to enact curriculum change is shaped by the interaction between individual professionalism and contextual resources, constraints, and institutional culture (Z. Chen, 2024). Therefore, the central issue is not merely whether schools implement projects, but how projects are designed, how knowledge domains are integrated, how assessment is aligned with learning goals, and how school ecosystems support or constrain implementation.

In the Indonesian vocational school context, interdisciplinary science projects are increasingly relevant because vocational learning requires students to connect scientific concepts with social, economic, environmental, and workplace-related problems. Project-based learning in science education can support this connection when students engage in scientific practices, authentic inquiry, collaboration, reflection, and real-world problem solving (Markula & Aksela, 2022). However, such projects require careful pedagogical enactment. Interdisciplinary learning should involve meaningful content integration, problem-centered learning, inquiry-based learning, design-based learning, and cooperative learning, rather than the mere aggregation of separate subject areas (Thibaut et al., 2018). Therefore, interdisciplinary science projects may become meaningful when students are guided to connect scientific concepts with social contexts and vocational problems through coherent project design, inquiry activities, and contextual assessment. Conversely, they may remain fragmented when knowledge domains are only placed side by side or when assessment emphasizes product completion rather than integrated reasoning. This risk is important because effective project-based learning requires alignment among learning objectives, instructional activities, and assessment practices (Zhao, Zhao, & Li, 2023).

Three components are particularly important for strengthening interdisciplinary science project implementation: epistemic integration, assessment alignment, and institutional ecosystem support. Epistemic integration is essential because interdisciplinary learning requires students to connect concepts, methods, and perspectives across knowledge domains rather than merely placing different subjects side by side (Thibaut et al., 2018). Assessment alignment is equally important because project-based learning should align intended learning goals, learning activities, and assessment practices, particularly when students are expected to demonstrate integrated reasoning rather than only produce final artifacts (Zhao et al., 2023). In interdisciplinary science projects, assessment should therefore capture not only product quality, but also inquiry processes, conceptual integration, reflection, vocational relevance, and social value. Without aligned assessment, interdisciplinary learning may become superficial because students may be rewarded for producing artifacts rather than for demonstrating interdisciplinary reasoning. Institutional ecosystem support is also necessary because project-based learning requires teacher collaboration, time management, resources, and sustained school-level support for implementation (Markula & Aksela, 2022).

Empirical studies in Indonesian vocational schools have begun to identify challenges related to interdisciplinary science project implementation. Chemistry teachers have been reported to face difficulties in integrating cross-disciplinary content, designing contextual projects, collaborating with fellow teachers, and developing appropriate assessment practices in vocational school projects (Lestari,

Oktiani, Lutfianasari, & Imaduddin, 2025). The importance of fostering critical thinking skills among vocational high school students, particularly in technical fields, has likewise been emphasized (Lestari, Haryani, & Sumarti, 2020). These studies provide an important foundation for understanding why interdisciplinary and competence-oriented learning is needed in vocational schools. However, they mainly address teacher perspectives, implementation challenges, strategic solutions, or student thinking skills. They have not yet explained, through a multisite empirical analysis, how interdisciplinary science projects are enacted across different vocational schools, how levels of epistemic integration vary across project designs, how assessment practices support or weaken interdisciplinary reasoning, and how school-level conditions shape implementation quality. Therefore, a framework-oriented multisite study is needed to move beyond descriptions of challenges or isolated outcomes toward an explanation of implementation patterns across diverse vocational contexts.

Building on the gap identified above, this study aims to construct an empirical framework for interdisciplinary science project implementation in Indonesian vocational schools. The novelty of this study lies in its multisite analysis of 20 public and private vocational schools and its focus on four interrelated dimensions of implementation quality, i.e., project design structure, epistemic integration, assessment alignment, and school ecosystem support. Unlike studies that examine project implementation mainly through teacher perceptions, isolated challenges, or learning outcomes, this study conceptualizes interdisciplinary science project implementation as a school-level enactment process that varies across institutional and vocational contexts. Accordingly, the study was guided by four research questions: how interdisciplinary science projects are implemented in terms of design, integration, assessment, and ecosystem support; what levels and patterns of epistemic integration are reflected in project implementation; what factors support or constrain implementation quality; and what empirical framework can explain interdisciplinary science project implementation in Indonesian vocational education. By constructing implementation typologies and an empirical framework from cross-case evidence, this study contributes an explanatory model for understanding how interdisciplinary project-based learning is designed, enacted, assessed, and institutionally supported in vocational schools.

2. Methods

2.1 Research Design

This study employed a qualitative-dominant multisite design with an exploratory–analytical orientation. This design was selected to construct an empirical framework explaining how interdisciplinary science projects are designed, enacted, assessed, and supported in Indonesian vocational schools. A multisite qualitative design is appropriate for examining complex educational phenomena across bounded institutional contexts and identifying both within-case particularities and cross-case patterns (Joyce et al., 2019; Chan & Hedges, 2022; Lu & Ben-michael, 2023). In this study, each vocational school was treated as a bounded case, while the overall analysis focused on patterns of interdisciplinary science project implementation across schools.

This design was also grounded in the view that curriculum implementation is not a direct transfer of policy into practice, but a process of interpretation, adaptation, and enactment within specific institutional, cultural, material, and professional conditions (Alvunger, 2024; Golding, 2024). Therefore, interdisciplinary science project implementation was treated as a school-level curriculum enactment process rather than as a uniform curricular practice. The primary unit of analysis was the school-level implementation of interdisciplinary science projects. To examine implementation quality systematically, the analysis used four predefined dimensions derived from literature on project-based learning, interdisciplinary learning, authentic assessment, and curriculum enactment: project design structure, epistemic integration, assessment alignment, and school ecosystem support (Kurup et al., 2021; Swist et al., 2025; Kong et al., 2026).

2.2 Research Sites and Participants

The study involved 20 public and private vocational schools in Semarang, Indonesia. They provides vocational schools with diverse institutional characteristics and vocational fields, allowing the study to examine variation in interdisciplinary science project implementation across multiple school settings. The participating schools represented engineering, automotive, electronics, software development, logistics, hospitality, culinary arts, beauty and spa, fashion, accounting, office management, marketing, visual communication design, animation, and social care. This diversity enabled comparison of whether interdisciplinary science projects were implemented as general projects across majors or adapted to specific vocational fields.

The participants of this study were teachers involved in designing or implementing interdisciplinary science projects, including science-related teachers and teachers connected to vocational programs. A total of 22 teacher responses were obtained from 20 schools. Two schools provided more than one response, and these were treated as complementary information within the same school case rather than as separate cases. To protect institutional and individual identities, schools were anonymized using codes from S01 to S20. These codes were used throughout data organization, analysis, and reporting.

2.3 Data Sources

Data were obtained from three sources: teacher survey responses, project-related documents, and field clarification notes. Using multiple data sources strengthened credibility by enabling triangulation across reported practices, written project designs, assessment evidence, and contextual clarification (Ahmed, 2024; Joubert & Reid, 2024; Stanley & Robertson, 2024; Mirhosseini, 2025). Teacher responses were used to capture project themes, learning activities, integration of scientific concepts with social and vocational contexts, project adaptation across vocational majors, assessment strategies, teacher collaboration, supporting factors, and implementation challenges.

The project-related documents were analyzed to verify whether reported practices were reflected in written project designs and assessment structures. These documents included teaching modules, lesson plans, student worksheets, assessment rubrics, and documentation of student project activities or products. Document analysis is relevant in educational research because curriculum documents,

worksheets, rubrics, and institutional records provide stable evidence of how educational practices are designed, formalized, communicated, and assessed (Bowen, 2009). Field clarification notes were used when responses or documents required further explanation, particularly regarding interdisciplinary integration, teacher collaboration, assessment practices, and project differentiation across vocational majors.

2.4 Data Collection Procedure

Data collection was conducted through a structured multisite procedure. Schools were first identified and contacted to obtain access and permission for data collection. Teachers involved in interdisciplinary science project implementation were then invited to complete a structured survey containing closed and open-ended questions. The survey explored project design, integration between scientific concepts and social contexts, adaptation of projects to vocational majors, assessment practices, teacher collaboration, supporting conditions, and implementation constraints.

Schools were then requested to provide relevant supporting documents, including teaching modules, lesson plans, worksheets, assessment rubrics, and documentation of student projects. Clarification was conducted when teacher responses or documents were incomplete, ambiguous, or context-dependent. This clarification was carried out as a data-verification step through follow-up communication with teacher respondents to confirm project themes, project adaptation across vocational majors, teacher collaboration, assessment practices, and evidence of interdisciplinary integration. It was not treated as a separate interview, but as a procedure to improve the accuracy and consistency of school-level case descriptions. All data were organized by school code to allow systematic comparison across sites. A systematic data collection procedure is important in qualitative research to maintain transparency, consistency, and traceability between research questions, data sources, and analytical conclusions; in multisite case studies, this procedure is particularly important for preserving a clear chain of evidence across cases (Burnard, 2024). The overall research design and analytical procedure are presented in Fig. 1.

2.5 Data Analysis

Data analysis was conducted through six interrelated stages: data cleaning and case consolidation, descriptive school profiling, thematic coding, rubric-based scoring, cross-case comparison and typology construction, and empirical framework development. These stages were designed to move the analysis from descriptive mapping to conceptual explanation. This procedure is consistent with qualitative case study analysis, in which researchers first organize data within cases, compare patterns across cases, and then develop conceptual synthesis (Fendt, 2025; Habersang & Reihlen, 2025). The analytical workflow is presented in Fig. 2.

The analytical process followed principles of multisite case analysis and cross-case synthesis. Each school was first treated as an individual case, and the cases were then compared to identify recurring patterns and variations. Data organization, case matrices, rubric-based scoring, and descriptive

summaries were managed using Microsoft Excel. Qualitative coding was conducted manually using a codebook developed from the four analytical dimensions because the data consisted of school-level narratives and documents requiring contextual interpretation.

Data cleaning and case consolidation ensured that each school was treated as one analytical case. Duplicate responses from the same school were reviewed and integrated as complementary information. The data were organized into a case matrix covering school profile, project themes, project design, integration of scientific concepts with social and vocational contexts, assessment practices, teacher collaboration, supporting factors, constraining factors, and available documents. Descriptive school profiling then mapped school status, vocational majors, project types, document availability, teacher involvement, and evidence of implementation.

Thematic coding used both deductive and inductive strategies. Deductive coding was guided by four predefined analytical dimensions: project design structure, epistemic integration, assessment alignment, and school ecosystem support. Project design structure captured how project problems, learning stages, inquiry activities, vocational relevance, and outputs were organized. Epistemic integration captured how scientific concepts, social issues, environmental contexts, and vocational relevance were conceptually connected. Assessment alignment examined whether assessment practices evaluated interdisciplinary reasoning rather than only final products. School ecosystem support captured institutional conditions such as teacher collaboration, leadership, facilities, time allocation, and coordination. Inductive coding was then used to identify emerging patterns from the data, such as project uniformity across majors, limited cross-subject collaboration, product-oriented assessment, insufficient facilities, time constraints, and variation in teachers' understanding of interdisciplinary integration.

Rubric-based scoring was used to interpret implementation quality across cases. Each school was scored on four dimensions using a four-level rubric. Project design structure was assessed based on problem clarity, contextual relevance, project stages, inquiry activities, outputs, and vocational orientation. Epistemic integration was assessed based on whether scientific concepts, social issues, environmental contexts, and vocational relevance were separated, juxtaposed, conceptually connected, or synthesized in problem solving. Assessment alignment was assessed based on whether assessment focused only on final products or also included process, reflection, interdisciplinary reasoning, and vocational relevance. School ecosystem support was assessed based on teacher collaboration, leadership support, facilities, time allocation, and institutional coordination. Rubrics support analytical consistency because they clarify performance criteria and differentiate levels of quality (Roberts et al., 2020; Phuong et al., 2024).

Epistemic integration was interpreted through four analytical levels: separated disciplinary logic, additive integration, contextual integration, and epistemic synthesis. These levels were developed from deductive coding, school-level evidence, and cross-case comparison, and were informed by interdisciplinary learning literature, which emphasizes disciplinary grounding, integration, and critical awareness in using knowledge across domains (Mansilla & Duraisingh, 2007). Lower levels were assigned when scientific

and social dimensions were separated or merely placed side by side, while higher levels were assigned when scientific concepts, social issues, environmental contexts, and vocational relevance were jointly used to interpret problems and develop solutions. These levels supported thematic analysis and typology construction, not inferential statistical testing.

The scoring scale ranged from 1 to 4. A score of 1 indicated technical or fragmented implementation, in which projects were mainly administrative tasks, weakly integrated, product-oriented, and minimally supported by the school ecosystem. A score of 2 indicated multidisciplinary implementation, in which more than one knowledge domain was present but the conceptual connection among domains remained limited. A score of 3 indicated vocational–contextual interdisciplinary implementation, in which scientific concepts were meaningfully connected with social, environmental, and vocational contexts, although assessment or institutional support was not always fully aligned. A score of 4 indicated systemic–integrative implementation, in which project design, epistemic integration, assessment alignment, and school ecosystem support were mutually reinforcing.

The mean score for each school was calculated by averaging the scores across the four analytical dimensions. The overall mean score reported in the findings was calculated descriptively from all school-level mean scores. These scores were not used for inferential statistical testing, but as an analytical aid for systematic cross-case comparison and typology construction. The final implementation typology was not determined by numerical mean score alone. Instead, typology assignment combined rubric scores, thematic coding evidence, and cross-case interpretation. This procedure was used because schools with similar mean scores could show different implementation patterns depending on which dimensions were strong or weak. Therefore, rubric-based scoring provided a transparent basis for comparison, while the final typology was constructed through the integration of scoring results and qualitative evidence.

Cross-case comparison was then conducted using coded themes, case matrices, and rubric scores to identify recurring patterns across the 20 schools. Schools were grouped into four implementation typologies: technical/fragmented, multidisciplinary, vocational–contextual interdisciplinary, and systemic–integrative. Finally, the empirical framework was constructed by integrating findings from thematic coding, rubric-based scoring, and cross-case synthesis. This framework explains how interdisciplinary science project implementation is shaped by the interaction among project design structure, epistemic integration, assessment alignment, and school ecosystem support.

2.6 Trustworthiness and Ethical Consideration

Several strategies were used to enhance trustworthiness. Credibility was strengthened through triangulation of teacher responses, project documents, assessment rubrics, and field clarification notes. Dependability was supported through a systematic analytical procedure, including case consolidation, coding, rubric-based scoring, cross-case comparison, and typology construction. Confirmability was supported through an audit trail consisting of case matrices, coding notes, scoring records, clarification records, and typology decisions. Transferability was supported by providing detailed descriptions of

research sites, vocational fields, data sources, analytical dimensions, and implementation typologies (Enworo, 2023; Toepper, Troitschanskaia, & Thees, 2022).

The confidentiality of participating schools and teachers was maintained throughout the study. School names and teacher identities were anonymized using school codes from S01 to S20. Participation was based on institutional access and teachers' willingness to provide information related to interdisciplinary science project implementation. Data were used only for research purposes and reported in aggregate form. The study did not aim to evaluate individual teacher or school performance, but to understand implementation patterns and construct an empirical framework for strengthening interdisciplinary project-based learning in vocational education.

3. Results

3.1 School Contexts and Data Sources

The school profiles in Table 1 show that interdisciplinary science projects were enacted across heterogeneous vocational contexts. The participating schools differed in status, number of vocational majors, and areas of specialization, resulting in diverse project themes and outputs. The reported projects ranged from environmental products, renewable energy prototypes, ecosystem models, and household chemical products to disaster mitigation media, digital games, animation, and entrepreneurship-oriented products. This variation indicates that interdisciplinary science project implementation was not uniform across schools. In some cases, projects were implemented as general activities for all vocational majors, whereas in others, project themes and outputs were adapted to the specific characteristics of vocational fields.

Table 1
Profile of participating vocational schools and examples of interdisciplinary science projects

School Code	Status	Number of Vocational Majors	Main Vocational Fields	Examples of Interdisciplinary Science Projects Reported
S01	Private	5	Accounting, marketing, office management, software engineering, automotive	Ecoprint, dishwashing soap, hand sanitizer, hydroponics, Batik Jumputan
S02	Public	5	Accounting, office management, software/game development, tourism, marketing	Plant growth observation, simple ice cream, solar system model, local potential mapping
S03	Private	3	Software engineering, automotive, agribusiness	Fermented tape, solar-powered miniatures, aquascape
S04	Public	9	Electrical, mechanical, automotive, electronics, broadcasting	Renewable energy prototypes, solar panel systems, micro-hydro models
S05	Public	5	Software engineering, networking, multimedia, social care, caregiver	Disaster mitigation media, renewable energy prototype, recycled products
S06	Public	9	Software engineering, shipping, logistics, automotive, ship construction, welding	Tree-condition sensor, biopore infiltration hole, bubble-wrap waste products, portable solar panels
S07	Public	5	Building design, electricity, mechanical engineering, automotive, networking	Virgin coconut oil, solar-powered house miniature, simple generator
S08	Public	3	Visual communication design, animation, software/game development	Compost packaging, worm-themed game, animation on waste management
S09	Private	4	Culinary, fashion design, software engineering, visual communication design	Artificial ecosystem, energy audit, sociodrama
S10	Public	4	Accounting, online business/marketing, office management, software/game development	Batik Ciprat, environmental-geographical analysis
S11	Private	2	Fashion design, visual communication design	Marine aquarium ecosystem, land ecosystem
S12	Public	8	Information systems, construction, mechatronics, automotive, electronics, electricity	Floor cleaner, glass cleaner

School Code	Status	Number of Vocational Majors	Main Vocational Fields	Examples of Interdisciplinary Science Projects Reported
S13	Private	5	Electronics, mechatronics, automotive, machining, visual communication design	Reused bottle pots, ice cream, lemongrass carbol, power plant miniatures
S14	Public	5	Construction, electronics, electrical installation, machining, automotive	Herbal drinks, eco-enzyme soap, banana-peel shoe polish, sensor aquarium
S15	Private	2	Motorcycle engineering, computer networking	Soap, paraffin candles, mind map, observation report
S16	Public	5	Building design, electricity, electronics, automotive, architecture	Aquarium ecosystem, electric stove, speaker, aromatherapy candle
S17	Private	4	Computer networking, software engineering, accounting, office management	Disaster mitigation video, ice cream project
S18	Public	7	Electricity, mechanical engineering, electronics, automotive, animation, building design	Aquaponics, sprouts, hand soap, entrepreneurship project
S19	Public	4	Hospitality, fashion design, culinary, beauty and spa	Ecoprint, hazardous chemical identification, renewable energy tools
S20	Private	2	Multimedia, fashion design	Aromatherapy candle, independent student project proposal

Table 1 shows that interdisciplinary science project implementation occurred in heterogeneous vocational settings. Some schools implemented projects as general activities across majors, while others adapted project themes, outputs, or learning activities to specific vocational fields. This variation confirmed the relevance of using the school as the unit of analysis because implementation quality was shaped not only by teacher perception, but also by school-level conditions, vocational specialization, and available institutional support.

3.2 Rubric-Based Scoring of Interdisciplinary Science Project Implementation

To compare implementation quality across school cases, the study used the four-dimensional analytical rubric described in the Methods section. The rubric assessed four dimensions of interdisciplinary science project implementation: project design structure, epistemic integration, assessment alignment, and school ecosystem support. Each dimension was scored on a four-level scale from 1 to 4, with higher scores indicating stronger interdisciplinary enactment and more coherent implementation. The scoring

was not used for inferential statistical testing, but as an analytical aid for comparing school-level cases and constructing implementation typologies. As presented in Table 2, the schools displayed different score profiles across the four dimensions.

Table 2
Rubric-based scoring of interdisciplinary science project implementation across vocational schools

Code	Project Design Structure	Epistemic Integration	Assessment Alignment	School Ecosystem Support	Mean Score	Implementation Typology
S01	2	1	2	1	1.50	Technical–Administrative
S02	2	1	3	2	2.00	Technical–Administrative
S03	3	2	3	2	2.50	Multidisciplinary
S04	4	4	3	4	3.75	Systemic–Integrative
S05	3	3	3	3	3.00	Vocational–Contextual Interdisciplinary
S06	4	4	3	4	3.75	Systemic–Integrative
S07	3	3	3	3	3.00	Vocational–Contextual Interdisciplinary
S08	4	4	4	4	4.00	Systemic–Integrative
S09	2	1	2	2	1.75	Technical–Administrative
S10	3	3	3	3	3.00	Vocational–Contextual Interdisciplinary
S11	1	1	2	1	1.25	Technical–Fragmented
S12	3	2	4	2	2.75	Multidisciplinary
S13	3	3	3	3	3.00	Vocational–Contextual Interdisciplinary
S14	4	4	3	4	3.75	Systemic–Integrative
S15	3	2	3	2	2.50	Multidisciplinary
S16	4	4	4	4	4.00	Systemic–Integrative
S17	2	2	2	2	2.00	Multidisciplinary

Code	Project Design Structure	Epistemic Integration	Assessment Alignment	School Ecosystem Support	Mean Score	Implementation Typology
S18	3	3	3	3	3.00	Vocational–Contextual Interdisciplinary
S19	3	3	2	3	2.75	Vocational–Contextual Interdisciplinary
S20	3	3	3	4	3.25	Vocational–Contextual Interdisciplinary

Table 2 shows substantial variation in implementation quality across schools. Schools with higher mean scores generally demonstrated stronger coherence among project design, epistemic integration, assessment alignment, and school ecosystem support. For example, schools in the systemic–integrative category showed stronger integration between scientific concepts, social or environmental contexts, vocational relevance, assessment practices, and institutional support. In contrast, schools with lower scores tended to show fragmented project design, weak conceptual integration, product-oriented assessment, or limited ecosystem support. Therefore, the typology column should not be interpreted as a purely numerical classification, but as a qualitative interpretation derived from the combination of rubric-based scoring and cross-case evidence.

The overall mean score was 2.82 out of 4.00, indicating that interdisciplinary science project implementation was generally in transition from multidisciplinary practice toward interdisciplinary enactment. However, the four analytical dimensions did not develop equally. As shown in Table 3, project design structure obtained the highest mean score, whereas epistemic integration obtained the lowest. This indicates that most schools had already implemented project activities, but the conceptual connection among scientific concepts, social issues, environmental contexts, and vocational relevance remained uneven.

Table 3
Summary of rubric-based scoring across analytical dimensions

Analytical Dimension	Mean Score	Interpretation
Project Design Structure	2.95	Most schools implemented project activities, but the complexity and vocational relevance varied.
Epistemic Integration	2.65	This was the weakest dimension; several schools still showed limited conceptual connection among scientific, social, environmental, and vocational dimensions.
Assessment Alignment	2.90	Assessment was generally present, but not all rubrics explicitly assessed interdisciplinary reasoning.
School Ecosystem Support	2.80	Support varied depending on teacher collaboration, facilities, leadership, and coordination.
Overall Mean	**2.82**	Implementation was in transition from multidisciplinary practice toward interdisciplinary enactment.

The scoring results showed that the major challenge was not the absence of project-based learning, but the depth and coherence of interdisciplinary implementation. In several schools, project activities were present, but scientific concepts, social issues, environmental concerns, and vocational contexts were not always connected as an integrated learning experience. Therefore, interdisciplinary science projects need to be analyzed as curriculum enactment processes that require coherent design, epistemic integration, aligned assessment, and school ecosystem support.

3.3 Typology of Interdisciplinary Science Project Implementation

Based on rubric-based scoring, thematic coding, and cross-case comparison, four implementation typologies were identified. As shown in Table 4, schools were distributed across technical–administrative or fragmented implementation, multidisciplinary implementation, vocational–contextual interdisciplinary implementation, and systemic–integrative implementation

Table 4
Distribution of implementation typologies

Implementation Typology	Number of Schools	Percentage (%)
Technical–Administrative / Fragmented	4	20
Multidisciplinary	4	20
Vocational–Contextual Interdisciplinary	7	35
Systemic–Integrative	5	25
Total	**20**	**100**

The distribution in Table 4 indicated that the largest proportion of schools was located in the vocational–contextual interdisciplinary category. This suggested that vocational contexts had begun to function as a bridge for connecting scientific concepts, social issues, environmental concerns, and workplace-related learning. However, the presence of technical–administrative and multidisciplinary categories indicated that not all schools had reached genuine interdisciplinary implementation.

To visualize this developmental pattern, Fig. 3 presents the continuum of interdisciplinary science project implementation typologies. The figure shows that implementation quality progresses from fragmented administrative practice to systemic interdisciplinary learning. Movement from left to right represents increasing levels of epistemic integration, vocational contextualization, assessment alignment, and school ecosystem support.

As illustrated in Fig. 3, the four typologies represent analytically derived levels of implementation maturity. The typology was constructed through cross-case synthesis, in which school-level cases were compared to identify recurring patterns, variations, and relationships across the four analytical dimensions (Miles, Huberman, & Saldana, 2014). Its conceptual interpretation was informed by studies on interdisciplinary competence and interdisciplinary project-based learning, which emphasize disciplinary grounding, integration, critical awareness, collaboration, authenticity, and creative problem solving (Brassler & Dettmers, 2017; Mansilla & Duraisingh, 2007; Warr & West, 2020). It was also informed by recent work on project-based learning implementation and evaluation, which highlights the importance of coherent project design, assessment models, contextual adaptation, and institutional commitment in sustaining high-quality implementation (Ram et al., 2024). Table 5 therefore clarifies the core characteristics, evidence patterns, main limitations, and development directions of each typology.

Table 5
Characteristics of interdisciplinary science project implementation typologies

Typology	Core Characteristics	Evidence Pattern	Main Limitation	Development Direction
Type 1. Technical–Administrative / Fragmented	Projects are conducted mainly as curriculum tasks. Scientific and social dimensions are often separated by semester, topic, or teacher focus.	Projects exist, but integration is weak. Assessment focuses on products, procedures, or task completion.	Interdisciplinary integration is superficial or absent.	Strengthen joint planning and redesign projects around shared science–social–vocational problems.
Type 2. Multidisciplinary	Scientific and social dimensions are present but still placed side by side.	Projects include science concepts, social interaction, economic value, environmental issues, or communication, but the links are not always explicit.	Students are not consistently guided to connect knowledge domains conceptually.	Move from additive integration to explicit epistemic connections.
Type 3. Vocational–Contextual Interdisciplinary	Projects are linked to vocational majors or workplace-related contexts.	Projects are adapted to technology, logistics, automotive, beauty, hospitality, creative industry, or technical fields.	Assessment does not always measure interdisciplinary reasoning.	Develop interdisciplinary rubrics and strengthen collaboration with vocational teachers.
Type 4. Systemic–Integrative	Project design, science–social integration, vocational contextualization, assessment, and school support are mutually reinforcing.	Projects involve planning stages, vocational adaptation, cross-subject collaboration, reports, presentations, reflection, and rubrics.	Sustainability across school years remains a challenge.	Institutionalize collaborative planning and develop reusable project models.

The interpretation of the four typologies was conceptually grounded in literature that distinguishes interdisciplinary learning from the mere co-presence of multiple subject areas. Interdisciplinary learning requires students to connect disciplinary contributions, integrate perspectives, and use knowledge across domains to address complex problems, rather than simply placing separate topics side by side (Brassler & Dettmers, 2017; Mansilla & Duraisingh, 2007; Warr & West, 2020). Within this lens, the technical–administrative type was characterized by weak epistemic integration and limited ecosystem

support, as seen in S01 and S02, where project implementation was still organized around separated disciplinary logic or standardized across majors. The multidisciplinary type represented a transitional form, as illustrated by S03, where scientific, environmental, cultural, and economic elements were present but not yet consistently integrated. The vocational–contextual interdisciplinary type emerged when vocational majors became contextual bridges between scientific concepts and social or workplace-related issues, as shown in S06, where projects were adapted to software, logistics, and automotive contexts. This interpretation is consistent with vocational competence literature, which emphasizes the integration of knowledge, skills, attitudes, workplace relevance, and contextual judgment (Baartman & Bruijn, 2011; Billett, 2020). The systemic–integrative type represented the strongest implementation, as reflected in S04 and S08, where project stages, vocational adaptation, cross-subject collaboration, assessment, and institutional support were more coherently organized. These findings indicate that strong interdisciplinary science project implementation requires coherence among project design, knowledge integration, assessment alignment, and school ecosystem support, as also emphasized in studies on project-based learning implementation and teaching–learning–assessment alignment (Lam, Cheng, & Choy, 2010; Markula & Aksela, 2022; Zhao et al., 2023).

3.4 Epistemic Integration and Assessment Alignment

The lowest mean score in Table 3 indicates that epistemic integration was the most critical challenge in interdisciplinary science project implementation. To clarify this finding, Table 6 presents four levels of epistemic integration identified across the school cases. These levels describe how scientific concepts, social issues, environmental contexts, and vocational relevance were connected within project activities.

Table 6
Levels of epistemic integration in interdisciplinary science projects

Level	Category	Main Characteristics	Example Pattern
1	Separated disciplinary logic	Scientific and social dimensions are separated by semester, topic, or teacher focus.	Science-oriented activities and social-oriented activities are implemented separately.
2	Additive integration	Scientific and social dimensions are both present but not conceptually connected.	A science product is linked to teamwork, selling activities, or social values without explicit conceptual integration.
3	Contextual integration	Scientific concepts are connected with environmental, economic, social, or vocational contexts.	Renewable energy projects include scientific principles, community needs, and workplace relevance.
4	Epistemic synthesis	Scientific, social, environmental, and vocational knowledge are jointly used to understand problems and develop solutions.	Energy, environment, economy, vocational expertise, communication, and product development are integrated in one project cycle.

As shown in Table 6, lower-level integration reflected fragmented or additive logic, whereas higher-level integration reflected contextual integration and epistemic synthesis. Several schools remained at lower

levels because project content was organized by semester, chapter, or disciplinary focus. In contrast, stronger cases used vocational problems as integrative anchors. S16 connected chemistry, physics, biology, entrepreneurship, communication, decision-making, and marketing across different interdisciplinary science projects. Similarly, S18 connected biological systems, chemical products, energy use, spatial connectivity, social interaction, and economic behavior through projects such as water spinach–catfish aquaponics, plant growth observation through sprout cultivation, food chemistry through ice-cream production, chemical formulation through candle and hand-soap making, and entrepreneurship-oriented product development.

Assessment alignment also varied across schools. Although many schools reported using rubrics, assessment practices did not always explicitly measure interdisciplinary reasoning. As shown in Table 7, assessment practices ranged from product-oriented assessment to authentic aligned assessment.

Table 7
Patterns of assessment alignment in interdisciplinary science projects

Assessment Pattern	Characteristics	Interpretation
Product-oriented assessment	Focuses on product quality, task completion, or procedural accuracy.	Integration may become superficial because reasoning is not assessed.
Process-and-product assessment	Assesses participation, collaboration, report, presentation, and product.	Stronger than product-only assessment, but not necessarily interdisciplinary.
Interdisciplinary assessment	Includes criteria on conceptual connection, contextual explanation, and vocational relevance.	Supports interdisciplinary reasoning.
Authentic aligned assessment	Assesses process, product, reflection, integration, vocational relevance, and social value.	Strongest alignment with interdisciplinary science project goals.

Table 7 summarizes the assessment alignment patterns derived from rubric-based scoring and cross-case interpretation. The interpretation was informed by authentic assessment literature, which emphasizes alignment among task, context, criteria, performance processes, and expected outcomes, as well as interdisciplinary assessment literature, which highlights the need to assess disciplinary grounding, integration, and critical awareness in students' work (Gulikers, Bastiaens, Kirschner, Bastioens, & Kirschner, 2004). Within this lens, S08 showed more systematic assessment through project rubrics, report rubrics, teacher observation, student products, written reports, consultation records, and project documentation. S12 also used varied assessment forms, including performance, label, product, self-, and peer assessment. However, varied assessment evidence did not necessarily indicate strong interdisciplinary alignment. In several cases, assessment still emphasized product quality, participation, presentation, or procedural completion rather than students' ability to explain the integration among scientific concepts, social issues, environmental contexts, and vocational relevance. This finding supports the need for assessment criteria that explicitly capture interdisciplinary reasoning,

as alignment among teaching, learning, and assessment is critical in project-based learning implementation (Zhao et al., 2023).

3.5 Determinants of Implementation Quality and Empirical Framework

High-quality project-based learning requires more than well-designed student tasks. Its implementation is shaped by the interaction among teacher collaboration, institutional support, resource availability, time allocation, student readiness, vocational relevance, and assessment alignment. Within this perspective, the cross-case analysis in this study identified several enabling and constraining factors that shaped the quality of interdisciplinary science project implementation. These factors are summarized in Table 8.

Table 8
Supporting and constraining factors in interdisciplinary science project implementation

Dimension	Supporting Factors	Constraining Factors
Teacher collaboration	Collaboration among science-related teachers, general subject teachers, and vocational teachers	Collaboration is incidental or not systematically planned
School support	Funding, flexible policy, facilities, leadership support, and display spaces	Limited budget, limited laboratory/workshop access, and limited storage/display space
Vocational relevance	Project adaptation to majors, industry/workplace synchronization, and vocational teacher input	Projects are standardized across majors due to time, workload, or small class size
Time management	Sufficient project allocation and flexible scheduling	School events, dense curriculum, and limited project duration
Student readiness	High enthusiasm during practice, creativity, and group work	Low motivation, uneven participation, and lack of preparation
Assessment	Rubrics, reports, presentations, observation, and peer/self-assessment	Rubrics do not explicitly assess interdisciplinary reasoning

The evidence in Table 8 indicates that schools in the systemic–integrative category tended to have stronger ecosystem support. S14 developed projects from students' daily needs in the boarding school context and involved collaboration across general and vocational subjects. In contrast, S11 reported that project implementation did not run optimally because of limited time, low student motivation, weak collaboration, and additional teacher responsibilities. This contrast suggests that school ecosystem support is not peripheral, but a central condition that determines whether interdisciplinary science projects remain fragmented or develop into systemic interdisciplinary learning.

Based on the cross-case synthesis, this study proposes an empirical framework consisting of four interconnected dimensions: school ecosystem support, project design structure, epistemic integration, and assessment alignment. As shown in Fig. 4, school ecosystem support functions as an enabling

condition for collaboration, coordination, resources, and continuity. Project design structure determines whether students encounter authentic and vocationally relevant problems, because vocational learning is strengthened when students connect school-based knowledge with workplace practices and real-world problem situations (Bakker & Akkerman, 2011; Esmond, 2021; Halttunen, Dragin-jensen, Kylänpää, & Karkov, 2023). Epistemic integration determines whether scientific concepts, social issues, environmental contexts, and vocational relevance are merely placed side by side or jointly used to interpret and solve problems, which is central to interdisciplinary competence (Brassler & Dettmers, 2017; Mansilla & Duraisingh, 2007). Assessment alignment reinforces or weakens integration by determining what forms of learning are valued and documented. In vocational education, authentic assessment should reflect realistic work-related contexts, cognitive complexity, feedback, and the application of knowledge to practice rather than only product completion (Gulikers, Theo J. Bastiaens, Paul A. Kirschner, & Liesbeth Kester, 2008; Villarroel, Melipillan, Santana, & Aguirre, 2024).

4. Discussion

4.1 From Project Activity to Curriculum Enactment

Project-based learning in vocational schools should be understood not merely as the assignment of project tasks, but as a curriculum enactment process. In this perspective, a project becomes educationally meaningful when teachers interpret curricular expectations, organize inquiry activities, connect learning with vocational contexts, align assessment with intended learning goals, and mobilize school-level support. Curriculum enactment theory explains that curriculum is not simply transferred from policy documents into classroom practice, but interpreted and transformed through teachers' decisions, instructional materials, classroom interactions, and institutional condition (Remillard & Heck, 2014). Similarly, implementation research emphasizes that the quality and fidelity of implementation must be examined before claims about educational effectiveness are made (Donnell, 2008). This view is particularly relevant to PjBL because teachers may define and enact project-based learning differently across contexts, while school support, teacher motivation, project integrity, inquiry activities, collaboration, artefacts, presentation, and reflection all influence the quality of implementation (Lam et al., 2010; Markula & Aksela, 2022; Tamim & Grant, 2013).

The findings of this study support this interpretation. Although all participating schools reported implementing interdisciplinary science projects, implementation quality varied substantially across project design structure, epistemic integration, assessment alignment, and school ecosystem support. The typology presented in Table 4 and Table 5 shows that schools enacted projects at different levels of maturity. In lower-level cases, projects tended to operate as curriculum tasks, administrative requirements, or product-oriented activities, whereas higher-level cases showed stronger coherence among inquiry stages, vocational relevance, interdisciplinary knowledge integration, assessment practices, and school support. This pattern is consistent with research showing that high-quality PjBL depends on alignment among teaching, learning, and assessment, as well as on the connection between project elements, curricular design, and classroom practices (Farrow et al., 2024; Zhao et al., 2023). The

present study extends these discussions by showing that, in vocational interdisciplinary science projects, implementation quality is also shaped by epistemic integration, vocational contextualization, and school ecosystem support. Therefore, before evaluating whether interdisciplinary science projects improve student learning outcomes, it is necessary to examine whether they are actually enacted as interdisciplinary learning experiences rather than isolated assignments, product-oriented tasks, or administrative curriculum obligations.

4.2 Vocational Context as an Epistemic Bridge

A central contribution of this study is the identification of vocational context as an epistemic bridge. The strongest cases did not simply combine scientific and social topics in one project; rather, they used vocational problems as meaningful contexts through which students could connect scientific concepts, environmental issues, economic considerations, communication, and workplace relevance. This is evident in the vocational–contextual interdisciplinary and systemic–integrative categories, where project themes were adapted to software engineering, logistics, automotive, hospitality, beauty, creative industry, construction, and other vocational fields.

This finding is important because it expands the discussion of interdisciplinary learning beyond the conventional STEM integration framework. Integrated STEM literature emphasizes the importance of content integration, problem-centered learning, inquiry-based learning, design-based learning, and cooperative learning (Kelley & Knowles, 2016; Thibaut et al., 2018). However, interdisciplinary science projects in vocational schools require an additional layer of contextualization. Scientific concepts must be connected not only with technology or engineering design, but also with social meaning, economic value, environmental responsibility, and vocational practice (Baartman & Bruijn, 2011; Cremers et al., 2016; Pavlova, 2011). Therefore, vocational context becomes more than an application site; it becomes an epistemic mediator that helps students understand why scientific knowledge matters in occupational and societal situations (Bakker & Akkerman, 2011). This interpretation is consistent with recent vocational education literature arguing that vocational institutions matter not only for skills preparation, but also for connecting students with knowledge, occupational pathways, and local socio-economic contexts (Billett, 2020; Wheelahan et al., 2025).

4.3 Why Epistemic Integration Remained the Weakest Dimension

Epistemic integration is a key indicator of whether a project has moved beyond the simple combination of several topics. In interdisciplinary learning, students need to be guided to connect and synthesize knowledge across domains, not merely encounter different subjects within the same activity (Wang & Song, 2021). As shown in Table 3, epistemic integration had the lowest mean score among the four analytical dimensions. This finding is theoretically significant because it indicates that many schools were able to organize projects, but struggled to construct conceptual connections among scientific concepts, social issues, environmental contexts, and vocational relevance. In several cases, project activities existed, but the knowledge domains remained separated, juxtaposed, or only loosely

connected. This confirms that interdisciplinary learning cannot be achieved by placing multiple topics within the same activity. It requires deliberate instructional design that helps students synthesize knowledge across domains (Spelt et al., 2009).

This finding is aligned with research on interdisciplinary competence, which emphasizes that students need opportunities to identify disciplinary contributions, connect ideas across domains, and apply integrated understanding to complex problems (Wang & Song, 2021). It also resonates with recent discussions of cross-disciplinary learning, which argue that students must activate, transform, and integrate prior knowledge when making sense of unfamiliar problems across disciplinary boundaries (Guvenir & Bagli, 2019; Pope et al., 2021; Helker et al., 2022; Mat & Jamaludin, 2024). In the present study, lower-level implementation occurred when projects remained structured around separate subject logics or final products. Higher-level implementation occurred when teachers designed projects around contextual problems that required students to use scientific reasoning, interpret social consequences, consider environmental responsibility, and make practice-oriented vocational decisions. This interpretation is consistent with socio-scientific issue research, which positions science learning within socially relevant problems requiring reasoning and decision-making (Sadler, 2004; Zeidler & Nichols, 2009), sustainability competence literature, which emphasizes problem-solving and responsible action in complex sustainability challenges (Wiek, Withycombe, & Redman, 2011), and vocational competence literature, which conceptualizes competence as the integration of knowledge, skills, attitudes, and professional judgment in work-related contexts (Mulder, Weigel, & Collins, 2007). Thus, epistemic integration emerged not as a natural consequence of PjBL, but as a design achievement.

4.4 Assessment Alignment as a Hidden Mechanism of Interdisciplinary Quality

Assessment alignment is important because assessment criteria determine what forms of learning are valued in project-based activities. In interdisciplinary projects, assessment should not only evaluate products, but also students' ability to integrate concepts, contexts, and reasoning across domains (Mansilla & Duraisingh, 2007). The results also show that assessment alignment was a critical mechanism in determining the quality of interdisciplinary science project implementation. Although many schools reported the use of rubrics, Table 7 indicates that assessment practices often focused on product quality, participation, reports, or presentations rather than the quality of interdisciplinary reasoning. This suggests that assessment may become a hidden source of fragmentation. When assessment criteria reward only completion, neatness, or product performance, students may not be encouraged to demonstrate how scientific concepts, social issues, environmental contexts, and vocational relevance are connected.

This finding is consistent with recent studies emphasizing that assessment alignment plays a crucial role in project-based and authentic learning. Alignment among teaching, learning, and assessment has been shown to be essential for understanding how teachers implement PjBL under curriculum standards (Zhao et al., 2023). Similarly, authentic assessment literature emphasizes that meaningful assessment

should require students to perform tasks resembling real-world contexts (Koh, 2023; Killam et al., 2024; Salinas-navarro et al., 2024) and demonstrate knowledge, skills, and attitudes in use (Abramenka-lachheb & Siqueira, 2022; Juanda, 2022). In interdisciplinary science projects, this means that assessment should evaluate not only what students produce, but also how they investigate, justify, integrate, communicate, and reflect. Evidence from Table 7 therefore suggests that improving interdisciplinary science projects requires assessment rubrics that explicitly include epistemic integration, contextual reasoning, vocational relevance, and reflective explanation. Without such alignment, interdisciplinary learning risks remaining invisible in assessment even when it is intended in the curriculum.

4.5 Theoretical and Practical Contribution of the Empirical Framework

The empirical framework presented in Fig. 4 explains that strong interdisciplinary science project implementation is shaped by the interaction among school ecosystem support, project design structure, epistemic integration, and assessment alignment. This framework contributes to the literature by shifting the focus from PjBL effectiveness to PjBL enactment quality. Previous reviews have shown that PjBL can support academic achievement, engagement, and broader learning outcomes (C. Chen & Yang, 2019; Guo et al., 2020; Sánchez-garcía & Reyes-de-cózar, 2025). However, the present study shows that such potential depends on whether schools can build coherent implementation systems.

The framework also contributes to vocational education by showing that interdisciplinary science projects require institutional support, not only teacher creativity. School ecosystem support enables collaborative planning, access to facilities, time allocation, documentation, and coordination across subjects and vocational majors (Lam et al., 2010; Markula & Aksela, 2022). Project design structure translates curriculum expectations into authentic and vocationally relevant learning experiences (Cremers et al., 2016). Epistemic integration determines whether the project becomes interdisciplinary rather than merely multidisciplinary (Gulikers et al., 2004)Mansilla & Duraisingh, 2007). Assessment alignment determines whether integrated reasoning is valued and documented. These four dimensions explain why some schools remained at the technical–administrative level, while others developed systemic–integrative practices.

Practically, the findings suggest that schools need more than encouragement to “do projects.” They need project templates that explicitly connect scientific concepts with social, environmental, and vocational contexts; collaborative planning mechanisms involving science-related, vocational, and supporting subject teachers; and assessment rubrics that capture interdisciplinary reasoning rather than only product completion. The synthesis in Fig. 5 reinforces this improvement pathway by showing that weak epistemic integration and limited assessment alignment are the main bottlenecks, while vocational contextualization and ecosystem support are key levers for improvement.

Overall, this study argues that interdisciplinary science project implementation in vocational schools should be understood as a coherent pedagogical and institutional system. Its quality depends not on the

number of projects conducted, but on the extent to which projects are intentionally designed, epistemically integrated, authentically assessed, and institutionally supported.

5. Conclusion

This study concludes that interdisciplinary science project implementation in Indonesian vocational schools varies substantially across school contexts and cannot be judged merely by the presence of project activities. The findings identified four implementation typologies: technical–administrative, multidisciplinary, vocational–contextual interdisciplinary, and systemic–integrative. These typologies show a developmental continuum in which stronger implementation is characterized by coherent project design, meaningful vocational contextualization, teacher collaboration, aligned assessment, and school ecosystem support.

The most critical challenge was epistemic integration. Although many schools had implemented project-based activities, scientific concepts, social issues, environmental contexts, and vocational relevance were not always conceptually connected. Assessment alignment also remained a key limitation because many assessment practices still emphasized products, participation, reports, or presentations rather than interdisciplinary reasoning. The empirical framework proposed in this study therefore positions school ecosystem support, project design structure, epistemic integration, and assessment alignment as four interconnected dimensions that explain the quality of interdisciplinary science project implementation.

The findings suggest that strengthening interdisciplinary science projects in vocational schools requires more than assigning students to produce project outputs. Schools need collaborative planning mechanisms, project designs grounded in authentic vocational problems, assessment rubrics that explicitly evaluate interdisciplinary reasoning, and sustained institutional support. Future research should test and refine the proposed framework in broader regional or national contexts, incorporate classroom observation and student learning evidence, and examine how framework-based interventions influence students' interdisciplinary reasoning, vocational competence, and contextual problem-solving skills.

Declarations

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Ethics approval and consent to participate:

This study was approved by the Research Ethics Committee of Universitas Negeri Semarang through a Full Board Review, with ethical clearance number B/7708/UN37.3.1/KEP.00/2026. The study was conducted in accordance with the institutional ethical guidelines of the Research Ethics Committee of Universitas Negeri Semarang, referring to the seven WHO 2011 ethical standards and the 2016 Council for International Organizations of Medical Sciences guidelines for research involving human participants. Participation was voluntary, and informed consent was obtained from all teacher respondents. School and respondent identities were anonymized to protect confidentiality.

Consent to publish:

Not applicable. The manuscript does not contain identifiable personal data, images, or individual participant details.

Author Contribution

D.L. was responsible for conceptualization, research design, data analysis, empirical framework development, and writing the original draft. S.K. contributed to conceptual refinement, academic writing, and manuscript revision. M.I. contributed to the STEM, sustainability, and pedagogical dimensions of the study. L.A.A. contributed to the science education and interdisciplinary learning perspectives. S.E.R. contributed to the social, cultural, and environmental dimensions of the framework. A. contributed to the STEM and project-based learning perspectives. All authors contributed to reviewing and editing the manuscript, and all authors read and approved the final version.

Data Availability

The datasets generated and/or analysed during the current study are not publicly available due to confidentiality and anonymity considerations involving participating schools and teacher respondents but are available from the corresponding author on reasonable request.

References

1. Abramenka-lachheb V, de Siqueira A. Authentic Assessments Through the Lenses of Diversity, Equity, Inclusion, and Justice in a Fully Online Course. J Teach Learn Technol. 2022;11(1):18–36. https://doi.org/10.14434/jotlt.v11i1.34591.
2. Ahmed SK. The pillars of trustwothiness in qualitative research. J Med Surg Public Health. 2024;2:1–4. https://doi.org/10.1016/j.glmedi.2024.100051.
3. Alvunger D. Curriculum Making Across Sites of Activity in Upper Secondary School Vocational Education and Training: A Review of the Research in Sweden. Int J Res Vocat Educ Train (IJRVET).

2024;11(3):303–33. https://doi.org/https://doi.org/10.13152/IJRVET.11.3.1.

4. Azmi Z, N AA. Memahami Penelitian Kualitatif Dalam Akuntansi. Akuntabilitas: Jurnal Ilmu Akuntansi. 2018;11(1):159–68. https://doi.org/10.15408/akt.v11i1.6338.
5. Baartman LKJ, Bruijn E, De. Integrating knowledge, skills and attitudes : Conceptualising learning processes towards vocational competence. Educational Res Rev. 2011;6:125–34. https://doi.org/10.1016/j.edurev.2011.03.001.
6. Bakker A, Akkerman S. The Learning Potential of Boundary Crossing in the Vocational Curriculum - The Wiley Online Library. Rev Educ Res. 2011;81(2):132–69. https://doi.org/https://doi.org/10.1002/9781119098713.ch18.
7. Billett S. Perspectives on enhancing the standing of vocational education and the occupations it serves. J Vocat Educ Train. 2020;72(2):161–9. https://doi.org/10.1080/13636820.2020.1749483.
8. Boon M, Orozco M, Sivakumar K. Epistemological and educational issues in teaching practice-oriented scientific research: roles for philosophers of science. Eur J Philos Sci. 2022;12(16):1–23. https://doi.org/https://doi.org/10.1007/s13194-022-00447-z.
9. Brassler M, Dettmers J. (2017). How to Enhance Interdisciplinary Competence— Interdisciplinary Problem-Based Learning versus Interdisciplinary Project-Based Learning. Interdisciplinary J Problem-Based Learn, *11*(2).
10. Burnard KJ. Developing a robust case study protocol. Manage Res Rev. 2024;47(2):204–25. https://doi.org/10.1108/MRR-11-2021-0821.
11. Chan W, Hedges LV. Pooling Interactions Into Error Terms in Multisite Experiments. J Educational Behav Stat. 2022;47(6):639–65. https://doi.org/10.3102/10769986221104800.
12. Chen C, Yang Y. Revisiting the effects of project-based learning on students ' academic achievement: A meta-analysis investigating moderators. Educational Res Rev. 2019;26(January):71–81. https://doi.org/10.1016/j.edurev.2018.11.001.
13. Chen Z. An ecological approach to understanding the agency of novice EFL teachers without initial teacher education background EFL teachers without initial teacher education background. Lang Learn J. 2024;1–14. https://doi.org/10.1080/09571736.2024.2421505.
14. Cremers PHM, Wals AEJ, Wesselink R, Mulder M. at the interface between school and workplace. Learn Environ Res. 2016;19(3):309–34. https://doi.org/10.1007/s10984-016-9209-6.
15. Donnell CLO. Defining, Conceptualizing, and Measuring Fidelity of Implementation and Its Relationship to Outcomes in K – 12 Curriculum Intervention Research. Rev Educ Res. 2008;78(1):33–84. https://doi.org/10.3102/0034654307313793.
16. English LD. STEM education K-12: perspectives on integration. Int J STEM Educ. 2016;1–8. https://doi.org/10.1186/s40594-016-0036-1.
17. Enworo OC. Application of Guba and Lincoln ' s parallel criteria to assess trustworthiness of qualitative research on indigenous social protection systems. Qualitative Res J. 2023;23(4):372–84. https://doi.org/10.1108/QRJ-08-2022-0116.

18. Esmond B. Vocational teachers and workplace learning_ integrative, complementary and implicit accounts of boundary crossing. Stud Continuing Educ. 2021;43(2):156–73. https://doi.org/https://doi.org/10.1080/0158037X.2020.1767564.
19. Farrow J, Kavanagh SS, Samudra P, Pupik C. (2024). The promise of the project to student-centered learning: Connections between elements, curricular design, and practices of project based learning. *Teaching and Teacher Education*, *152*(October 2023), 104776. https://doi.org/10.1016/j.tate.2024.104776
20. Fendt J. Embracing emergence in qualitative meta-analysis: A guide to higher-order synthesis. Methodological Innovations. 2025;18(3):143–67. https://doi.org/10.1177/20597991251352414.
21. Golding J. Teachers, Learners and Edu-Business Co-Constructing Mathematics Curriculum Implementation : An Insider ' s Lens in Cross-Phase Longitudinal Research. Educ Sci. 2024;14(12):1–20. https://doi.org/https://doi.org/10.3390/educsci14121322.
22. Gulikers JTM, Bastiaens TJ, Kirschner PA, Bastioens TJ, Kirschner PA. A Five-Dimensional Framework for Authentic Assessment A Five-Dimensional Framework for Authentic Assessment. Education Tech Research Dev. 2004;52(3):67–86. https://doi.org/https://doi.org/10.1007/BF02504676.
23. Gulikers JTM, Theo J, Bastiaens PA, Kirschner, Liesbeth Kester. Authenticity is in the eye of the beholder_ student and teacher perceptions of assessment authenticity_ _ 60, 4. J Vocat Educ Train. 2008;60(4):401–12. https://doi.org/https://doi.org/10.1080/13636820802591830.
24. Guo P, Saab N, Post LS, Admiraal W. A review of project-based learning in higher education: Student outcomes and measures. Int J Educational Res. 2020;102:1–13. https://doi.org/10.1016/j.ijer.2020.101586.
25. Guvenir C, Bagli HH. The Potentials of Learning Object Design in Design Thinking Learning. Int Soc Markets Dev. 2019;4(2):1–34. https://doi.org/10.23860/MGDR-2019-04-02-03.
26. Habersang S, Reihlen M. Advancing Qualitative Meta- Studies (QMS): Current Practices and Re fl ective Guidelines for Synthesizing Qualitative Research. Organizational Res Methods. 2025;28(2):210–44. https://doi.org/10.1177/10944281241240180.
27. Halttunen T, Dragin-jensen C, Kylänpää C, Karkov A. Collaborative problem solving: A pedagogy for workplace relevance. Nordic J Vocat Educ Train. 2023;13(2):45–73. Volhttps://doi.org/10.3384/njvet.2242-458X.2313245. https://doi.org/NJVET.
28. Helker K, Lazendic-Galloway J, Bruns M, Reymen IMMJ, Vermunt JD. (2022). What do we need to consider when designing and researching student learning in chellenge-based learning? *50th Annual Conference in September 2022 WHAT*, 1961–1966. https://doi.org/10.5821/conference-9788412322262.1256
29. Joubert A, Reid M. Development of a framework for community health workers to contribute to interprofessional learning teams. Afr J Health Professions Educ. 2024;X(X):2–7. https://doi.org/https://doi.org/10.7196/ajhpe.2024.v16i3.384.

30. Joyce BL, Msn MJH, Gina R, Msn HJ, Assistant C, Rn VH, Beth AEJ. Using a quality improvement model to enhance community / public health nursing education. Public Health Nurs. 2019;36(6):847–55. https://doi.org/10.1111/phn.12656.
31. Juanda A. Classroom Management: How Important is Authentic Assessment of 21st Century Skills in Biology Education Students? Jurnal Penelitian Pendidikan IPA. 2022;8(1):188–94. https://doi.org/10.29303/jppipa.v8i1.1206.
32. Karaca-Atik A, Meeuwisse M, Gorgievski M, Smeets G. Uncovering important 21st-century skills for sustainable career development of social sciences graduates: A systematic review Ays. Educational Res Rev. 2023;39:1–15. https://doi.org/10.1016/j.edurev.2023.100528.
33. Kelley TR, Knowles JG. A conceptual framework for integrated STEM education. Int J STEM Educ. 2016;3(11):1–11. https://doi.org/10.1186/s40594-016-0046-z.
34. Killam LA, Camargo-Plazas P, Luctkar-flude M. Learner-Educator Co-creation: A Case for Enhancing Authentic Assessment in Nursing Education. Can J Scholarsh Teach Learn. 2024;15(1):1–22. https://doi.org/https://doi.org/10.5206/cjsotlrcacea.2024.1.15194.
35. Klein JT. Evaluation of Interdisciplinary and Transdisciplinary Research. Am J Prev Med. 2008;35(2S):116–23. https://doi.org/10.1016/j.amepre.2008.05.010.
36. Koh K. Designing Culturally Responsive Online Assessments for Equity-Deserving Students. Cult Pedagogical Inq. 2023;15(1):71–88. https://doi.org/https://doi.org/10.18733/cpi29712.
37. Kokotsaki D, Menzies V, Wiggins A. Improving Schools Project-based learning: A review of the literature. Improving Schools. 2016;19(3):267–77. https://doi.org/10.1177/1365480216659733.
38. Kong J, Liu J, Chen G, Zhao J, Chan CKK. Designing A Principle-Based Knowledge Building Environment for Collaborative Inquiry and Process Documentation in STEM Learning. J Comput Assist Learn. 2026;42(2):1–17. https://doi.org/https://doi.org/10.1002/jcal.70207.
39. Kurup PM, Yang Y, Li X, Dong Y. Interdisciplinary and Integrated STEM. Encyclopedia. 2021;1(4):1192–9. https://doi.org/https://doi.org/10.3390/encyclopedia1040090.
40. Lam S, Cheng RW, Choy HC. School support and teacher motivation to implement project-based learning. Learn Instruction. 2010;20(6):487–97. https://doi.org/10.1016/j.learninstruc.2009.07.003.
41. Lestari D, Haryani S, Sumarti S. (2020). Analysis of Critical Thinking Skills in Vocational High School Automotive Engineering Students. *Journal of Innovative Science Education*, *9*(1), 103–108. Retrieved from http://journal.unnes.ac.id/sju/index.php/jise
42. Lestari D, Oktiani R, Lutfianasari U, Imaduddin M, Solutions. JTK (Jurnal Tadris Kimiya), 1(June), 76–91. https://doi.org/https://doi.org/10.15575/jtk.v10i1.37830 1.
43. López IC, López BR. The relevance of transversal competences in vocational education and training: a bibliometric analysis. Empir Res Vocat Educ Train. 2020;12(12):1–19. https://doi.org/10.1186/s40461-020-00100-0.
44. Lu B, Ben-michael E. Is It Who You Are or Where You Are ? Accounting for Compositional Differences in Cross-Site Treatment Effect Variation. J Educational Behav Stat. 2023;48(4):420–53. https://doi.org/10.3102/10769986231155427.

45. Mansilla VB, Duraisingh ED. Targeted Assessment of Students' Interdisciplinary Work: An Empirically Grounded Framework Proposed. J High Educ. 2007;78(2):215–37.
46. Markula A, Aksela M. The key characteristics of project-based learning: how teachers implement projects in K-12 science education. Disciplinary Interdisciplinary Sci Educ Res. 2022;4(2):1–17. https://doi.org/https://doi.org/10.1186/s43031-021-00042-x.
47. Mat NC, Jamaludin KA. Effectiveness of Practices and Applications of Student-Centered Teaching and Learning in Primary Schools: A Systematic Literature Review. Int J Acad Res Progressive Educ Dev. 2024;13(3):1025–44. https://doi.org/10.6007/IJARPED/v13-i3/21733.
48. Mcgrath S, Ramsarup P, Zeelen J, Wedekind V, Allais S, Lotz-sisitka H, Wedekind V. Vocational education and training for African development: a literature review. J Vocat Educ Train. 2020;72(4):465–87. https://doi.org/10.1080/13636820.2019.1679969.
49. Miharja S. Perspektif baru penelitian konseling: metode kualitatif dan kuantitatif secara online. Sociocouns: J Islamic Guidance Couns. 2022;2(1):23–42. https://doi.org/10.35719/sjigc.v2i1.25.
50. Miles MB, Huberman AM, Saldana J. Qualitative data analysis: A methods sourcebook. 3rd ed. SAGE; 2014.
51. Mirhosseini S. (2025). *How do language education researchers attend to quality in qualitative studies ?* 99–115. https://doi.org/10.1017/S0261444824000053
52. Mulder M, Weigel T, Collins K. The concept of competence in the development of vocational education and training in selected EU member states: a critical analysis. J Vocat Educ Train. 2007;59(1):67–88. https://doi.org/https://doi.org/10.1080/13636820601145630.
53. Pavlova M. Fostering inclusive, sustainable economic growth development in learning cities through partnerships and green skill s. Int Rev Educ. 2011;64(3):339–54. https://doi.org/10.1007/s11159-018-9718-x.
54. Phuong H-Y, Nguyen A-T, Nguyen H-T, Pham T-T, Phan Q-T, Thanh-Thao Le. The Impact of Training Vietnamese EFL Learners for Self-Assessment on Writing Performance. Int J Instruction. 2024;17(2):237–58. https://doi.org/https://doi.org/10.29333/iji.2024.17214a.
55. Pope H, Frece A, De, Wells R, Borrelli R, Ajates R, Arnall A, Häsler B. Developing a Functional Food Systems Literacy for Interdisciplinary Dynamic Learning Networks. Front Sustainable Food Syst. 2021;5(November):1–13. https://doi.org/10.3389/fsufs.2021.747627.
56. Ram M, Cruz M, Lara-bercial PJ. (2024). education sciences Evaluation of the Implementation of Project-Based-Learning in Engineering Programs: A Review of the Literature. Educ Sci, *14*(1107).
57. Remillard JT, Heck DJ. Conceptualizing the curriculum enactment process in mathematics education. ZDM. 2014;46:705–18. https://doi.org/10.1007/s11858-014-0600-4.
58. Roberts MR, Cook M, Chao ICI. Exploring assessor cognition as a source of score variability in a performance assessment of practice-based competencies. BMC Med Educ. 2020;20(168):1–14. https://doi.org/https://doi.org/10.1186/s12909-020-02077-6.
59. Sadler TD. Informal reasoning regarding socioscientific issues_ A critical review of research - Sadler – 2004 - Journal of Research in Science Teaching - Wiley Online Library. J Res Sci Teach.

2004;41(5):513–36. https://doi.org/https://doi.org/10.1002/tea.20009.

60. Salinas-navarro DE, Vilalta-perdomo E, Michel-villarreal R, Montesinos L. Using Generative Artificial Intelligence Tools to Explain and Enhance Experiential Learning for Authentic Assessment. Educ Sci. 2024;14(83):1–24. https://doi.org/https://doi.org/10.3390/educsci14010083.
61. Sánchez-garcía R, Reyes-de-cózar S. (2025). Enhancing Project-Based Learning: A Framework for Optimizing Structural Design and Implementation — A Systematic Review with a Sustainable Focus. *Sustainability*, *17*(4978), 1–24. https://doi.org/https://www.mdpi.com/2071-1050/17/11/4978
62. Spelt EJH, Biemans HJA, Tobi H, Luning PA, Mulder M. Teaching and Learning in Interdisciplinary Higher Education: A Systematic Review. Educ Psychol Rev. 2009;21:365–78. https://doi.org/10.1007/s10648-009-9113-z.
63. Stanley SD, Robertson WB. Qualitative research in science education: A literature review of current publications. Eur J Sci Math Educ. 2024;12(2):175–99. https://doi.org/https://doi.org/10.30935/scimath/14293.
64. Sukack V, Guerra AOP, de Ellinger C, Carlos D, Petronien˙ V, ¯unien˙ S, Brose LG, A. Towards Active Evidence-Based Learning in Engineering Education: A Systematic Literature Review of PBL, PjBL, and CBL. Sustainability. 2022;14(13955):1–31. https://doi.org/https://doi.org/10.3390/su142113955.
65. Swist T, Markauskaite L, Mosely G, Goodyear P, Wrigley C. Approaches to strengthening teachers ' interdisciplinary expertise: From configurative review to design patterns. Rev Educ. 2025;13(3):1–28. https://doi.org/10.1002/rev3.70113.
66. Tamim SR, Grant MM. Definitions and Uses: Case Study of Teachers Implementing Project-based Learning. Interdisciplinary J Problem-Based Learninf. 2013;7(2):5–16. https://doi.org/https://doi.org/10.7771/1541-5015.1323.
67. Thibaut L, Ceuppens S, Loof H, De, Meester J, De, Goovaerts L, Brussel VU. Integrated STEM Education: A Systematic Review of Instructional Practices in Secondary Education. Eur J STEM Educ. 2018;3(1):1–12. https://doi.org/https://doi.org/10.20897/ejsteme/85525.
68. Toepper M, Troitschanskaia OZ, Thees CK. Literature review of international empirical research on transfer of vocational education and training. Int J Train Dev. 2022;26:686–708. https://doi.org/10.1111/ijtd.12276.
69. Villarroel V, Melipillan R, Santana J, Aguirre D. How authentic are assessments in vocational education? An analysis from Chilean teachers, students, and examinations. Front Educ. 2024;9(1308688):1–12. https://doi.org/https://doi.org/10.3389/feduc.2024.1308688.
70. Wang Z, Song G. Towards an assessment of students ' interdisciplinary competence in middle school science. Int J Sciense Educ. 2021;43(5):693–716. https://doi.org/https://doi.org/10.1080/09500693.2021.1877849.
71. Warr M, West RE. Bridging Academic Disciplines with Interdisciplinary Project-based Learning: Challenges and Opportunities. Interdisciplinary J Problem-Based Learn. 2020;14(1):1–23.
72. Wheelahan L. Not just skills: what a focus on knowledge means for vocational education. J Curriculum Stud. 2015;47(6):750–62. https://doi.org/10.1080/00220272.2015.1089942.

73. Wheelahan L, Moodie G, Wheelahan L. What do vocational colleges do and why do they matter ? Thinking about the role of colleges as local actors Thinking about the role of colleges as local actors. J Vocat Educ Train. 2025;77(1):36–57. https://doi.org/10.1080/13636820.2024.2427778.
74. Wiek A, Withycombe L, Redman CL. Key competencies in sustainability: a reference framework for academic program development. Sustain Sci. 2011;6:203–18. https://doi.org/10.1007/s11625-011-0132-6.
75. Xu L, Zhang W, Philbin SP, Guo BHW. Assessing the impact of digital education and the role of the big data analytics course to enhance the skills and employability of engineering students. Front Psychol. 2022;1–20. https://doi.org/10.3389/fpsyg.2022.974574.
76. Zeidler DL, Nichols BH. Socioscientific issues: Theory and practice. J Elementary Sci Educ. 2009;21:49–58. https://doi.org/https://doi.org/10.1007/BF03173684.
77. Zhao L, Zhao B, Li C. Alignment analysis of teaching – learning – assessment within the classroom: how teachers implement project – based learning under the curriculum standards. Disciplinary Interdisciplinary Sci Educ Res. 2023;5(13):1–23. https://doi.org/10.1186/s43031-023-00078-1.
78. Biographical, Notes.
79. Devy Lestari S. M.Pd. is a lecturer in Chemistry Education at Universitas Negeri Semarang, Indonesia. Her research focuses on chemistry education, interdisciplinary science learning, vocational science projects, critical thinking, and innovative teaching materials. In this study, she contributed to research design, data analysis, and framework development.
80. Sri Kadarwati MS. Ph.D. is a Professor of Physical Chemistry at Universitas Negeri Semarang, Indonesia. Her expertise includes physical chemistry, catalytic materials, renewable energy, chemistry education, and scientific writing. In this study, she contributed to conceptual strengthening, academic writing, and manuscript refinement.

Figures

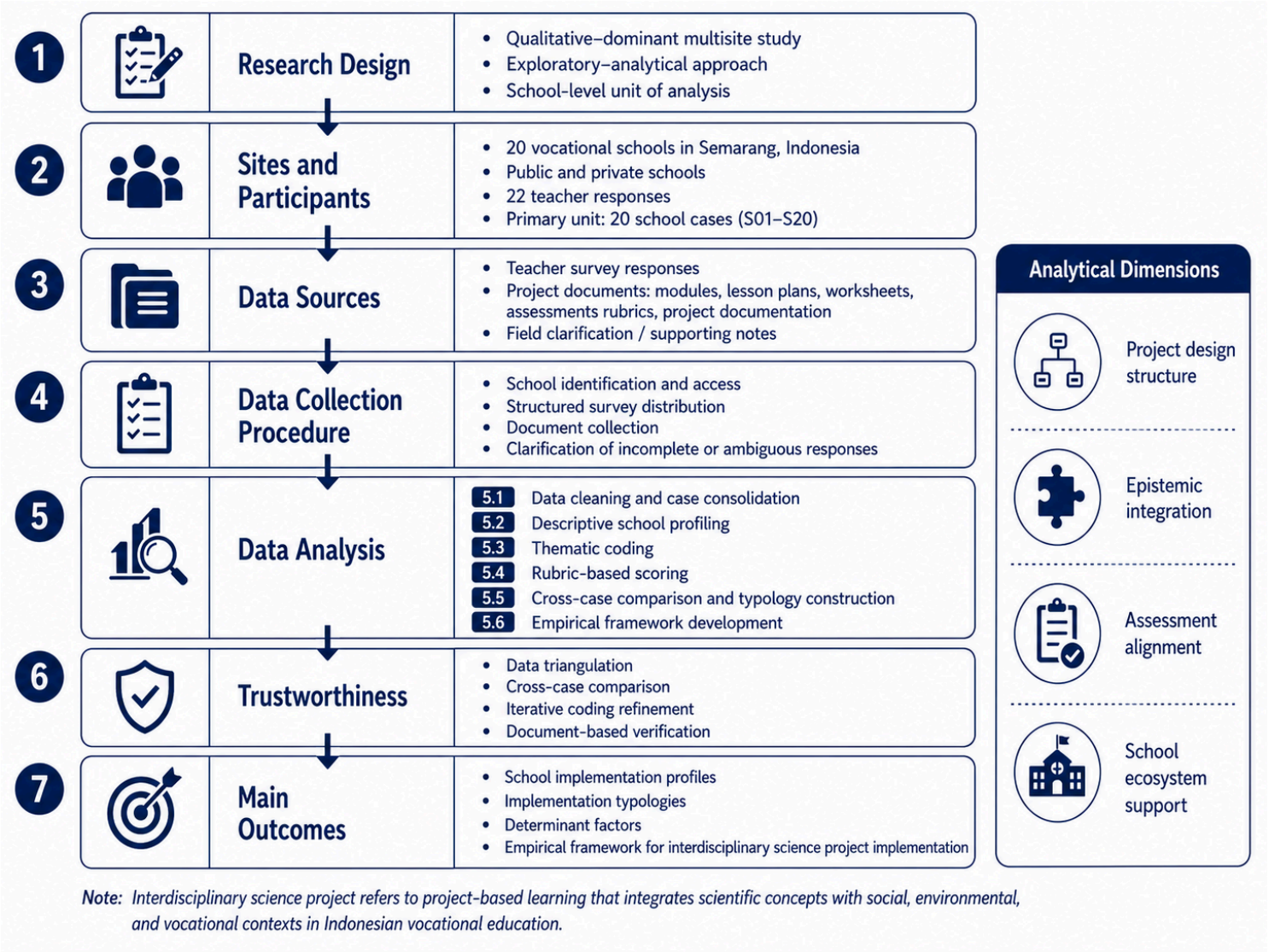


Figure 1

Research design and analytical procedure of the multisite study.

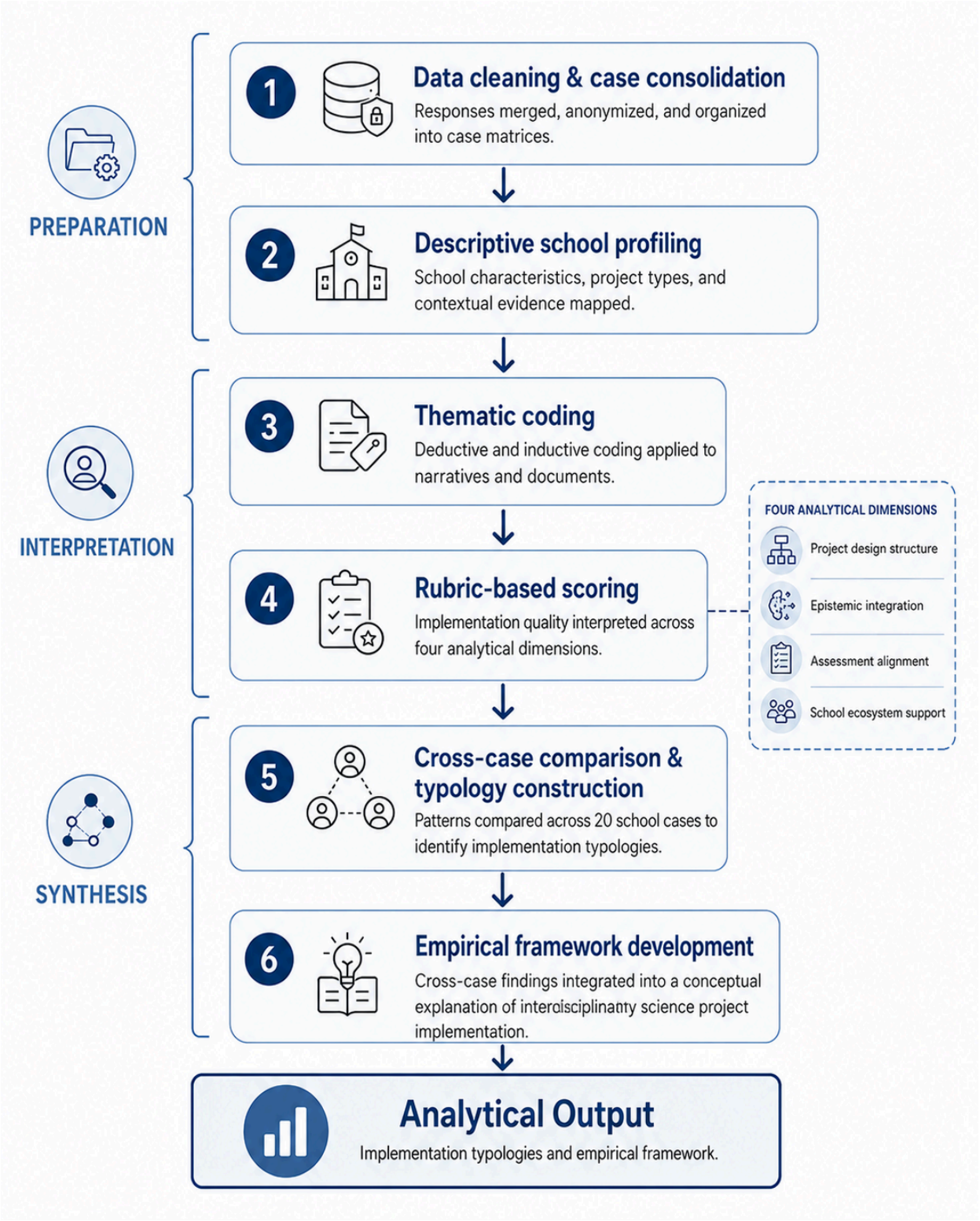


Figure 2

Data analysis workflow for constructing implementation typologies and an empirical framework.

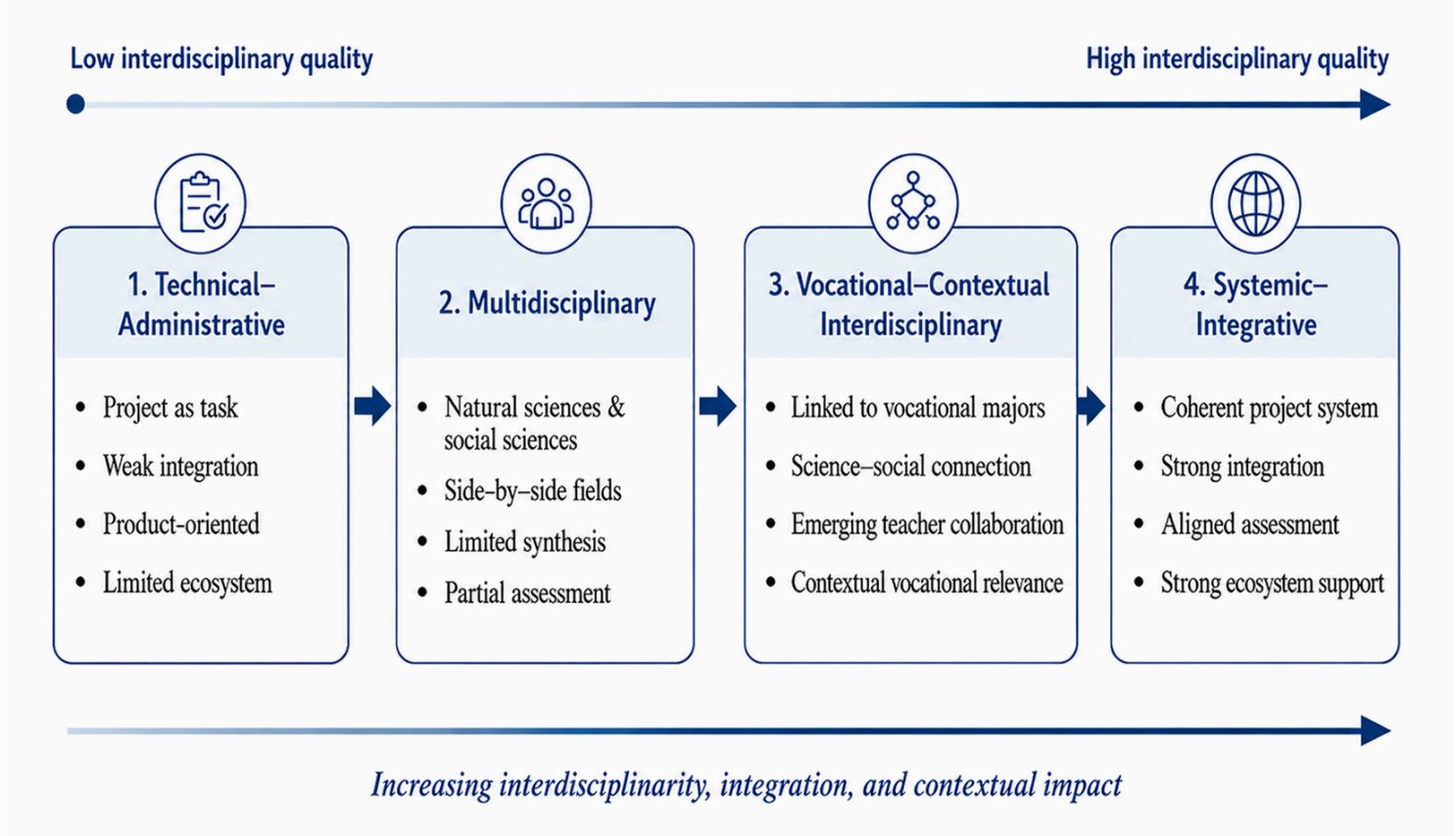


Figure 3

Developmental continuum of interdisciplinary science project implementation typologies.

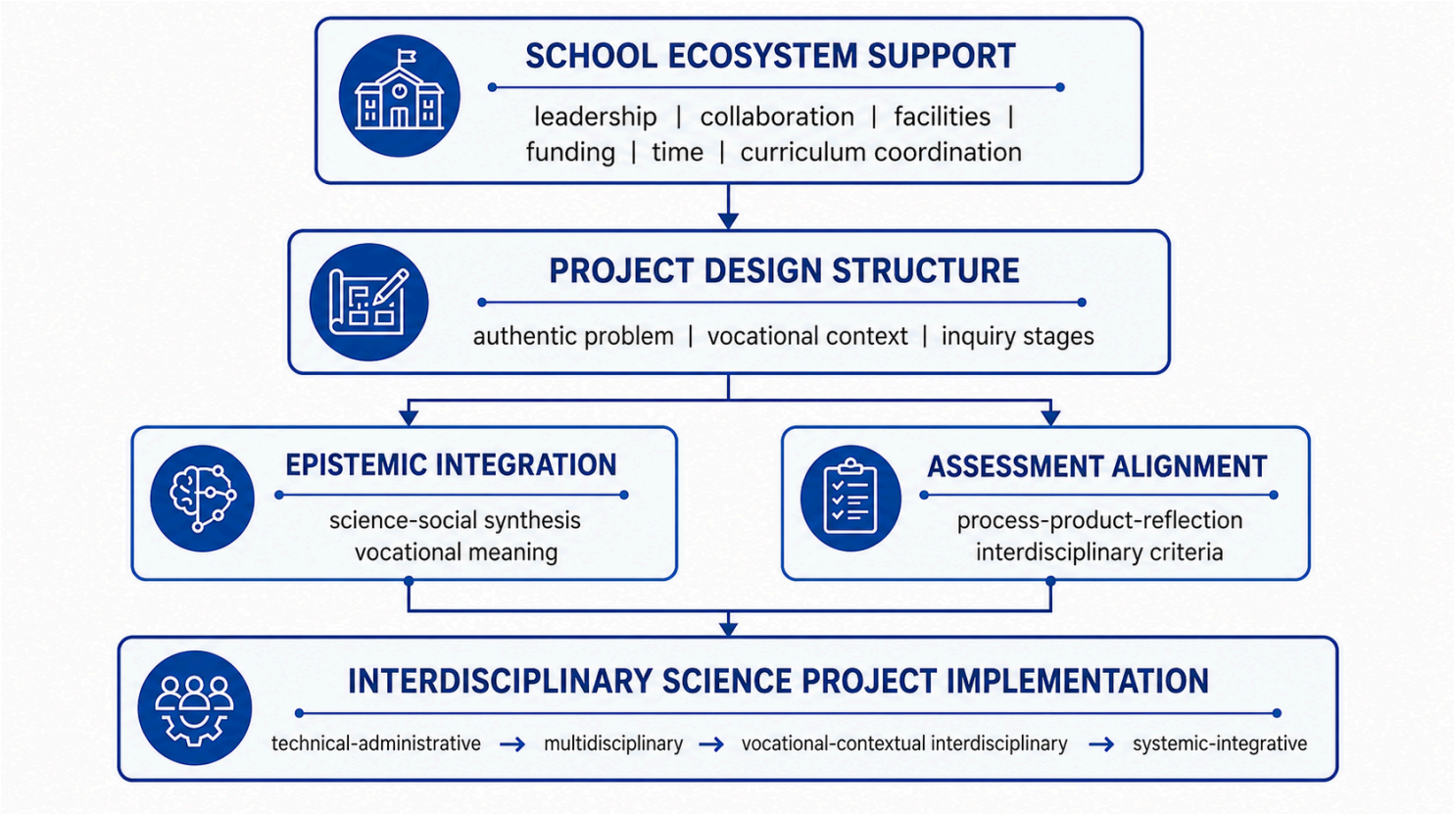


Figure 4

Empirical framework for interdisciplinary science project implementation.

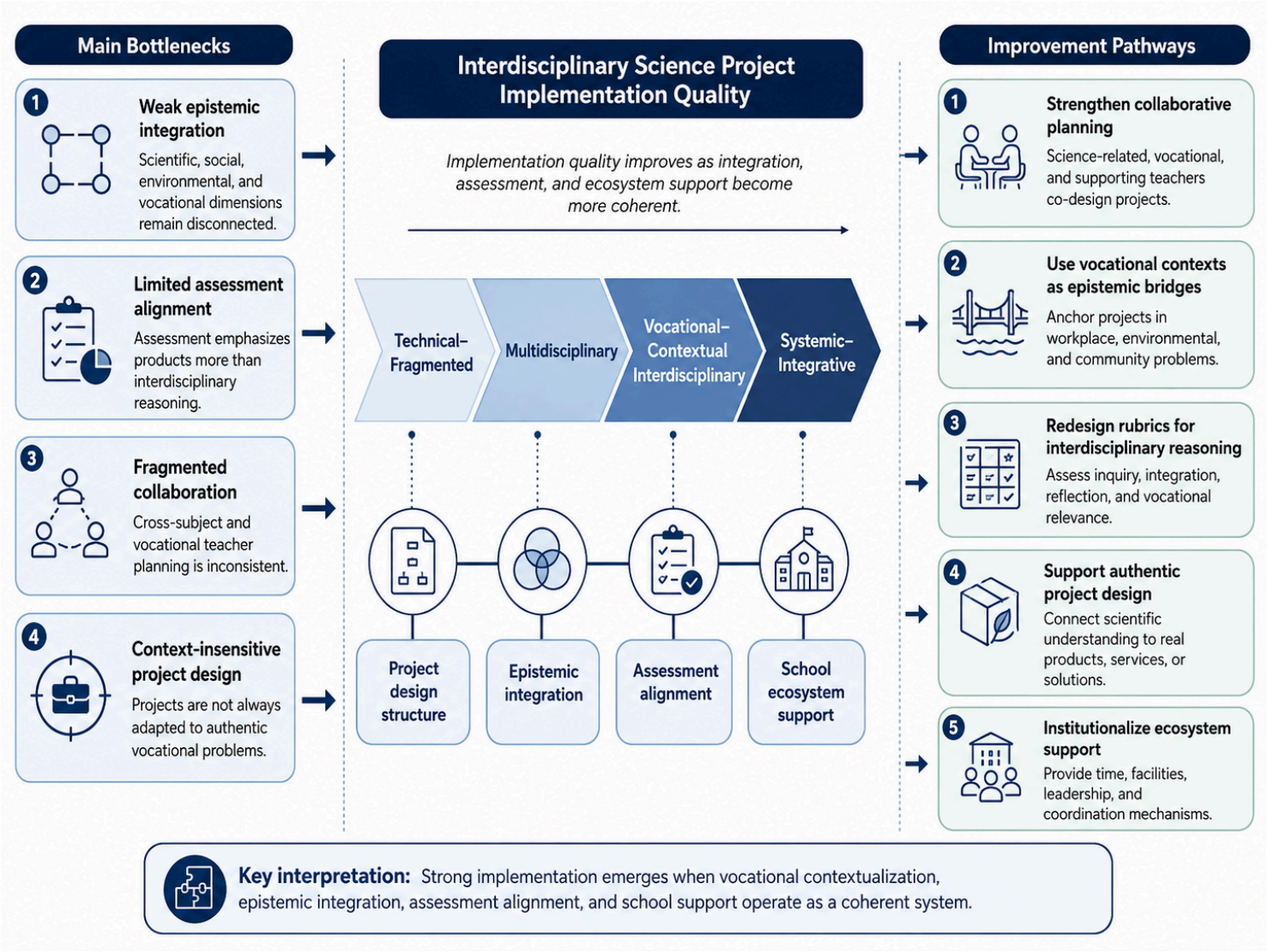


Figure 5

Interpretive synthesis of bottlenecks and improvement pathways in interdisciplinary science project implementation.

Supplementary Files

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- BiographicalNotes.docx