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C-STEM Education: Chemistry-Centred Interdisciplinary Education

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Abstract: Regarded universally as the 'central science', chemistry naturally serves as an indispensable interdisciplinary hub for the effective implementation of STEM (Science, Technology, Engineering, and Mathematics) education. Nevertheless, current STEM pedagogical practices within the field of chemistry are generally characterised by a concerning weakening of chemistry's central role and a superficial approach to rigorous disciplinary thinking. Consequently, interdisciplinary integration often remains merely cosmetic, failing to leverage the true epistemological value of chemical sciences. To systematically address this critical gap, this paper proposes an innovative C-STEM educational philosophy that is firmly centred on chemistry. It constructs a comprehensive theoretical model for C-STEM education and meticulously clarifies the functional boundaries and complex mechanisms of interaction between chemistry and the other STEM disciplines. Furthermore, drawing upon the foundational pedagogical principles of authenticity, collaborative inquiry, project-based learning, and multidimensionality, this study designs a robust applied model for C-STEM. This framework details actionable implementation pathways for defining project objectives, structuring content, establishing real-world contexts, designing tasks, evaluating outcomes, and conducting holistic assessments. Extensive research and theoretical analysis indicate that the C-STEM approach, by steadfastly upholding the intrinsic value of chemistry while achieving deep, meaningful interdisciplinary integration, can provide a transformative theoretical framework and a highly practical paradigm. Ultimately, this model serves as a catalyst for the comprehensive reform of chemistry education and the effective localisation of STEM curricula in contemporary educational settings.

Keywords: stem education; chemistry education; interdisciplinary integration; educational models; project-based learning

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1. Introduction

Driven by global technological innovation, STEM education has become a crucial educational strategy worldwide to cultivate innovative talents. Owing to its unique interdisciplinary strengths, chemistry serves as a bridge between physics, biology and other natural sciences; it is often referred to as the 'central science' and acts as a natural vehicle for the integration of STEM disciplines [1]. As a pillar discipline of the natural sciences, chemistry centres its research on the composition, microstructure, physical and chemical properties, and transformation patterns of matter. Its fundamental theories and experimental methods permeate the entire industrial chain, spanning basic research, modern chemical engineering, biomedicine, and resource conservation and environmental protection, serving as an indispensable theoretical cornerstone for the practical application of modern science and technology.

Chemistry has the dual attributes of independent discipline and interdisciplinary integration. It not only maintains independent discipline value in the STEM system, but also connects various disciplines to promote interdisciplinary learning and innovative development. From the perspective of disciplinary value, chemistry enables a profound understanding of matter at the molecular level, providing core support for major breakthroughs in numerous fields such as medical development, environmental governance and new materials research [2]. Against the backdrop of global adjustments in basic education curricula, the integration of chemistry with STEM education has gradually been implemented in many parts of the world. However, in long-term teaching practice, existing chemistry-STEM curricula have generally faced practical challenges such as the marginalisation of chemistry as the central discipline, interdisciplinary integration becoming merely a formality, and the superficiality of disciplinary inquiry. Engineering and technical content dominate the classroom, whilst core chemical concepts and ontological thinking are relegated to secondary status, making it difficult to leverage chemistry's integrative strengths as a central science.

In light of these issues, this paper anchors itself in the intrinsic value of chemistry to propose a chemistry-centred C-STEM educational philosophy. It constructs a systematic theoretical model and practical application paradigm to resolve the implementation challenges of traditional chemistry-STEM integration, thereby offering new insights for optimising chemistry teaching and refining interdisciplinary STEM practices.

2. Current State of Research and Challenges

2.1. Current State of Research

In chemistry education, research on STEM education primarily concentrates on the following two areas.

2.1.1. Exploring Methods of Integration

Early research primarily focused on integrating established teaching models such as Project-Based Learning (PBL) and the 5E learning cycle with chemistry STEM, emphasizing the cultivation of students' practical skills and collaborative competencies through structured processes. For example, one study incorporated PBL into university-level organic chemistry teaching, using a chemical dye synthesis project to foster innovation skills; another combined STEAM principles with PBL, using the theme of 'water flea cultivation' to establish links between chemical concepts and real-world contexts [3]. Subsequently, models such as the 5E learning cycle and gamified learning (e.g., STEM-PTTraveler) were introduced into the teaching of foundational content such as atomic structure and the periodic table, effectively enhancing students' motivation to learn [4].

In recent years, research has further expanded the pathways for integration: the development of STEM modules has deeply integrated chemical principles with engineering practice and mathematical modeling, significantly enhancing students' ability to apply knowledge; service-learning has broken down barriers between higher education and basic education by organizing undergraduate students to collaborate with primary and secondary school teachers and pupils in designing chemistry experiments, thereby combining chemical knowledge with community service and social value, and imbuing STEM education with humanistic significance [5].

Overall, the approach to integrating chemistry with STEM has shifted from a 'discipline-centered' superimposition of knowledge to a 'problem-centered' context-driven approach; however, most research remains confined to the level of methodological transplantation, failing to explore in depth the intrinsic logic of alignment between the distinctive characteristics of the chemistry discipline and the principles of STEM.

2.1.2. Case Study Development

The development of STEM teaching cases in chemistry has always centred on real-world contexts, extending from everyday life to the integration of digital technology, thereby giving rise to a diverse range of practical approaches. Early cases focused on everyday scenarios, such as 'Making Ice Cream' and 'Kitchen Chemistry,' which incorporated chemical concepts---such as the dissolution of substances, reaction rates, and material properties---into real-world tasks, thereby balancing the acquisition of knowledge with the cultivation of a sense of STEM identity [6, 7].

With the advancement of digital technology, technologies such as Arduino microcontrollers, 3D printing, and augmented reality (AR) are gradually being integrated into chemistry STEM classrooms. For instance, Arduino microcontrollers have been used to explore topics related to water solubility; by combining this with Microsoft Excel software, data was automatically collected while students conducted experiments. This integration of programming into chemistry lessons has demonstrated a positive impact on enhancing student engagement and interest [8]. Other approaches have utilised the Unity Proxy plugin to train agents, guiding students in learning about chemical reactions. Through the Manomotion and AR Foundation frameworks, interaction between students' gestures and 3D objects has been enabled. As this method requires only a smartphone to implement, it offers a practical reference for delivering STEM education in resource-limited areas [9]. Additionally, 3D printing technology makes visual concepts in introductory chemistry courses---such as molecular models and the properties of the periodic table---more vivid and tangible, facilitating student understanding [10].

2.2. Challenges

Despite numerous initiatives aimed at integrating chemistry within STEM education, the subject often becomes overshadowed. With an emphasis on STEM projects and engineering technology, chemistry is relegated to a secondary role, diminishing its core knowledge and critical thinking aspects. This imbalance leads to a misalignment of priorities in interdisciplinary integration.

2.2.1. The Erosion of Disciplinary Autonomy: The Marginalisation of Chemistry's Intrinsic Value

In STEM integration activities, while chemistry is formally included, its core knowledge system, intrinsic logical structure, and cognitive characteristics are not fully incorporated into the main thread of the lesson. An empirical study of secondary school chemistry teachers revealed that, although teachers generally recognize the value of STEM integration, they encounter significant methodological obstacles and practical challenges. When designing lessons, teachers often prioritize topics that are highly technical in nature but low in chemical conceptual density. This results in chemistry learning remaining at the level of describing phenomena and using tools, making it difficult to guide students toward developing a systematic understanding of the composition, structure, and changes of matter. For example, triple representation—a mode of thinking unique to the discipline of chemistry—often sees its intrinsic logic overshadowed by the linear processes of engineering design or the operational requirements of technical tools. As a result, students find it challenging to form a complete chain of thought progressing from macroscopic phenomena to microscopic essence and finally to symbolic expression, leading to a significant lack of depth and systematic rigor in their chemistry learning.

2.2.2. Deviations in Disciplinary Thinking: The Superficialisation of Chemical Inquiry Logic

Furthermore, technology or engineering activities are often superimposed onto chemistry teaching, rather than achieving interdisciplinary integration within the framework of chemical thinking itself. Engineering and technical thinking are goal- and means-oriented, meaning that once a goal is established, the focus is on seeking the optimal solution; chemical thinking, by contrast, is mechanism- and explanation-oriented, involving the observation of phenomena and the pursuit of answers to questions such as 'what is matter?' and 'why do changes occur?'. There is no difference between the two, only the attributes are different. However, in the practice of STEM integration, chemical thinking is often simply replaced by technical thinking. Research indicates that the core challenges faced by chemistry teachers in STEM education include a lack of systematic teaching support tools, difficulties in interdisciplinary collaboration, and insufficient capacity to effectively integrate complex STEM activities (such as project-based tasks and laboratory work) into the chemistry curriculum. This implies that when chemistry teachers attempt to maintain the subject's distinct characteristics, they often find themselves in a situation of isolation and helplessness—lacking both examples of STEM integration that embody the characteristics of chemical thinking and theoretical frameworks capable of linking core chemical concepts with other STEM disciplines.

3. Conceptual Framework: The Theoretical Framework of C-stem

This section systematically examines the essence, theoretical foundations, and structural model of the C-STEM concept, addressing both current research trends and practical challenges.

3.1. Defining the Concept of C-stem

C-STEM education is an interdisciplinary approach centred on chemistry, which integrates science, technology, engineering, and mathematics into the teaching of core chemical concepts within the STEM framework. Its essence lies in the integration of core chemical knowledge, inquiry-based methods, and STEM principles, utilising real-world contexts and project-based inquiry to cultivate students' STEM literacy and interdisciplinary problem-solving skills. C-STEM is not a revision or replacement of the STEM concept but provides epistemological and methodological guidance for implementing STEM in chemistry education. It differs from a simple combination of subject knowledge, upholding a chemistry-centred approach. With core chemical concepts and thinking as the main thread, it achieves the systematic integration of multidisciplinary elements around chemical problems, fully leveraging the integrative value of chemistry as the 'central science'.

Unlike many existing approaches to chemistry teaching that incorporate STEM—which merely combine knowledge points from different disciplines under a single theme without achieving deep integration—C-STEM distinguishes itself in this respect, as illustrated in Table 1.

Table 1. The Comparison between C-stem and STEM Education in Chemistry Teaching

Dimension	C-STEM (Chemistry-centred STEM)	Implementing STEM Education in Chemistry Teaching
Core Focus	Chemistry-led, with STEM serving chemistry	STEM takes the lead, with chemistry playing a supporting role
Learning Objectives	Chemical literacy + interdisciplinary skills	Emphasis on STEM skills, with little focus on understanding chemistry
Interdisciplinary Links	Deep integration and organic interconnection	A simple superimposition or patchwork approach
Integration Methods	Chemistry as the anchor, problem-driven	Thematic packaging and piecemeal assembly of knowledge
Thinking Orientation	Prioritising chemical inquiry thinking	Prioritisation of technical/engineering thinking

Assessment Focus	Multi-dimensional assessment, emphasising depth of understanding in chemistry	Focus on project completion and technical operations
Practical Value	Balancing the core of chemistry with interdisciplinary integration	Integration remains superficial, with limited effectiveness

3.2. The Theoretical Basis of C-stem

3.2.1. Theories of Interdisciplinary Learning

The framework of the US 'Next Generation Science Standards' is divided into three sections: 'Science and Engineering Practices', 'Core Concepts of the Disciplines' and 'Cross-Disciplinary Concepts', with cross-disciplinary concepts constituting a key component [11]. Regarding cross-disciplinary learning, scholars primarily hold the following views. Morrison et al. point out that cross-disciplinary learning can compensate for the shortcomings of single-discipline approaches. STEM education emphasises the equal status of all disciplines, using real-world problems as a vehicle to guide learners in engaging in divergent thinking, thereby enabling them to thoroughly clarify the intrinsic connections and interactions between the elements of a problem [12]. In contrast to the above view, this study defines interdisciplinary learning as the integration of disciplines, while proposing that each discipline retains its own characteristics and pedagogical core during the integration process [13]. Although this type of teaching comprehensively utilises knowledge from multiple disciplines, teachers and students must be clear about the boundaries and characteristics of different disciplines, and teaching will still have specific emphases. Chinese scholar Liu Denghui proposes that interdisciplinary learning can be categorised into three tiers: the leading discipline, the primary associated disciplines, and the generally related disciplines. By maintaining the leading discipline's central role and effectively integrating and utilising knowledge from multiple disciplines in a hierarchical manner, students are helped to transcend the limitations of their own discipline, deepen their understanding of knowledge, and enhance their ability to transfer and apply knowledge in practice.

In summary, for C-STEM, the key insight from interdisciplinary learning theory is that chemistry should always take centre stage; STEM elements should be organically integrated at key teaching junctures to guide students in integrating multidisciplinary approaches to investigate chemical problems, thereby deepening their understanding of the fundamental principles of chemistry and enhancing their ability to transfer and apply knowledge.

3.2.2. Theory of Project-Based Learning

The theory of project-based learning incorporates the core principles of various educational psychology theories, including pragmatist educational theory, constructivism, discovery learning, and multiple intelligences theory. It is a teaching approach grounded in project-based learning. There are differing definitions of project-based learning within the academic community. One definition describes it as a systematic teaching methodology, emphasizing a process where students explore problems within complex yet authentic contexts, formulate and implement project tasks, and construct knowledge by solving problems through the creation of carefully designed project outcomes. Through this process, students acquire knowledge and skills [14]. Another perspective views project-based learning as a teaching model in which students, focusing on specific, authentic, and complex themes, design tasks and activities based on actual circumstances, engage in long-term, open-ended inquiry, and ultimately achieve knowledge construction and skill enhancement [15]. These definitions share common keywords such as authentic contexts, the inquiry process, and the construction of knowledge and skills.

Within the C-STEM framework, project-based learning serves as a vital mechanism for integrating core chemical issues with STEM elements. Driven by authentic chemical topics and guided by a comprehensive project-based inquiry approach, it maintains a focus on chemistry while leveraging STEM elements to empower students. This approach enables students to deepen their understanding of chemistry and develop interdisciplinary skills while solving complex problems, thereby achieving the synergistic development of knowledge, abilities, and literacy.

3.2.3. A Holistic Approach to Curriculum

In 1926, the philosopher Jan Smuts proposed the concept of holism, advocating for a holistic view of the world to address the fragmentation between matter, life, and spirit caused by the specialization of academic disciplines [16]. The holistic curriculum has evolved from principles emphasizing the cultivation of the whole person and promoting balanced development of students' intellect, emotions, psychology, and spirit. Recent research in chemistry education suggests that integrating holistic evolutionary concepts into chemistry teaching can yield positive outcomes. Studies have shown that using poetry materials imbued with holistic ideas to teach the periodic table and acid-base topics can elicit deep, personally meaningful engagement, even among students who previously had limited interest in chemistry [17]. It follows that the acquisition of fragmented, isolated, and unsystematic knowledge undermines the unity of knowledge, thereby limiting students' capacity for deep learning. The holistic view of curriculum emphasizes the development of dynamic and diverse content through holistic thinking, tailored to meet students' individualized learning needs.

Guided by a holistic approach, C-STEM education reorganizes multidisciplinary knowledge through themes and projects, avoiding a mere accumulation of content, and achieves an organic integration of learners with the curriculum, subject teaching with practical activities, and school-based learning with real-world contexts. This holistic view of curriculum provides a solid foundation for interdisciplinary teaching, advocating the establishment of a comprehensive educational system centered on core competencies, thereby effectively addressing the limitations of single-subject teaching.

3.3. The C-stem Educational Model

Building on the theoretical foundations outlined above, this paper proposes the C-STEM educational model, as illustrated in Figure 1. Centred on chemistry, this model establishes an interdisciplinary integration framework characterised by 'one core driving force, four supporting pillars, and holistic synergy.' It defines the intrinsic logical relationships between chemistry and science, technology, engineering, and mathematics, thereby ensuring the central role of chemistry at a structural level and preventing interdisciplinary integration from becoming superficial or misaligned.

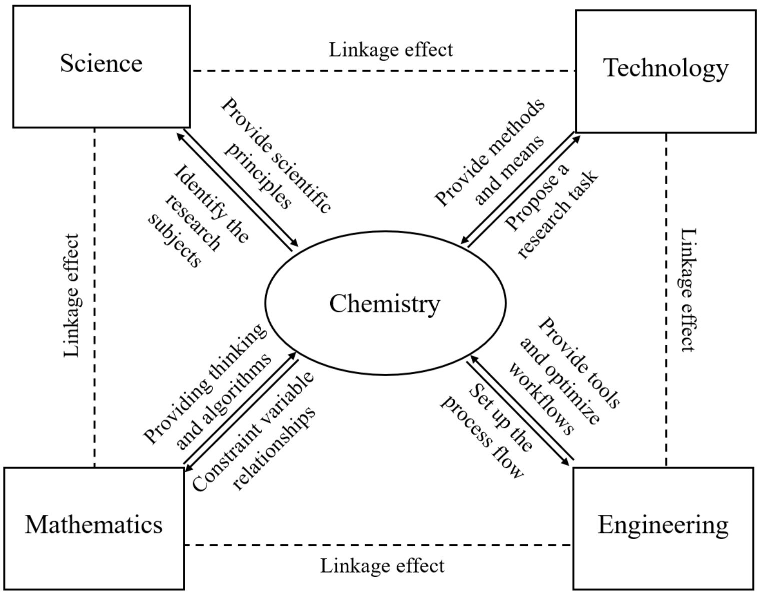

Figure 1. C-stem Educational Model

Within the model structure, chemistry occupies a central hub position, serving as the ontological anchor and logical backbone of the entire interdisciplinary learning process. It is responsible for selecting research subjects, defining inquiry tasks, establishing procedural workflows, and constraining variable relationships, thereby ensuring that interdisciplinary activities revolve around core chemical concepts, triple-representation thinking, and inquiry logic. Centred on chemistry, science, technology, engineering, and mathematics provide support from four distinct dimensions: science is grounded in the research subjects selected by chemistry, providing fundamental scientific principles and natural laws to consolidate the theoretical foundation; technology addresses the investigative tasks set by chemistry, providing methods, tools, and implementation strategies; engineering follows the material transformation pathways determined by chemistry, providing apparatus design, process planning, and optimisation schemes; mathematics, based on the variable boundaries and quantitative relationships proposed by chemistry, provides thinking methods, quantitative models, and algorithmic support for chemistry learning. These four disciplines are not simply juxtaposed or superimposed but form a two-way interaction and dynamic linkage through chemistry: scientific principles guide the rational selection of technical means; technological applications support the effective implementation of engineering solutions; engineering practice relies on mathematical models to achieve optimisation and iteration; and mathematical conclusions, in turn, promote the deepening of scientific understanding and the reinterpretation of chemical laws.

Overall, through the central unifying role of chemistry, this model organically integrates science, technology, engineering, and mathematics into an interpenetrating and mutually reinforcing system. It realises an educational framework centred on chemistry, guided by interdisciplinary integration and aimed at the development of core competencies, thereby providing a clear, stable, and practical theoretical framework and structural paradigm for the curriculum design, teaching organisation, and practical implementation of C-STEM education.

4. Design of an Implementation Model for C-stem Education

This section builds upon the foundational principles of the C-STEM concept to propose an applied model for C-STEM education. The aim is to offer theoretical insights and practical strategies for enhancing the design and implementation of STEM education within the context of chemistry teaching.

4.1. Principles Governing the Design of C-stem Educational Application Models

4.1.1. Authenticity

Global challenges such as climate change, new energy sources, new materials, and drug development all revolve around chemical issues. The principle of authenticity requires that teaching scenarios must be rooted in real-world chemical problems or social science issues, rather than artificially constructed scenarios focused solely on exercises. As a central science concerned with the transformation and application of matter, the essence of chemistry lies in uncovering patterns and creating value in the real world. Consequently, C-STEM education should utilize real-life tasks—such as material synthesis, environmental management, materials development, or health screening—as a vehicle, enabling students to conduct investigations within the context of genuine problems, data, and limitations. Authenticity refers not only to the origin of the problem but also to the cognitive process—students should experience the chemist's pathway of observation, hypothesis, verification, and revision, rather than a simplified replication of steps. Only in this way can C-STEM avoid becoming training focused solely on examinations disguised as contextual learning and truly achieve the transformation from disciplinary knowledge to practical competence.

4.1.2. Collaboration

In real-world interdisciplinary problem-solving, a single perspective or individual capability is often insufficient to address the entire process—from analyzing chemical principles and selecting technical tools to designing engineering solutions and validating them through mathematical modeling. Therefore, the teaching model should incorporate structured collaborative mechanisms, including heterogeneous grouping (where students with different knowledge backgrounds and thinking styles complement one another), role rotation (where students take on roles such as chemical analyst, technical engineer, and mathematical modeler), and cooperative argumentation (where groups jointly complete project reports and present their findings). Collaboration should not be limited to a simple 'division of labor' but should evolve into 'synergistic thinking'—through dialogue and debate, students learn to appreciate the contributions of other disciplines from a chemical perspective while also reflecting on the significance of chemistry from the viewpoints of other fields. This approach embodies the principle that 'all things are interconnected, yet distinct.'

4.1.3. Project-Based

C-STEM education begins with real-world chemical problems or social science issues (SSI) as its contextual foundation. Within these contexts, students engage with complex, open-ended tasks rather than exercises with predetermined solutions. To transform such real-world challenges into effective learning opportunities, they must be restructured into projects with defined boundaries and inquiry-driven scopes. The core of learning emerges through the problem-solving and meaning-making processes inherent in these projects. Unlike isolated laboratory activities or short-term tasks, projects are characterized by clear objectives, a sustained research cycle, and outcomes that can be publicly shared. In the C-STEM framework, project design is guided by 'chemical anchor questions,' such as "How can valuable metals be recovered from waste lithium-ion batteries?" or "How can a biodegradable straw be designed and its environmental impact assessed?" These questions inherently integrate core chemical concepts, such as redox reactions, polymer synthesis, and substance separation, while naturally extending to include technology (testing methods), engineering (process design), and mathematics (cost and efficiency optimization). The project-based approach also necessitates a structured teaching sequence: "project selection -- plan formulation -- investigative activities -- product creation -- presentation of outcomes -- activity evaluation." This sequence enables students to progressively build a problem-centred, interdisciplinary cognitive framework while addressing complex challenges.

4.1.4. Multidimensional

STEM fosters inquiry-based learning environments rooted in real-world challenges, integrating multidisciplinary knowledge with modern technology to cultivate students' comprehensive competencies. A multidimensional design is essential for effective curriculum implementation, encompassing four key dimensions: objectives, content, resources, and assessment. Regarding educational objectives, the curriculum establishes a broad developmental direction for students, progressively refining indicators aligned with the core competencies of the chemistry discipline. It sets specific goals focused on innovation and comprehensive thinking, forming a hierarchical system of objectives. The curriculum content is closely tied to real-life contexts, with chemical problems or societal issues driving inquiry activities. Digital platforms are employed to overcome the limitations of printed textbooks, incorporating online platforms, virtual environments, and real-world scenarios to enrich teaching materials, while emphasizing real-world inquiry as the primary instructional method. Resource provision extends beyond textbooks; in addition to tools like 3D printers and programming software, supplementary materials such as micro-lectures, study guides, and exemplary case studies are included. Experimental equipment, such as microscopes and measuring instruments, can be flexibly added based on course requirements. Institutions with ample resources may also leverage teaching staff from within and outside the institution to provide specialized guidance. The assessment phase shifts from traditional, results-focused evaluation models to prioritize formative assessment. It adopts multi-stakeholder, personalized, and comprehensive evaluation criteria, utilizing electronic learning portfolios to store learning data and applying data analysis to achieve thorough and individualized assessments.

4.2. The Specific Process of Designing C-stem Educational Application Models

This study has developed a C-STEM educational application model based on the characteristics and design principles of C-STEM education. As illustrated in Figure 2, the model consists of six key components: project objectives, project content, project context, project tasks, project outcomes, and project evaluation.

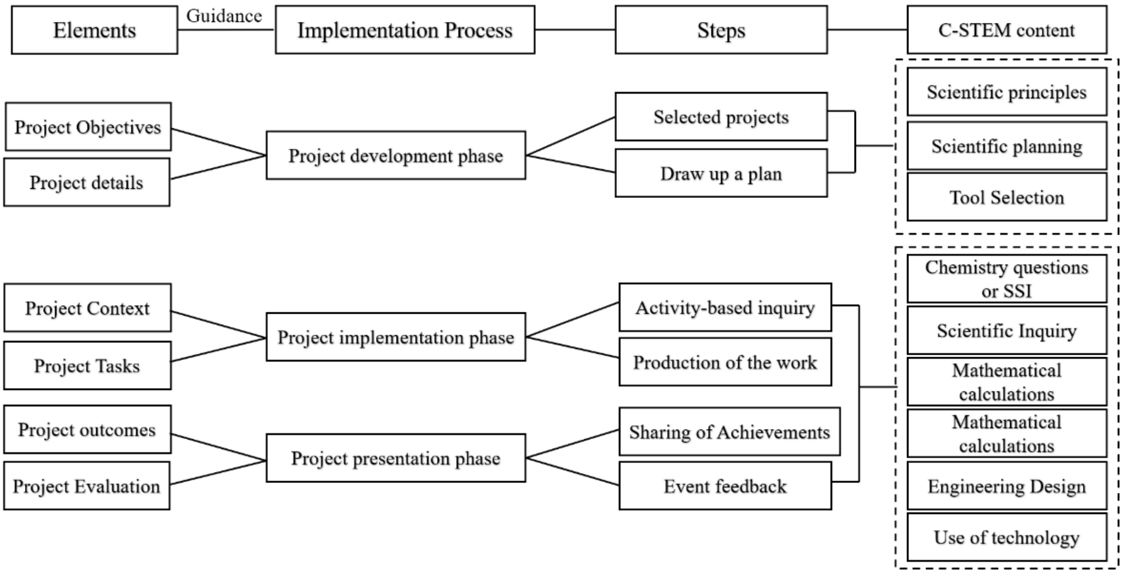

Figure 2. C-stem Educational Application Model

4.2.1. Project Objectives

The primary aim of the C-STEM programme is to guide students in applying scientific principles, technological tools, engineering design, and mathematical modelling to address real-world tasks focused on chemistry-based anchor problems. Within this overarching aim, the programme is further structured around the core competencies of the chemistry discipline: students should be able to connect macroscopic phenomena with microscopic particles and symbolic representations, thereby fostering a mindset of 'macroscopic identification and microscopic analysis'; comprehend changes in matter, energy, and dynamic equilibrium in chemical reactions, thereby establishing a 'concept of change and equilibrium'; derive logical conclusions based on experimental evidence and construct or utilise chemical models, thereby developing 'evidence-based reasoning and model cognition'; propose hypotheses, design investigative plans, and demonstrate a willingness to innovate in solving real-world problems, thereby cultivating a "scientific inquiry and innovative mindset"; and, through hands-on experience, develop a rigorous and pragmatic scientific attitude while considering the social and environmental impacts of chemical technology, thereby nurturing a "scientific spirit and social responsibility." These five dimensions are integrated throughout the project's implementation, collectively reflecting the educational philosophy of "chemistry as the foundation, with the four wings serving as its applications."

4.2.2. Project Content

The project content serves as the central link between the project objectives and the various stages of implementation. It builds upon the educational goals set and, in turn, shapes the selection of investigative materials, the organisation of investigative activities, and the development of the assessment framework. Unlike traditional subject-based curricula, which rely on fixed knowledge frameworks provided by textbooks, C-STEM project content is anchored in real-world issues to generate learning materials. It draws on authentic problems to drive the integrated application of multidisciplinary knowledge. Learners acquire and apply cross-disciplinary content through the process of problem-based inquiry. Consequently, the content is inherently under-structured, interdisciplinary, and innovative, making the development of the curriculum significantly more challenging than that of conventional subject-based teaching models. The curriculum design is grounded in educational objectives, selecting topics from daily life and the social sciences based on learners' cognitive levels and areas of interest. It follows a content framework centred on chemistry, supplemented by other disciplines, drawing inspiration from the design approach of science and engineering courses, where core subjects are supported by supplementary content. With key chemical concepts as the central axis, relevant content from science, technology, engineering, and mathematics is integrated as required. This content paradigm transcends the limitations of textbook knowledge, organising course resources around real-world scenarios to highlight the content's comprehensiveness, flexibility, and practical relevance. By organically integrating multidisciplinary content, it fosters the coordinated development of students' core chemical literacy and comprehensive scientific literacy.

4.2.3. Project Context

Project contexts serve as the practical framework for conducting inquiry-based activities based on project content, creating a tangible environment in which inquiry tasks can be carried out. Grounded in the principle of authenticity, C-STEM creates teaching contexts based on social science issues and real-life scenarios from production and daily life; these issues are inherently open-ended and problem-oriented. The creation of such contexts requires the refinement of multi-dimensional background elements, including an analysis of the origin of the problem and the relevant stakeholders, as well as a clarification of real-world factors such as cost, environmental considerations, and safety. Concurrently, available implementation conditions---such as laboratory equipment, facilities, and off-campus resources---must be clearly outlined. Taking the recycling of waste lithium-ion batteries as an example, constructing inquiry scenarios based on real-world industrial challenges not only stimulates students' curiosity through authentic dilemmas but also anchors the core content of chemistry, allowing for the natural derivation of subsequent inquiry tasks and ensuring a seamless integration between project objectives and the design of individual tasks.

4.2.4. Project Tasks

Project tasks are pivotal for integrating inquiry-based activities into the curriculum, requiring the conversion of structured subject knowledge into practical inquiry projects. These projects should center on fundamental chemical concepts, using real-world questions as the foundation for exploration. A sequence of inquiry activities should be designed around these core concepts, encouraging students to engage in hands-on investigation throughout the process. By systematically completing these tasks, students will assimilate chemical knowledge, develop practical skills, and foster scientific inquiry literacy. The design of C-STEM project tasks must adhere to five principles: first, topics should be grounded in real-life scenarios, with inquiry questions derived from authentic contexts; second, project presentation formats should be optimized with innovative and engaging themes to inspire students' exploratory initiative; third, projects must align closely with curriculum standards, thoroughly addressing core chemistry topics; fourth, tasks should be complex and multifaceted to promote collaborative group work in solving intricate problems; fifth, projects should follow a progressive sequence, moving logically from simple to complex, enabling students to gradually acquire knowledge, enhance their application skills, and address diverse learning needs.

4.2.5. Project Outcomes

Project outcomes are works produced by students upon completion of project tasks, which are suitable for public presentation. C-STEM project outcomes emphasize diversity and integration, and typically include tangible outcomes, such as prototypes of recycling devices, product samples, experimental reports, and design drawings, which directly demonstrate engineering and technical outputs; explanatory outcomes, such as reports analyzing chemical principles, material balance calculation tables, and explanations of mathematical models, which demonstrate in-depth engagement with chemistry and mathematics; and presentational outputs, such as posters, presentation slides, short videos, or project display boards, used for the communication and evaluation of results. Project outcomes should be evaluated primarily on the extent to which they address core chemical problems, while also considering the quality of integration of interdisciplinary elements. Outcomes with practical value or social significance are encouraged to enhance students' sense of achievement and responsibility.

4.2.6. Project Evaluation

Project assessment serves as a feedback and improvement mechanism within the C-STEM educational model. Following the principle of multidimensionality, assessment integrates both formative and summative evaluation. Formative assessment examines students' performance at each stage of the project, with specific indicators including accuracy in applying chemical concepts, effective use of interdisciplinary resources, level of collaborative engagement, adherence to experimental protocols, and thoroughness in data recording. Summative assessment evaluates the quality of project outcomes using a comprehensive scoring system based on dimensions such as scientific rigour in chemistry (accuracy of principles, depth of explanation), technical feasibility (efficacy of detection methods), soundness of engineering design (process completeness, prototype functionality), mathematical rigour (accuracy of modelling and optimisation), and the innovativeness of results. Assessment should adopt a multi-faceted approach, incorporating teacher evaluation, peer review within groups, and self-reflection to promote the development of students' metacognitive skills. Results from assessments should not only determine grades but also inform the project design phase, thereby fostering a cycle of continuous improvement.

5. Conclusion

As a key paradigm driving change in science education, STEM holds considerable promise for educational development worldwide. However, the implementation of chemistry-oriented STEM still faces multiple practical challenges, including curriculum development, technology integration, assessment design, interdisciplinary teaching and research, and alignment with curriculum standards. In addition, pathways for cultivating students' innovative and investigative abilities remain to be further refined. Building on the scientific nature of chemistry as a central discipline, this study addresses problems such as the marginalization of chemistry and superficial thinking in traditional STEM integration by establishing a theoretical and applied framework for C-STEM. It clarifies the interconnections between chemistry and other disciplines and refines implementation pathways across the full project process, thereby providing theoretical support for addressing existing practical challenges. Future work should continue to refine and optimize relevant implementation strategies on the basis of empirical evidence from frontline teaching, thereby further strengthening the practical value of C-STEM.

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