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Designing a Research Oriented and Industry Connected Catalysis Principles Course: An Outcome Based Teaching Reform Study Based on the Yangtze University Syllabus

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ABSTRACT

Catalysis is both a conceptual core of modern chemistry and an engineering foundation of chemical manufacturing, petroleum processing, environmental protection, and sustainable materials development. Yet the teaching of catalysis is difficult because the subject asks undergraduate students to integrate thermodynamics, adsorption, surface kinetics, transport phenomena, catalyst preparation, catalyst deactivation, and structure-performance reasoning within a limited number of contact hours. This study develops a teaching research framework based on the syllabus of the course Catalysis Principles offered by the College of Chemistry and Environmental Engineering at Yangtze University. The syllabus defines Catalysis Principles as an elective course for Applied Chemistry students, allocates 32 classroom hours to eight content modules, emphasizes lecture-based but heuristic and discussion-supported instruction, and uses a two-part assessment structure consisting of in-class training and a final research report. Building on outcome-based education, constructive alignment, active learning, problem-based learning, formative feedback, and contemporary catalysis education literature, the study proposes a coherent reform model for transforming the course from a mainly content-delivery course into a research-oriented, literature-supported, data-informed, and industry-connected learning experience. The proposed model aligns course outcomes, module-level learning tasks, problem scenarios, reading assignments, formative assessment, and the final research report. It also integrates ideological and professional values such as scientific spirit, safety awareness, environmental responsibility, and innovation into disciplinary problem solving rather than treating them as separate slogans. The article provides a complete research design, a module-by-module teaching framework, assessment rubrics, literature-based learning tasks, quality assurance measures, and an implementation plan suitable for a 32-hour elective course. As a design-based curriculum study, it does not report classroom outcome data; instead, it presents an implementable and evaluable model for future teaching cycles.

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Introduction

Catalysis occupies a distinctive position in undergraduate chemistry and chemical engineering education because it links molecular events with industrial performance. The field cannot be mastered through memorizing definitions or reproducing isolated reaction examples. Instead, students must learn how surface structure, adsorption, reaction thermodynamics, kinetic modeling, material preparation, transport phenomena, deactivation, regeneration, safety, and sustainability operate together. Authoritative catalysis handbooks and reviews emphasize precisely this integration of molecular chemistry and process relevance [1,2]. Schlögl further frames heterogeneous catalysis as a field that connects atomic-level understanding with technologically important transformations, while Thomas and Thomas present heterogeneous catalysis as a discipline in which principles and practice must be learned together [3,4]. For students in Applied Chemistry, Catalysis Principles therefore should not be judged only by whether students can define a catalyst; it should be judged by whether they can explain why catalysts create different pathways, selectivities, rates, lifetimes, and industrial consequences. The syllabus on which this paper is based positions Catalysis Principles as an elective course for Applied Chemistry students after they have studied higher mathematics, physical chemistry, and chemical engineering principles. The course is expected to help students master the essence and basic laws of catalysis, understand major industrial catalytic technologies, and build a theoretical foundation for later research and development work. The syllabus covers adsorption, fundamentals of gas-solid heterogeneous catalytic reaction kinetics, promoters and supports, solid acid catalysts, catalytic cracking, metal catalysts, and common preparation methods for solid catalysts. These topics reflect a traditional but still highly relevant structure of heterogeneous catalysis education. They also reflect a practical orientation toward petroleum processing, petrochemicals, fine chemicals, and catalyst development. However, the teaching challenge is immediately visible. The total classroom time is 32 hours. Within this compact schedule, students must move from introductory concepts to adsorption and kinetics, from catalyst components to solid acidity, from catalytic cracking to metal catalysis, and finally to synthesis and shaping methods. At the same time, the syllabus requires students to connect theory with practical production, broaden their academic vision, cultivate independent thinking, and develop research-report writing ability. The assessment design gives 30 percent of the grade to in-class training, including tests, questioning, and attendance, and 70 percent to a final research report on hot issues, frontiers, and new technologies in catalysis. The final report also requires students to consult domestic and international literature and to develop individual research topics. This assessment structure shows that the course is not intended to be a conventional closed-book knowledge course; it is already designed to cultivate scientific reading, synthesis, and writing.

The central problem addressed in this paper is therefore how a 32-hour Catalysis Principles course can be designed so that its compressed content, professional values, industrial relevance, and research-report assessment form a coherent learning system. The paper argues that the course should be redesigned according to five principles. First, the course outcomes should be expressed as observable performances, not only as content coverage. Second, the eight syllabus modules should be connected by a small number of recurring conceptual threads: adsorption-energy balance, structure-performance relationship, kinetics-transport coupling, active-site identification, catalyst life cycle, and sustainable process selection. Third, teaching should combine short conceptual lectures with problem-based and data-based tasks so that students practice catalytic reasoning during class rather than only after class. Fourth, the final research report should be scaffolded throughout the semester through literature-search tasks, annotated bibliographies, research-question workshops, and peer review. Fifth, assessment should reward not only final conclusions but also evidence use, mechanism reasoning, data interpretation, safety and environmental awareness, and quality of scientific communication. Accordingly, the study is framed as a design-based curriculum study rather than an empirical effectiveness report. Its contribution is a literature-grounded and syllabus-specific model that can be implemented in subsequent offerings of the course and evaluated through mixed methods. This framing supports research integrity because the claims are limited to curriculum design, alignment logic, teaching activities, assessment structure, and evaluation planning. The model is therefore intended to guide implementation and later empirical evaluation, not to substitute for classroom evidence that has yet to be collected. The research questions are as follows. How can the existing syllabus of Catalysis Principles be translated into an outcome-based and constructively aligned course design? What teaching activities can help Applied Chemistry students integrate catalytic theory, industrial cases, and literature-based inquiry within 32 hours? How can the final research report be scaffolded so that students genuinely learn to read English literature, analyze frontier problems, and write a scientific paper rather than simply compile information? What assessment instruments can be used to evaluate conceptual understanding, catalytic reasoning, research literacy, and professional values in a transparent manner? By answering these questions, the paper aims to provide a practical model for similar catalysis courses in applied chemistry and chemical engineering programs.

Course Context and Syllabus Analysis

The syllabus describes Catalysis Principles as an elective course in the Applied Chemistry program. Its prerequisite knowledge includes higher mathematics, physical chemistry, and chemical engineering principles. This prerequisite structure is pedagogically meaningful. Catalysis requires mathematical thinking for rate equations and diffusion limitations, physical chemistry for thermodynamics, kinetics, adsorption, and surface phenomena, and chemical engineering for process intensification, mass transfer, reactor design, and scale-up. A student who has only organic or inorganic chemistry knowledge may recognize catalytic transformations, but may not yet understand why adsorption strength, pore diffusion, heat release, and active-site density determine industrial performance. The course therefore occupies an intermediate position between basic theory and professional application [5,6]. The syllabus states that Catalysis Principles integrates catalyst preparation, catalytic application, and the essential laws of catalytic reaction processes. It also emphasizes that catalysis solves both chemical and engineering problems and provides a theoretical foundation for research, development, and design in chemical processes. This wording indicates that the course has a dual identity. It is a chemistry course because it concerns active sites, reaction pathways, adsorption, acid-base properties, and metal surfaces. It is an engineering course because it concerns industrial catalysts, process conditions, deactivation, regeneration, and the selection of reaction conditions. A teaching design that treats catalysis only as physical chemistry would underplay the engineering identity; a design that treats it only as process technology would underplay mechanistic understanding. The reform proposed in this paper therefore uses a dual-track structure: each module includes a conceptual core and an application or research task. The 32 classroom hours are allocated across eight chapters. The introduction receives 2 hours and establishes the meaning of catalysis, the relationship between catalysis and thermodynamics, definitions and properties of catalysts, classification of catalytic systems, and the development and scope of catalysis science. Adsorption receives 4 hours and includes adsorption phenomena, heat of adsorption, states of adsorbed particles, adsorption isotherms, adsorption rates, and desorption rates. Gas-solid heterogeneous catalytic reaction kinetics receives 4 hours and includes the overall heterogeneous catalytic process, surface mass action law, surface-process kinetic equations, internal and external diffusion effects, and identification of reaction regimes. Promoters and supports receive 2 hours. Solid acid catalysts receive 6 hours and include acid-base catalyst classification, formation of acid-base centers, measurement of surface acidity, carbenium-ion formation, relationships among acid-center type, strength, number, activity, and selectivity, catalytic cracking of petroleum hydrocarbons, deactivation, and regeneration. Catalytic cracking receives 6 hours and focuses on overview, reactions of petroleum hydrocarbons, cracking catalysts, deactivation, and regeneration. Metal catalysts receive 4 hours and include the relationship between metal structure and catalytic performance, metal catalysis, crystal structure and surface atomic arrangement, and multiplet theory. Preparation methods for solid catalysts receive 4 hours and include precipitation, sol-gel, microemulsion, impregnation, and shaping.

This distribution shows two important priorities. First, the course gives substantial time to solid acid catalysis and catalytic cracking, which together occupy 12 hours, more than one third of the course. This is consistent with the professional orientation toward petroleum processing and petrochemicals. Second, the course gives only 4 hours to adsorption and 4 hours to heterogeneous kinetics, even though these topics are the conceptual foundation of later modules. This creates a teaching risk: if adsorption and kinetics are taught too abstractly or too quickly, students may later learn about solid acid catalysts and metal catalysts as separate lists of facts rather than as applications of the same catalytic principles. The reform model therefore treats adsorption and kinetics not merely as early chapters but as recurring lenses that appear again in later cases. The syllabus also includes ideological and professional value integration points. The introduction is linked with respect for science and professional identity. Adsorption and kinetics are linked with innovation spirit. Promoters and supports are linked with the ecological idea that clear waters and green mountains are as valuable as mountains of gold and silver. Solid acid catalysts are linked with safety production awareness. Catalytic cracking is linked with coordinated development and environmental consciousness. Metal catalysts are linked with technological innovation. Catalyst preparation methods are linked with respect for science and innovation. These points are important, but they can easily become superficial if they are added as separate moral statements. A stronger approach is to embed them in catalytic decision making. For example, environmental responsibility can be taught through catalyst selectivity and waste reduction; safety awareness can be taught through exothermic cracking, coke formation, regeneration, and thermal runaway; innovation spirit can be taught through comparison of traditional catalysts, zeolites, supported metals, single-atom catalysts, and data-driven catalyst discovery. The stated teaching method is mainly classroom lecture, but the syllabus encourages flexible teaching methods that connect theory with practice, heuristic teaching, classroom discussion, multimedia resources, models, charts, slides, videos, and computer-assisted teaching. It also requires some content to be self-studied because of limited hours. This provides an opportunity for blended learning without abandoning the lecture format. In a course like Catalysis Principles, lectures remain necessary because students need structured explanations of adsorption, kinetic equations, catalytic cracking mechanisms, and catalyst preparation. However, lectures should be short enough to leave time for interpretation tasks, peer explanation, and research-oriented questions. The reform model proposed here therefore retains lectures but changes their function: lectures introduce conceptual tools, while class activities require students to use those tools. The assessment design is particularly noteworthy. The final research report is worth 70 percent of the grade and asks each student to choose an individualized topic related to hot issues, frontier questions, or new technological developments in catalysis. Students are expected to consult domestic and foreign literature and write a research report. This assessment can strongly promote research literacy if it is scaffolded; without scaffolding, it can create uneven quality and may encourage superficial compilation. The paper therefore proposes a staged report process consisting of topic selection, database search, annotated bibliography, concept map, draft outline, peer review, oral mini-presentation, and final submission. Each stage is linked to a rubric, and each rubric reflects the course outcomes. In summary, the syllabus already contains many elements of a research-oriented course: professional relevance, frontier awareness, literature use, problem solving, and scientific writing. The main task is not to replace the syllabus but to strengthen its internal alignment. Alignment means that learning outcomes, content sequencing, activities, feedback, and assessment all point in the same direction. The next sections develop the theoretical and practical basis for such alignment.

Theoretical Framework

The proposed reform draws on several connected bodies of scholarship: learning sciences, outcome-oriented curriculum design, constructive alignment, active learning, problem-based learning, formative feedback, research-oriented teaching, and catalysis education. The sequence matters. General learning theory clarifies how students build usable understanding; curriculum design then converts that understanding into outcomes; classroom and assessment research explains how students can practice and demonstrate those outcomes. Ambrose et al. provide research-based principles for teaching, Barr and Tagg argue for a shift from content delivery to learning evidence, and Wiggins and McTighe offer a backward-design logic that begins with desired performance [7-9]. These sources provide the broad educational foundation for a compact professional course. Outcome-based education begins with the question of what students should be able to demonstrate after instruction. In a catalysis course, an outcome is not simply "understand adsorption" or "know catalyst preparation." Observable outcomes should include the ability to explain how adsorption strength affects activity and selectivity, derive or interpret a surface-rate expression, distinguish kinetic control from diffusion limitation, compare catalyst supports and promoters for a given reaction, analyze deactivation and regeneration strategies, and design a literature-supported research report on a catalytic technology. The course should also cultivate professional values such as safety awareness, environmental responsibility, and innovation. Expressing outcomes as performances enables the teacher to design tasks and rubrics that make learning visible. Once course outcomes are stated as performances, constructive alignment provides the next layer of logic. Biggs defines constructive alignment as the systematic connection among intended learning outcomes, teaching-learning activities, and assessment tasks [10]. Biggs and Tang later extend this idea into practical university teaching, emphasizing that assessment should ask students to perform the same kind of thinking that the course values [11]. For Catalysis Principles, this means that if the intended outcome is the ability to analyze catalyst structure-performance relationships, then students must repeatedly perform structure-performance analysis during the course, and the final assessment must evaluate that analysis. If the intended outcome is the ability to consult English literature, then literature reading cannot be postponed until the final week; it must be practiced in smaller tasks. If the intended outcome includes engineering problem solving, then assessment cannot consist only of definitions and short-answer questions. The syllabus ratio of 30 percent in-class training and 70 percent research report can therefore be aligned if both parts use a shared set of competencies. Alignment explains what should connect; active learning explains how those connections can be practiced in class. Freeman et al. report that active learning improves student performance in science, engineering, and mathematics [12]. Prince's engineering-education review similarly supports structured engagement rather than uninterrupted lecturing [13]. Wieman interprets this evidence as a clear signal that STEM courses should use teaching methods that require students to think during class [14]. In Catalysis Principles, this does not mean abandoning concise explanation. It means interspersing explanation with prediction, data interpretation, mechanism comparison, and decision justification. Catalysis is especially suitable for this approach because many concepts can be taught through contrasting cases: strong adsorption versus weak adsorption, kinetic control versus diffusion control, Bronsted acid sites versus Lewis acid sites, fresh catalyst versus coked catalyst, supported metal versus unsupported metal, and precipitation versus impregnation.

Problem-based learning extends active learning from short engagement episodes to more authentic professional situations. Hmelo-Silver describes PBL as a way for students to learn through complex problems and self-directed inquiry [15]. In chemistry education, Nagarajan and Overton connect project- and problem-based learning with systems thinking, and Varadarajan and Ladage synthesize theory and practice for undergraduate chemistry laboratories [16,17]. Catalysis problems are naturally ill-structured: a refinery may need to increase gasoline yield while reducing coke formation, an environmental engineer may need to remove bromate from water using a catalytic process, or a researcher may need to identify whether decreased activity results from sintering, poisoning, pore blockage, or site coverage. These problems require students to integrate theory, data, literature, and constraints. The course does not need to become a full PBL curriculum; each module can instead include one carefully designed problem scenario that anchors the theory in practice. Because a 32-hour elective cannot rely only on full-scale PBL, the ICAP framework helps calibrate the depth of classroom engagement. Chi and Wylie distinguish passive, active, constructive, and interactive modes of engagement [18]. This distinction helps the teacher design tasks that are short but cognitively meaningful. After a lecture on adsorption isotherms, for example, students can actively identify parameters in a data table, constructively explain why a Langmuir model fits or fails, and interactively compare their explanation with a peer group. The final research report is a constructive product, while peer review and oral discussion add interactive elements. Activity alone is insufficient unless students receive feedback before high-stakes assessment. Nicol and Macfarlane-Dick connect formative feedback with self-regulated learning, showing why feedback should help students monitor and improve their own work [19]. Sadler argues that formative assessment should help students understand standards, compare their current work with those standards, and close the gap [20]. This principle is crucial in Catalysis Principles because the final report carries 70 percent of the grade. If students receive feedback only at the end, the report becomes a judgment rather than a learning process. Formative milestones therefore make the assessment more educational: students refine topics, improve literature quality, revise concept maps, and strengthen arguments before the final submission. The need for feedback leads directly to research-oriented teaching. A research-oriented course does not simply introduce frontier topics; it asks students to practice parts of the research process. Kosinov's catalysis teaching article shows how students can learn from raw catalytic and characterization data [21]. Pagliaro proposes a unified catalysis course that connects science and technology [22]. Rodriguez et al. review process-oriented guided inquiry learning in chemistry education, and Shultz and Li show how problem-based laboratory work can develop information-literacy skills [23,24]. Taken together, these studies support a Catalysis Principles course in which students identify problems, search literature, compare evidence, interpret graphs, evaluate methods, and write supported arguments. Even without laboratory hours, students can analyze published data on conversion, selectivity, turnover frequency, acidity, surface area, XRD patterns, IR spectra, pore distribution, and catalyst lifetime.

General pedagogy still has to be translated into catalysis-specific practice. IUPAC definitions of catalysis and catalyst provide a stable conceptual starting point for terminology in the course [25,26]. Dumeignil, Paul, and Paul demonstrate that heterogeneous catalysis can be taught through principles, theories, and concepts that connect classical and modern viewpoints [27]. Pagliaro's unified-course proposal reinforces the value of integrating fundamentals with technology and research applications [22]. Schlögl's review provides a disciplinary map that helps students see heterogeneous catalysis as an evolving research field rather than a fixed list of catalyst types [3]. These sources justify the use of data packets, problem scenarios, and literature-supported writing in a lecture-dominant 32-hour Applied Chemistry elective. The final bridge in the literature review connects the syllabus's classical content with contemporary catalysis research. The syllabus emphasizes adsorption, gas-solid kinetics, solid acid catalysts, catalytic cracking, metal catalysts, and preparation methods. These topics remain essential, but students should also see how they connect to operando spectroscopy, single-atom catalysis, metal-support interactions, sustainable catalysis, machine learning for catalyst discovery, and high-throughput experimentation. Frontier topics should not replace fundamentals; they should function as interpretive bridges. Single-atom catalysis helps students revisit active-site isolation and metal-support interaction. Operando spectroscopy shows why catalysts must be studied under working conditions. Machine learning helps students understand descriptors and structure-performance relationships. In this way, the literature review does not add isolated trends to the course; it explains how modern research can deepen students' grasp of the syllabus fundamentals. The integrated theoretical framework can be summarized as follows. Course outcomes define the performances students should demonstrate. Constructive alignment connects outcomes with learning activities and assessment. Active and problem-based learning create opportunities for students to practice catalytic reasoning. Formative feedback scaffolds the final research report. Research-oriented teaching builds literature and data literacy. Discipline-specific catalysis education and contemporary catalysis research provide authentic content. This framework is used in the following sections to design a complete course model.

Methodological Design of the Teaching Research

This paper adopts a design-based research orientation. Design-based work is appropriate when the goal is to develop and refine an educational intervention in a real teaching context while also generating transferable design principles. The present study is based on documentary analysis of the course syllabus, literature review, constructive alignment, and the development of teaching instruments. The syllabus provides the course content, objectives, teaching methods, assessment structure, and reference resources, and therefore serves as the primary design document. Because classroom implementation is outside the scope of this article, the argument does not rely on experimental or quasi-experimental claims. Instead, the design draws on Biggs's alignment theory, Freeman et al.'s evidence for active learning, and Hmelo-Silver's analysis of problem-based learning to formulate an implementable and researchable course model [10,12,15]. The design process consists of five steps. The first step is syllabus interpretation. The content modules, hour allocation, teaching objectives, ideological integration points, teaching method statements, and assessment requirements are extracted and translated into pedagogical constraints. The second step is outcome reconstruction. The broad value, knowledge, and ability goals in the syllabus are converted into measurable course outcomes. The third step is literature alignment. Educational literature on active learning, constructive alignment, PBL, feedback, and chemistry education is connected with catalysis-specific literature and frontier catalysis research. The fourth step is learning activity design. Each module is redesigned with a conceptual lecture component, a problem or data task, a literature connection, and a formative product. The fifth step is assessment design. The in-class training and final research report are linked through rubrics and milestone tasks. The intended participants in a future implementation would be undergraduate Applied Chemistry students who have completed prerequisite courses in physical chemistry and chemical engineering principles. The instructor would be responsible for adapting cases to the students' background and for selecting research articles that are challenging but readable. The class format would remain compatible with the syllabus: 32 hours of classroom theoretical teaching, supplemented by after-class self-study. The design does not require adding laboratory hours, although laboratory examples and published data are used. The proposed research data for a future empirical study would include pre- and post-course concept questions, short in-class task artifacts, annotated bibliographies, research report drafts, final reports, peer-review records, student reflection logs, and optional interviews. Quantitative analysis could compare pre- and post-course performance on catalytic reasoning tasks, rubric scores across milestones, and correlations between literature engagement and final report quality. Qualitative analysis could examine changes in students' explanation patterns, use of evidence, and integration of theory with industrial or environmental constraints. Such a mixed-methods design would allow the teacher-researcher to evaluate not only whether students perform better but also how their thinking changes. Ethical considerations are straightforward but important. If the design is later implemented as research, students should be informed that ordinary course assessment and research data analysis are different. Participation in research analysis should not affect grades. Student work should be anonymized before analysis. If examples of student writing are published, permission should be obtained. Because the present article is a conceptual and documentary study, it involves no human-subject data; nevertheless, the proposed instruments should be used responsibly in any future empirical cycle. A design-based approach also recognizes that a course reform is rarely perfect in its first cycle. The implementation should be iterative. In the first cycle, the instructor may discover that students need more support in English literature reading, that a kinetic-modeling activity is too difficult for the allocated time, or that peer review needs clearer criteria. These findings should lead to revisions in the second cycle. The value of the design is therefore not only in its current plan but also in its capacity to generate evidence for continuous improvement.

Reconstructed Course Outcomes

The first major design task is to reconstruct course outcomes in performance language. The syllabus already includes value goals and knowledge-ability goals. It emphasizes the application of prior theoretical knowledge, engineering and production perspectives, flexible use of theory to solve practical problems, innovation thinking, understanding of different catalytic processes and catalyst systems, structure-performance relationships, catalytic reaction principles, characteristics and development directions of catalysis, and the ability to engage in catalyst development research. These goals can be translated into six outcome clusters. Outcome 1 is conceptual explanation. By the end of the course, students should be able to explain the meaning of catalysis, the relationship between catalysis and thermodynamics, the classification of catalytic systems, the nature of adsorption, the role of active sites, and the meaning of catalytic activity, selectivity, and stability. This outcome corresponds to the introduction and adsorption modules, but it also supports every later chapter. Conceptual explanation should be assessed through short written explanations, concept maps, and oral questioning rather than only through multiple-choice items. Outcome 2 is kinetic and transport reasoning. Students should be able to interpret surface-reaction mechanisms, write or analyze simple kinetic expressions, distinguish intrinsic kinetics from internal and external diffusion limitations, and identify reaction regimes. This outcome is essential for understanding why measured rates may not represent true surface kinetics and why catalyst particle size, pore structure, flow condition, and temperature affect industrial performance. Assessment should include data interpretation and scenario-based questions. Outcome 3 is structure-performance analysis. Students should be able to relate catalyst composition, support, promoter, acidity, metal structure, crystal face, dispersion, and preparation method to activity, selectivity, and stability. This outcome is central to solid acid catalysts, catalytic cracking, metal catalysts, and preparation methods. Assessment should include comparison tasks, such as choosing between catalyst preparation routes or explaining why two catalysts with similar composition show different selectivity. Outcome 4 is industrial and environmental problem solving. Students should be able to analyze catalytic technologies in petroleum processing, petrochemical production, fine chemicals, and environmental protection from the perspectives of efficiency, safety, resource use, pollution prevention, and sustainable development. This outcome integrates professional values with disciplinary reasoning. It can be assessed through cases such as catalytic cracking catalyst regeneration, NOx reduction, bromate removal, or the design of catalysts that reduce waste. Outcome 5 is research and information literacy. Students should be able to search, select, read, cite, and synthesize English literature in catalysis; identify research questions; compare methods and evidence; and write a research report with a clear argument. This outcome is directly linked to the 70 percent final report. It should be scaffolded through annotated bibliography, article analysis worksheets, and draft feedback.

Outcome 6 is scientific communication and reflective learning. Students should be able to communicate catalytic concepts through diagrams, tables, short presentations, and research writing; respond to feedback; and reflect on the quality of their reasoning. This outcome supports lifelong learning and professional identity. It can be assessed through peer review, oral reporting, and revision notes. These six outcome clusters align with the syllabus while making learning more observable. They also provide the basis for assessment. For example, in-class training can assess Outcomes 1 to 4 through short tasks and discussions, while the final research report can assess Outcomes 3 to 6. The relationship between outcomes and modules is cumulative. Adsorption supports kinetic reasoning; kinetics supports reaction-regime identification; promoters and supports support structure-performance analysis; solid acid catalysis and catalytic cracking support industrial problem solving; metal catalysts support microscopic structure analysis; preparation methods support catalyst design and development.

Overall Course Reform Model

The proposed model is called the Fundamental-Industrial-Research Integration model. It contains three strands that run through the 32-hour course. The fundamental strand ensures that students master core concepts and laws. The industrial strand connects these concepts with petroleum processing, petrochemicals, fine chemicals, environmental catalysis, catalyst production, deactivation, and regeneration. The research strand prepares students to read English literature, analyze data, and write a final report. The three strands are not separate weeks; they are integrated within every module. The fundamental strand begins with the meaning of catalysis and the relationship between catalysis and thermodynamics. A common misconception is that a catalyst changes the equilibrium position of a reaction. The course should explicitly confront this misconception by using energy diagrams and equilibrium examples. Students should understand that a catalyst changes the pathway and rate of approach to equilibrium but does not modify the overall standard Gibbs energy change. This idea should later reappear in catalytic cracking and metal catalysis: higher activity does not automatically mean higher equilibrium conversion, and selectivity depends on pathways rather than thermodynamics alone. The industrial strand begins with the question: why do industries invest in catalysts? Students should see catalysts as tools for lowering energy demand, increasing selectivity, reducing waste, enabling milder conditions, improving safety, and supporting circular and low-carbon chemical production. Industrial cases should be selected according to the syllabus. Catalytic cracking is the obvious anchor, but other cases can include ammonia synthesis, automobile exhaust catalysis, NOx selective catalytic reduction, hydrogenation, biomass conversion, and water-pollutant removal. These cases should be short enough for a 32-hour course but rich enough to show professional relevance. The research strand begins in the first week, not at the end. Students should receive a short guide to literature searching, DOI tracing, citation management, and the difference between review articles, research articles, educational articles, and industrial reports. The teacher can provide a small curated reading list including one general catalysis education paper, one heterogeneous catalysis review, one catalysis application paper, and one research-data analysis article. Students then gradually build their own topic-specific bibliography. By the time they submit the final report, they should have already received feedback on the quality of their sources and the logic of their research question.

The classroom format follows a repeated cycle: activate, explain, apply, extend, and reflect. Activate means beginning a module with a problem, image, graph, or industrial question. Explain means providing a concise lecture on the necessary concepts. Apply means asking students to solve a structured task using the concepts. Extend means connecting the task to literature or frontier research. Reflect means asking students to summarize what changed in their understanding and what evidence supports their conclusion. This cycle can be completed in one or two class periods depending on the module. For example, in the adsorption module, the teacher can begin with a question: if adsorption is necessary for surface reaction, why can too strong adsorption lower activity? After a short lecture on adsorption heat and isotherms, students analyze a small dataset comparing weak, moderate, and strong adsorption. They then connect this to the Sabatier principle and volcano plots. Finally, they reflect on how adsorption explains both activity and poisoning. The same cycle can be used in kinetics: students begin with a rate anomaly, learn surface mass action and diffusion limitations, analyze apparent activation energies, and reflect on how to identify kinetic regimes. The reform model also changes the role of self-study. The syllabus notes that some content must be self-studied because of limited hours. In the proposed design, self-study is not simply "read the textbook after class." It is structured around guiding questions, short reading tasks, and products that feed into class discussion. For example, before the solid acid catalyst module, students can read a short text on Bronsted and Lewis acid sites and answer three questions. Before the catalytic cracking module, they can view a process diagram and identify where catalyst deactivation and regeneration occur. Before the preparation-method module, they can compare the advantages and limitations of precipitation, sol-gel, microemulsion, and impregnation. A crucial feature of the model is the research report pipeline. The final report is broken into seven milestones. Milestone 1 is topic orientation: students choose a broad area such as solid acid catalysis, catalytic cracking catalyst deactivation, supported metal catalysts, environmental catalysis, single-atom catalysis, operando characterization, or data-driven catalyst discovery. Milestone 2 is research-question formulation: students turn a broad topic into a question that can be answered through literature. Milestone 3 is literature search: students submit a list of English references with DOI or stable URLs. Milestone 4 is annotated bibliography: students summarize and evaluate selected sources. Milestone 5 is concept and evidence map: students connect theory, catalyst structure, methods, and performance. Milestone 6 is draft and peer review. Milestone 7 is final report submission with a revision note. This pipeline makes the 70 percent final assessment fairer and more educational. It also reduces the risk of plagiarism because students must show the development of their topic over time. It teaches students that scientific writing is a process of inquiry and revision. It also directly supports the syllabus goal of cultivating comprehensive application ability and scientific paper writing ability.

Module-by-Module Teaching Design

Introduction to Catalysis. This module is allocated 2 hours in the syllabus and covers meaning of catalysis, catalysis and thermodynamics, definitions and properties of catalysts, classification and development of catalysis science. The teaching design should begin with the anchor problem: misconception that catalysts change thermodynamic equilibrium. This problem is deliberately phrased as a question rather than a definition because students need to experience catalysis as explanatory reasoning. The instructor first activates prior knowledge from physical chemistry and chemical engineering principles, then introduces the conceptual tools needed to solve the problem. The lecture segment should be concise and visual, using reaction-coordinate diagrams, catalyst surface sketches, process diagrams, or data tables. After the explanation, students complete a structured task in which they compare uncatalyzed and catalyzed energy profiles; classify catalytic systems from examples; write a one-page reflection on why catalysis is a professional identity topic for applied chemists. This task functions as both practice and formative assessment [25,26]. The research connection for this module should be explicit. Students should not only learn what the textbook says, but also see how the same idea appears in current literature. IUPAC definitions can anchor the language of catalysis, while Dumeignil et al. provide a concept-oriented entry into heterogeneous catalysis [27]. Pagliaro's unified approach can be used to show how catalysis science and technology belong in the same course [22], and Schlögl's review can help students connect introductory concepts with the broader development of the field [3]. The aim is not to make students read every paper in full during class. It is to train them to extract problem-relevant information from authentic scientific sources. The ideological and professional value point should be embedded in the disciplinary task. In this module, students can be asked to state what a responsible chemist or engineer must consider when applying the concept to production or research. The answer should be evidence-based. For example, environmental awareness should appear as selectivity, waste reduction, catalyst regeneration, solvent choice, or energy efficiency. Safety awareness should appear as temperature control, coke combustion, pressure operation, or hazardous intermediate management. Innovation should appear as a comparison between conventional methods and emerging methods. This approach makes value education inseparable from catalytic reasoning. Adsorption. This module is allocated 4 hours in the syllabus and covers adsorption phenomena, heat of adsorption, states of adsorbed species, adsorption isotherms, adsorption and desorption rates. The teaching design should begin with the anchor problem: why adsorption must be neither too weak nor too strong. This problem is deliberately phrased as a question rather than a definition because students need to experience catalysis as explanatory reasoning. The instructor first activates prior knowledge from physical chemistry and chemical engineering principles, then introduces the conceptual tools needed to solve the problem. The lecture segment should be concise and visual, using reaction-coordinate diagrams, catalyst surface sketches, process diagrams, or data tables. After the explanation, students complete a structured task in which they fit or qualitatively interpret adsorption data; explain poisoning and desorption; connect adsorption strength with catalytic activity and selectivity. This task functions as both practice and formative assessment [28,29]. The research connection for this module should be explicit. Students should not only learn what the textbook says, but also see how the same idea appears in current literature. For the introduction, students can examine definitions from IUPAC and a short review on heterogeneous catalysis. For adsorption and kinetics, students can read simplified excerpts on volcano relationships, surface science, or kinetic regimes. For promoters, supports, solid acids, catalytic cracking, metal catalysts, and preparation methods, students can use short literature packets containing an abstract, a figure, a catalyst table, and one guiding question. The aim is not to make students read every paper in full during class; the aim is to train them to extract problem-relevant information from authentic scientific sources.

The ideological and professional value point should be embedded in the disciplinary task. In this module, students can be asked to state what a responsible chemist or engineer must consider when applying the concept to production or research. The answer should be evidence-based. For example, environmental awareness should appear as selectivity, waste reduction, catalyst regeneration, solvent choice, or energy efficiency. Safety awareness should appear as temperature control, coke combustion, pressure operation, or hazardous intermediate management. Innovation should appear as a comparison between conventional methods and emerging methods. This approach makes value education inseparable from catalytic reasoning. Gas-Solid Heterogeneous Catalytic Kinetics. This module is allocated 4 hours in the syllabus and covers heterogeneous reaction processes, surface mass action law, surface-process kinetic equations, internal and external diffusion, reaction-regime identification. The teaching design should begin with the anchor problem: difference between intrinsic rate and observed rate. This problem is deliberately phrased as a question rather than a definition because students need to experience catalysis as explanatory reasoning. The instructor first activates prior knowledge from physical chemistry and chemical engineering principles, then introduces the conceptual tools needed to solve the problem. The lecture segment should be concise and visual, using reaction-coordinate diagrams, catalyst surface sketches, process diagrams, or data tables. After the explanation, students complete a structured task in which they analyze apparent rate data; identify kinetic, internal-diffusion, or external-diffusion control; justify what additional data are needed. This task functions as both practice and formative assessment [30,31]. The research connection for this module should be explicit. Students should not only learn what the textbook says, but also see how the same idea appears in current literature. For the introduction, students can examine definitions from IUPAC and a short review on heterogeneous catalysis. For adsorption and kinetics, students can read simplified excerpts on volcano relationships, surface science, or kinetic regimes. For promoters, supports, solid acids, catalytic cracking, metal catalysts, and preparation methods, students can use short literature packets containing an abstract, a figure, a catalyst table, and one guiding question. The aim is not to make students read every paper in full during class; the aim is to train them to extract problem-relevant information from authentic scientific sources. The ideological and professional value point should be embedded in the disciplinary task. In this module, students can be asked to state what a responsible chemist or engineer must consider when applying the concept to production or research. The answer should be evidence-based. For example, environmental awareness should appear as selectivity, waste reduction, catalyst regeneration, solvent choice, or energy efficiency. Safety awareness should appear as temperature control, coke combustion, pressure operation, or hazardous intermediate management. Innovation should appear as a comparison between conventional methods and emerging methods. This approach makes value education inseparable from catalytic reasoning. Promoters and supports. This module is allocated 2 hours in the syllabus and covers promoters, supports, support effects, dispersion, mechanical strength, thermal stability and environmental considerations. The teaching design should begin with the anchor problem: how a small amount of promoter or a different support changes catalyst performance. This problem is deliberately phrased as a question rather than a definition because students need to experience catalysis as explanatory reasoning. The instructor first activates prior knowledge from physical chemistry and chemical engineering principles, then introduces the conceptual tools needed to solve the problem. The lecture segment should be concise and visual, using reaction-coordinate diagrams, catalyst surface sketches, process diagrams, or data tables. After the explanation, students complete a structured task in which they choose a support for a target reaction; explain trade-offs among activity, stability, cost, and environmental impact. This task functions as both practice and formative assessment [1,32]. The research connection for this module should be explicit. Students should not only learn what the textbook says, but also see how the same idea appears in current literature. For the introduction, students can examine definitions from IUPAC and a short review on heterogeneous catalysis. For adsorption and kinetics, students can read simplified excerpts on volcano relationships, surface science, or kinetic regimes. For promoters, supports, solid acids, catalytic cracking, metal catalysts, and preparation methods, students can use short literature packets containing an abstract, a figure, a catalyst table, and one guiding question. The aim is not to make students read every paper in full during class; the aim is to train them to extract problem-relevant information from authentic scientific sources. The ideological and professional value point should be embedded in the disciplinary task. In this module, students can be asked to state what a responsible chemist or engineer must consider when applying the concept to production or research. The answer should be evidence-based. For example, environmental awareness should appear as selectivity, waste reduction, catalyst regeneration, solvent choice, or energy efficiency. Safety awareness should appear as temperature control, coke combustion, pressure operation, or hazardous intermediate management. Innovation should appear as a comparison between conventional methods and emerging methods. This approach makes value education inseparable from catalytic reasoning.

Solid Acid Catalysts. This module is allocated 6 hours in the syllabus and covers acid-base catalyst classification, formation and measurement of acid centers, carbenium ions, acid-site type, strength and number, activity and selectivity, deactivation and regeneration. The teaching design should begin with the anchor problem: how acid-site properties control hydrocarbon conversion. This problem is deliberately phrased as a question rather than a definition because students need to experience catalysis as explanatory reasoning. The instructor first activates prior knowledge from physical chemistry and chemical engineering principles, then introduces the conceptual tools needed to solve the problem. The lecture segment should be concise and visual, using reaction-coordinate diagrams, catalyst surface sketches, process diagrams, or data tables. After the explanation, students complete a structured task in which they compare Bronsted and Lewis acid sites; interpret acidity characterization; explain coke formation and regeneration strategies. This task functions as both practice and formative assessment [33,34]. The research connection for this module should be explicit. Students should not only learn what the textbook says, but also see how the same idea appears in current literature. For the introduction, students can examine definitions from IUPAC and a short review on heterogeneous catalysis. For adsorption and kinetics, students can read simplified excerpts on volcano relationships, surface science, or kinetic regimes. For promoters, supports, solid acids, catalytic cracking, metal catalysts, and preparation methods, students can use short literature packets containing an abstract, a figure, a catalyst table, and one guiding question. The aim is not to make students read every paper in full during class; the aim is to train them to extract problem-relevant information from authentic scientific sources. The ideological and professional value point should be embedded in the disciplinary task. In this module, students can be asked to state what a responsible chemist or engineer must consider when applying the concept to production or research. The answer should be evidence-based. For example, environmental awareness should appear as selectivity, waste reduction, catalyst regeneration, solvent choice, or energy efficiency. Safety awareness should appear as temperature control, coke combustion, pressure operation, or hazardous intermediate management. Innovation should appear as a comparison between conventional methods and emerging methods. This approach makes value education inseparable from catalytic reasoning. Catalytic Cracking. This module is allocated 6 hours in the syllabus and covers overview, petroleum hydrocarbon cracking reactions, cracking catalysts, deactivation and regeneration. The teaching design should begin with the anchor problem: how catalytic cracking balances conversion, selectivity, coke and environmental responsibility. This problem is deliberately phrased as a question rather than a definition because students need to experience catalysis as explanatory reasoning. The instructor first activates prior knowledge from physical chemistry and chemical engineering principles, then introduces the conceptual tools needed to solve the problem. The lecture segment should be concise and visual, using reaction-coordinate diagrams, catalyst surface sketches, process diagrams, or data tables. After the explanation, students complete a structured task in which they analyze a refinery-oriented scenario; link zeolite acidity, pore structure and product distribution; evaluate regeneration safety. This task functions as both practice and formative assessment [35,36]. The research connection for this module should be explicit. Students should not only learn what the textbook says, but also see how the same idea appears in current literature. For the introduction, students can examine definitions from IUPAC and a short review on heterogeneous catalysis. For adsorption and kinetics, students can read simplified excerpts on volcano relationships, surface science, or kinetic regimes. For promoters, supports, solid acids, catalytic cracking, metal catalysts, and preparation methods, students can use short literature packets containing an abstract, a figure, a catalyst table, and one guiding question. The aim is not to make students read every paper in full during class; the aim is to train them to extract problem-relevant information from authentic scientific sources.

The ideological and professional value point should be embedded in the disciplinary task. In this module, students can be asked to state what a responsible chemist or engineer must consider when applying the concept to production or research. The answer should be evidence-based. For example, environmental awareness should appear as selectivity, waste reduction, catalyst regeneration, solvent choice, or energy efficiency. Safety awareness should appear as temperature control, coke combustion, pressure operation, or hazardous intermediate management. Innovation should appear as a comparison between conventional methods and emerging methods. This approach makes value education inseparable from catalytic reasoning. Metal Catalysts. This module is allocated 4 hours in the syllabus and covers relationship between metal structure and catalytic performance, metal catalysis, crystal structure, crystal faces and atomic arrangement, multiplet theory. The teaching design should begin with the anchor problem: why metal surface structure changes catalytic activity. This problem is deliberately phrased as a question rather than a definition because students need to experience catalysis as explanatory reasoning. The instructor first activates prior knowledge from physical chemistry and chemical engineering principles, then introduces the conceptual tools needed to solve the problem. The lecture segment should be concise and visual, using reaction-coordinate diagrams, catalyst surface sketches, process diagrams, or data tables. After the explanation, students complete a structured task in which they compare structure-sensitive and structure-insensitive reactions; connect crystal faces with adsorption and activation; discuss supported metals and single-atom catalysts. This task functions as both practice and formative assessment [29,37]. The research connection for this module should be explicit. Students should not only learn what the textbook says, but also see how the same idea appears in current literature. For the introduction, students can examine definitions from IUPAC and a short review on heterogeneous catalysis. For adsorption and kinetics, students can read simplified excerpts on volcano relationships, surface science, or kinetic regimes. For promoters, supports, solid acids, catalytic cracking, metal catalysts, and preparation methods, students can use short literature packets containing an abstract, a figure, a catalyst table, and one guiding question. The aim is not to make students read every paper in full during class; the aim is to train them to extract problem-relevant information from authentic scientific sources. The ideological and professional value point should be embedded in the disciplinary task. In this module, students can be asked to state what a responsible chemist or engineer must consider when applying the concept to production or research. The answer should be evidence-based. For example, environmental awareness should appear as selectivity, waste reduction, catalyst regeneration, solvent choice, or energy efficiency. Safety awareness should appear as temperature control, coke combustion, pressure operation, or hazardous intermediate management. Innovation should appear as a comparison between conventional methods and emerging methods. This approach makes value education inseparable from catalytic reasoning. Preparation Methods for Solid Catalysts. This module is allocated 4 hours in the syllabus and covers precipitation, sol-gel, microemulsion, impregnation and catalyst shaping. The teaching design should begin with the anchor problem: how preparation history determines catalyst structure and performance. This problem is deliberately phrased as a question rather than a definition because students need to experience catalysis as explanatory reasoning. The instructor first activates prior knowledge from physical chemistry and chemical engineering principles, then introduces the conceptual tools needed to solve the problem. The lecture segment should be concise and visual, using reaction-coordinate diagrams, catalyst surface sketches, process diagrams, or data tables. After the explanation, students complete a structured task in which they design a preparation route for a target catalyst; justify method choice; identify characterization needed to verify success. This task functions as both practice and formative assessment [38]. The research connection for this module should be explicit. Students should not only learn what the textbook says, but also see how the same idea appears in current literature. For the introduction, students can examine definitions from IUPAC and a short review on heterogeneous catalysis. For adsorption and kinetics, students can read simplified excerpts on volcano relationships, surface science, or kinetic regimes. For promoters, supports, solid acids, catalytic cracking, metal catalysts, and preparation methods, students can use short literature packets containing an abstract, a figure, a catalyst table, and one guiding question. The aim is not to make students read every paper in full during class; the aim is to train them to extract problem-relevant information from authentic scientific sources. The ideological and professional value point should be embedded in the disciplinary task. In this module, students can be asked to state what a responsible chemist or engineer must consider when applying the concept to production or research. The answer should be evidence-based. For example, environmental awareness should appear as selectivity, waste reduction, catalyst regeneration, solvent choice, or energy efficiency. Safety awareness should appear as temperature control, coke combustion, pressure operation, or hazardous intermediate management. Innovation should appear as a comparison between conventional methods and emerging methods. This approach makes value education inseparable from catalytic reasoning.

Research Report Design and Scaffolding

The final research report is the most important assessment in the syllabus, worth 70 percent of the course grade. This high weight can be justified only if the report measures the intended advanced outcomes: literature use, research synthesis, catalytic reasoning, scientific communication, and professional judgment. Studies of laboratory learning, guided inquiry, and catalysis-oriented undergraduate activities show that students need staged support when they are asked to connect concepts, evidence, and scientific communication [39-41]. The report therefore cannot be treated as a last-minute assignment. It must be built gradually through the semester. The first stage is topic orientation. During the first two weeks, the instructor introduces broad research areas that match the syllabus: adsorption and catalytic activity, gas-solid catalytic kinetics, promoters and supports, solid acid catalysts, catalytic cracking, metal catalysts, catalyst preparation, catalyst deactivation, environmental catalysis, operando characterization, single-atom catalysis, and data-driven catalyst discovery. Students are encouraged to choose a topic that is specific enough to investigate but broad enough to support literature synthesis. A weak topic would be "catalytic cracking." A stronger topic would be "the relationship between zeolite acidity, coke formation, and regeneration strategy in fluid catalytic cracking catalysts." Another weak topic would be "metal catalysts." A stronger topic would be "metal-support interactions in supported noble-metal catalysts for low-temperature oxidation reactions." Students submit a short topic statement and receive feedback. The second stage is research-question formulation. Students are asked to transform their topic into one main question and two or three subquestions. The main question should require explanation or evaluation, not only description. For example, "What are the main methods for preparing solid acid catalysts?" is descriptive. "How do preparation route and post-treatment affect the acidity, pore structure, and catalytic stability of solid acid catalysts?" is analytical. The teacher can provide a template: object, variable, mechanism, evidence, and significance. This template helps students move from topic names to researchable arguments. The third stage is literature search and source validation. Students learn to use databases such as Web of Science, Scopus, ACS Publications, ScienceDirect, SpringerLink, Wiley Online Library, RSC, PubMed where relevant, and Google Scholar for cross-checking. They are taught to record full bibliographic information, DOI, publication year, journal title, and article type. The instructor should emphasize that traceability means a reader can locate the source through DOI, publisher page, library database, or stable institutional repository. Students submit at least ten preliminary English sources by the middle of the course and expand the list for the final report. Because the syllabus emphasizes international English literature, the report rubric should reward the relevance and quality of sources, not merely the number of references.

The fourth stage is annotated bibliography. Students select five to eight key English sources and write short annotations. Each annotation includes the research problem, catalyst system, method, main finding, limitation, and relevance to the student's report question. This task prevents superficial citation. It also helps the teacher detect misunderstanding early. For example, a student writing about solid acid catalysts may cite a paper on homogeneous acid catalysis that is not relevant; the annotation stage allows correction before the final report. The fifth stage is concept and evidence mapping. Students draw a map that connects core concepts from the course with evidence from literature. For catalytic cracking, the map may connect zeolite framework, Bronsted acid site, carbenium ion, beta-scission, product distribution, coke formation, diffusion limitation, regeneration, and environmental impact. For metal catalysts, the map may connect metal crystal face, adsorption energy, active site ensemble, support effect, dispersion, deactivation, and performance metrics. This map becomes the skeleton of the report. The sixth stage is drafting and peer review. Students submit an outline or partial draft. Peer review is guided by a checklist: Is the research question clear? Are the sources traceable? Does the report explain mechanisms rather than only list facts? Are figures and tables interpreted? Are claims supported by evidence? Is the relationship to Catalysis Principles explicit? Does the report consider safety, sustainability, or industrial relevance where appropriate? Peer review helps students see examples of different approaches and improves their ability to evaluate scientific writing. The seventh stage is final submission and reflection. The final report should include title, abstract, keywords, introduction, body sections organized by argument, conclusion, and references. Students also submit a short revision note explaining how they used feedback. The revision note reinforces self-regulated learning and makes the writing process visible. The teacher evaluates the report using a rubric with five dimensions: research question and structure, catalytic theory and mechanism reasoning, evidence and literature quality, industrial/environmental/professional relevance, and scientific writing and citation. A report assignment designed in this way becomes more than a summative product. It becomes the organizing spine of the course. Each module contributes concepts and evidence that students can use in their reports. The final assessment therefore measures the cumulative learning intended by the syllabus.

Assessment Rubric and Feedback System

The assessment system should preserve the syllabus ratio of 30 percent in-class training and 70 percent final research report, but the meaning of each part should be clarified. The 30 percent in-class training can be divided into attendance and preparation, short concept checks, problem/data tasks, literature microtasks, and participation in discussion or peer review. Nicol and Macfarlane-Dick's feedback principles indicate why these tasks should help students regulate their learning [19], while Sadler's formative-assessment model explains why students need explicit standards and opportunities for improvement [20]. Wiggins and McTighe's backward-design logic also supports the use of assessment evidence that is directly connected with desired learning outcomes [9]. In this structure, attendance supports engagement, concept checks test understanding, data tasks assess catalytic reasoning, literature microtasks prepare the final report, and peer review strengthens communication. The 70 percent final report can be assessed through a rubric totaling 100 points, later converted to the course grade. Research question and organization can account for 15 points. A high-quality report states a focused question, explains why it matters, and organizes sections around an argument. Catalytic principles and mechanism reasoning can account for 25 points. A high-quality report accurately uses concepts such as adsorption, acidity, active sites, kinetics, diffusion, deactivation, support effects, or preparation-structure relationships. Evidence and literature use can account for 25 points. A high-quality report uses sufficient English literature, prioritizes peer-reviewed and traceable sources, interprets figures or data, compares findings, and cites correctly. Industrial, safety, environmental, or innovation relevance can account for 15 points. A high-quality report connects catalysis with real production, sustainability, safety, or frontier technology. Scientific writing can account for 20 points. A high-quality report is coherent, concise, properly formatted, and academically honest. Feedback should be distributed across the semester. After topic orientation, feedback should focus on scope. After research-question formulation, feedback should focus on analytical depth. After literature search, feedback should focus on source quality and traceability. After annotated bibliography, feedback should focus on understanding and relevance. After concept mapping, feedback should focus on logic. After draft submission, feedback should focus on argument, evidence, and writing. The final feedback should summarize strengths and future directions rather than only justify the grade. Rubrics also support equity. Students may enter the course with different levels of English reading ability and scientific writing experience. A transparent rubric helps them understand expectations. Milestone feedback helps students improve before the final grade. Peer review helps students learn from each other. The teacher can also provide sentence frames for scientific writing, such as "The observed increase in selectivity can be attributed to...", "This result suggests that the rate is limited by...", and "Compared with catalyst A, catalyst B shows... because..." Such support is especially useful when students are reading and writing in English. Academic integrity should be addressed explicitly. Because the final report requires literature synthesis, students must understand citation, paraphrasing, quotation, and plagiarism. They should be taught that changing a few words from a source is not enough; they must write their own synthesis and cite the source. They should also learn that generative tools, if permitted by institutional policy, cannot replace source verification, mechanism reasoning, or original organization. A report without traceable references should not receive a high score even if the language is fluent.

Integration of Frontier Catalysis Topics

The syllabus is grounded in classical heterogeneous catalysis, but a modern Catalysis Principles course should connect classical principles with frontier topics. Frontier integration should be selective and concept-driven. The goal is not to overload students with fashionable terms but to show how new research grows from basic principles. Single-atom catalysis is a useful frontier topic in the metal catalyst module because it allows students to revisit dispersion, active-site isolation, metal-support interaction, and atom economy. Qiao et al.'s report on Pt1/FeOx for CO oxidation can be used to introduce the evidentiary demands of claiming isolated metal atoms [42]. Zhang et al.'s work on stabilizing a platinum single-atom catalyst can then help students discuss how support chemistry influences stability and activity [43]. Students can compare nanoparticles, clusters, and isolated atoms and ask whether a single metal atom behaves like a metal surface or like a coordination complex. This discussion reinforces the syllabus topics of metal structure, catalytic performance, supports, and preparation methods. Operando spectroscopy is a useful frontier topic in adsorption, kinetics, deactivation, and solid acid catalysis. Groppo et al. review how in situ and operando infrared spectroscopy can reveal adsorbate-induced structural changes in heterogeneous catalysis [44]. Nuguid et al. translate in situ infrared spectroscopy of NOx reduction catalysts into a laboratory exercise that can be used in both in-person and virtual learning contexts [45]. These sources help students understand why ex situ characterization may not reveal the actual working state of a catalyst. A short teaching activity can show an IR spectrum before and during reaction and ask students what changes in surface species imply. This connects directly to adsorption states, acid-site measurement, NOx reduction, and catalyst deactivation. Machine learning and high-throughput experimentation are useful frontier topics near the end of the course because they give students a modern reason to care about descriptors. The Open Catalyst 2020 dataset illustrates the scale at which catalytic surface problems can now be represented computationally [46]. Esterhuizen et al. emphasize that interpretable machine learning should generate chemical knowledge rather than only predictions [47]. Goldsmith et al. review how machine learning can support heterogeneous catalyst design and discovery [48]. A catalysis-focused undergraduate course in modern drug discovery can also help students recognize that catalytic thinking extends from petrochemical and environmental processes to fine-chemical and pharmaceutical innovation [49]. In teaching, these sources should be connected to concepts students already know: acidity, surface area, pore size, adsorption energy, and metal dispersion. The teacher should also discuss limitations such as data quality, extrapolation, interpretability, and the continuing need for chemical judgment. This prevents students from seeing machine learning as a magical replacement for catalysis principles. Sustainable catalysis should be integrated throughout the course rather than placed in one final lecture. Adsorption and selectivity relate to waste prevention, while kinetics and diffusion relate to energy efficiency. Solid acid catalysis and catalytic cracking introduce petroleum resource utilization, emissions, and regeneration issues; Corma's review of inorganic solid acids and Busca's review of acid catalysts provide disciplinary support for this connection [33,34]. Laboratory-oriented work by Seery also reminds instructors that practical chemistry education should teach students how chemists actually make decisions, not only how they recall concepts [39]. By repeatedly connecting course concepts with sustainability, students learn that green development is both a technical and an ethical dimension of catalyst design. Industrial cases should also be updated without weakening the syllabus focus on catalytic cracking. Ullmann's entry on fluid catalytic cracking provides an industrial anchor for petroleum processing, while the Handbook of Heterogeneous Catalysis and Schlögl's review place such cases in a wider field of catalytic technology and research [1-3]. Catalytic cracking can therefore be compared with biomass upgrading, plastic waste conversion, CO2 utilization, hydrogen production, ammonia synthesis under milder conditions, and environmental catalysis. These cases help students see the development direction of catalysis science and support professional identity: applied chemists can contribute to cleaner production, energy transition, pollution control, and material innovation.

Implementation Plan for a 32-Hour Course

A practical implementation plan must respect the 32-hour limit. The following schedule is one possible arrangement. Week 1 introduces the course, outcomes, report pipeline, and basic concepts of catalysis. Week 2 focuses on catalysis and thermodynamics, classification, and the first literature microtask. Weeks 3 and 4 focus on adsorption, adsorption heat, isotherms, and adsorption-rate reasoning. Week 5 focuses on heterogeneous catalytic processes and surface mass action. Week 6 focuses on kinetic equations and diffusion limitations. Week 7 covers promoters and supports with an environmental and catalyst-life-cycle task. Weeks 8 to 10 cover solid acid catalysts, acidity measurement, carbenium-ion mechanisms, deactivation, and regeneration. Weeks 11 to 13 cover catalytic cracking, catalyst properties, product selectivity, coke formation, and industrial regeneration. Weeks 14 and 15 cover metal catalysts, surface structure, crystal faces, and frontier extensions such as single-atom catalysts. Week 16 covers catalyst preparation methods, shaping, course integration, and final report consultation. Because 32 hours may be distributed differently by the institution, the plan can be adjusted. The key is not the exact week number but the rhythm of conceptual instruction and report scaffolding. The report milestones should occur in parallel. Topic orientation occurs in Week 1. Research-question submission occurs around Week 3. Preliminary reference list occurs around Week 5. Annotated bibliography occurs around Week 8. Concept map occurs around Week 10. Draft outline occurs around Week 12. Peer review occurs around Week 14. Final submission occurs after the last class according to the examination schedule. The teacher's preparation includes three resource packages. The first is a concept package containing diagrams, short notes, and problem sets for each module. The second is a data package containing simplified catalytic data: adsorption isotherm data, rate data, diffusion scenarios, acidity characterization summaries, catalytic cracking product distributions, metal catalyst comparison tables, and preparation-structure-performance examples. The third is a literature package containing a curated list of English articles with DOI links, including educational papers and catalysis research papers. These packages reduce students' cognitive load while still exposing them to authentic materials. Classroom management should encourage participation without consuming too much time. A useful pattern is the five-minute individual response, five-minute pair discussion, and ten-minute class synthesis. For data tasks, students can work in groups of three or four, each group assigned a role: mechanism analyst, data interpreter, literature checker, and reporter. Roles can rotate. This structure prevents one student from doing all the work and helps quieter students participate. Digital tools can support implementation. A learning management system can host reading materials, quizzes, submission links, and feedback. Citation managers such as Zotero, Mendeley, or EndNote can be introduced briefly. Shared documents can support peer review. Simple spreadsheet tools can be used for plotting adsorption or rate data. The teacher should ensure that technology serves learning rather than distracts from concepts.

Expected Educational Contributions

The proposed reform is expected to contribute to student learning in several ways. First, it strengthens conceptual coherence. Instead of encountering each chapter as a separate block, students repeatedly use a small set of catalytic ideas across modules. This repetition supports transfer. Adsorption is not only a chapter; it explains metal catalysis, poisoning, solid acid reactions, and catalyst deactivation. Kinetics is not only equations; it explains rate control, diffusion, and process optimization. Preparation methods are not only procedures; they explain structure-performance relationships. Second, the reform strengthens professional relevance. Students in Applied Chemistry need to see why catalysis matters beyond examinations. Industrial cases and environmental scenarios help them connect learning with petroleum processing, petrochemicals, fine chemicals, pollution control, and sustainable development. This can strengthen professional identity and motivation. When students understand that catalyst design affects energy use, product selectivity, safety, and waste generation, they can see the social responsibility of applied chemistry. Third, the reform strengthens research literacy. Many undergraduate students struggle with English literature because they are asked to read papers without being taught how to search, select, annotate, and synthesize them. The report pipeline makes literature work visible and manageable. Students learn that a scientific report is built from questions, evidence, comparison, and argument. They also learn to value DOI traceability and source quality. Fourth, the reform strengthens assessment validity. If the course aims to cultivate problem solving and scientific writing, the final report is a suitable assessment only when it is aligned with learning activities and rubrics. The proposed system makes the 70 percent report meaningful and fair. The 30 percent in-class training no longer functions only as attendance and questioning; it becomes a collection of formative evidence that supports the final product. Fifth, the reform supports teacher development. Preparing data tasks, literature packets, and rubrics requires the teacher to rethink the course from the learner's perspective. The teacher becomes not only a lecturer but also a designer of learning environments and a mentor for scientific inquiry. This is consistent with the broader direction of higher education reform in which teachers integrate teaching, research, industry, and moral cultivation.

Discussion

The proposed course reform has several advantages. It is realistic because it does not require a complete change in institutional structure or additional laboratory hours. It respects the existing syllabus, hour allocation, and assessment ratio. It is also flexible because individual problem scenarios and literature articles can be updated each year. A teacher can begin with a small number of redesigned activities and expand gradually. The reform also addresses a common tension in specialized undergraduate courses: the tension between content coverage and deep learning. Catalysis Principles contains many topics, and the teacher may feel pressure to cover all details. However, deep learning does not require abandoning content; it requires organizing content around transferable principles. By using recurring conceptual threads, students can learn more efficiently. They may not memorize every catalyst type, but they will understand how to analyze a new catalyst system. Another advantage is the integration of values with disciplinary reasoning. In some courses, ideological or professional value education is presented separately from scientific content, which can make it feel disconnected. In the proposed design, values are embedded in authentic decisions. Environmental responsibility appears when students compare selectivity and waste. Safety appears when students analyze regeneration and exothermic processes. Innovation appears when students compare traditional and frontier catalysts. Professional identity appears when students see how catalysis supports industrial and societal needs. The report pipeline is perhaps the most important innovation. A final report worth 70 percent can motivate students, but it can also create problems if students lack support. Scaffolding turns the report into a semester-long inquiry process. It also allows the teacher to intervene before misunderstandings become final products. For example, if a student chooses a topic that is too broad, the teacher can guide narrowing. If a student cites low-quality sources, the teacher can guide database use. If a student summarizes papers without analysis, the teacher can use the concept map to push toward synthesis. There are also challenges. The first challenge is time. Active tasks and report workshops consume classroom minutes. The teacher must decide what can be moved to self-study and what must be taught directly. The solution is not to add more work indiscriminately but to make every task serve multiple purposes. A data task can teach a concept, assess understanding, and provide material for the report. A literature annotation can teach reading, source evaluation, and scientific writing. The second challenge is student readiness. Some students may not have strong English reading skills or may be unfamiliar with scientific databases. The teacher should provide models, vocabulary lists, and reading strategies. For difficult articles, students can focus on title, abstract, figures, tables, conclusions, and one key method rather than reading every line. Gradually, they can handle more complexity. The third challenge is assessment workload. Rubrics and milestone feedback require time. The teacher can manage workload by using concise feedback codes, peer review, group consultations, and sample comments. Not every milestone needs a long written response. Sometimes a short note such as "question too broad," "source lacks DOI," "mechanism missing," or "evidence not compared" is enough to guide revision. The fourth challenge is maintaining academic standards. A research report should not become a collection of translated paragraphs. Students need explicit instruction in paraphrasing, citation, and synthesis. The teacher can require students to include an evidence table showing how each key claim is supported by sources. This makes the relationship between literature and argument visible. Overall, the reform is best understood as a practical alignment strategy. It does not claim to solve every problem in catalysis education, but it provides a coherent pathway from syllabus goals to classroom activities and assessment evidence.

Limitations and Future Research

This paper has several limitations. First, it is based on a syllabus and literature review rather than classroom implementation data. Therefore, it cannot claim empirical improvement in student performance. Future research should implement the design and collect evidence from multiple cohorts; the National Research Council's review of discipline-based education research provides a useful model for building such evidence in undergraduate science and engineering education [6]. Second, the design is tailored to one 32-hour elective course in an Applied Chemistry program. Other institutions may have different prerequisites, laboratory resources, student backgrounds, and assessment regulations. The model should therefore be adapted rather than copied mechanically. Third, the proposed report pipeline assumes that students have at least basic access to English literature databases. If access is limited, the teacher may need to provide more open-access sources or use institutional library support. The principle of traceability should remain, but the source pool may vary. Fourth, the reform emphasizes heterogeneous catalysis because the syllabus focuses on adsorption, gas-solid kinetics, solid acid catalysts, catalytic cracking, metal catalysts, and solid catalyst preparation. Homogeneous catalysis, enzymatic catalysis, photocatalysis, and electrocatalysis can be included as frontier extensions or report topics, but they are not central in the proposed classroom sequence. If the program wants broader catalysis coverage, the syllabus itself may need revision. Future research can proceed in three directions. The first is empirical evaluation of learning outcomes using pre- and post-tests, report rubrics, and student interviews. The second is development of validated concept inventories for catalysis principles, especially adsorption, kinetics, and structure-performance reasoning. The third is comparative study of different teaching formats, such as lecture-plus-data tasks, flipped classroom, full PBL, and laboratory-integrated catalysis teaching. Such research would contribute not only to one course but also to the broader field of chemistry and chemical engineering education.

Conclusion

Catalysis Principles is a compact but professionally significant course. The Yangtze University syllabus already contains a strong foundation: clear disciplinary scope, emphasis on theory-practice connection, attention to industrial catalysis, integration of professional values, and a research-report-based final assessment. The challenge is to align these elements so that students do not merely receive information but learn to reason, investigate, and communicate like beginning catalysis professionals. This paper has proposed an outcome-based, constructively aligned, research-oriented reform model for the course. The model integrates fundamental concepts, industrial cases, and literature-based inquiry. It redesigns each module around anchor problems, active tasks, and research connections. It scaffolds the final report through topic selection, research-question development, source validation, annotated bibliography, concept mapping, peer review, and revision. It also provides rubrics and implementation strategies compatible with a 32-hour course. The central message is that catalysis education should make the logic of catalytic reasoning visible. Students should learn how adsorption, kinetics, active sites, catalyst structure, diffusion, deactivation, regeneration, and preparation methods work together. They should also learn that catalysis is tied to safety, sustainability, innovation, and industrial responsibility. When the course is designed in this way, a final research report becomes not only an examination product but also evidence that students can connect theory, literature, and practice.

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