

FROM MOLECULAR COORDINATION TO SUSTAINABLE PRODUCTION: INTEGRATING GREEN CATALYSIS, SDG 12, AND CHEMISTRY EDUCATION

Sutiono

Pendidikan Kimia Pascasarjana Universitas Negeri Gorontalo
sutionochemistry3@gmail.com

Abstract

This study examines the conceptual relationships among coordination bonding, environmentally responsible catalyst design, Sustainable Development Goal 12, and sustainability-oriented chemistry education. The study used a qualitative research approach through document analysis, narrative literature review, and thematic synthesis of peer-reviewed publications published mainly between 2020 and 2025. The researcher selected documents purposively according to their relevance to coordination chemistry, green catalysis, green chemistry, sustainable production, systems thinking, and chemistry education. The analysis produced five interconnected themes: coordination bonding as the molecular basis of catalytic interaction, molecular and electronic structures as determinants of catalytic performance, green catalysis as a pathway toward energy and resource efficiency, SDG 12 as a framework for evaluating responsible production, and chemistry education as a space for developing sustainability reasoning. The findings show that catalytic sustainability depends not only on reaction activity but also on selectivity, energy demand, material availability, catalyst stability, recovery, toxicity, and waste generation. This study proposes an integrated conceptual framework that connects molecular interactions, catalyst performance, green chemistry, sustainable production, and chemistry learning through systems thinking and Project Based Learning. The framework expands the educational role of coordination chemistry from structural knowledge toward a basis for understanding and evaluating the sustainability consequences of chemical decisions.

Keywords: coordination chemistry; green catalysis; green chemistry; SDG 12; sustainability-oriented chemistry education

Introduction

The transition toward sustainable production systems has placed chemistry at the center of contemporary environmental and technological challenges. Modern societies depend on chemical knowledge to produce medicines, materials, fertilizers, fuels, electronics, and other products that support daily life. However, conventional chemical production frequently depends on non-renewable raw materials, hazardous reagents, energy-intensive operations, and multistep pathways that generate considerable waste. Zimmerman et al. [1] argue that chemistry should move beyond controlling pollution after its formation and instead redesign chemicals and processes from the beginning. This approach requires scientists to consider toxicity, resource renewability, degradation, energy requirements, and life-cycle

impacts as components of chemical performance. Such a shift changes sustainability from an external environmental concern into an intrinsic criterion of molecular and process design.

Green chemistry provides one of the most established frameworks for this transformation. It encourages waste prevention, atom economy, safer synthesis, safer solvents, energy efficiency, renewable feedstocks, catalysis, and designs that reduce hazards throughout chemical processes. Contemporary scholarship, however, distinguishes green chemistry from sustainable chemistry and circular chemistry. Mutlu and Barner [2] explain that green chemistry primarily addresses the design of safer and less wasteful chemical processes, while sustainable chemistry includes broader environmental, economic, and societal dimensions. Circular chemistry focuses more explicitly on closing material loops through reuse, recovery, recycling, and redesign. This conceptual distinction matters because researchers cannot evaluate sustainability through one indicator alone. A process that reduces hazardous waste may still require scarce materials, high energy inputs, or difficult recovery procedures.

Catalysis occupies a strategic position within this discussion. Catalysts enable reactions to follow alternative pathways and can reduce activation barriers, improve selectivity, decrease energy requirements, and reduce undesirable products. Papanikolaou et al. [3] identify catalysis as a central technological component in the transition toward chemical production systems that reduce dependence on fossil resources. Centi and Perathoner [16] similarly emphasize the need to redesign chemical production through integrated approaches that connect renewable energy, alternative feedstocks, and catalytic conversion routes. These arguments indicate that catalyst development does not concern reaction rates alone. Catalyst design also affects resource consumption, energy demand, process complexity, and waste generation.

Electrocatalysis illustrates this relationship clearly. Luo et al. [4] show that catalysts intended for high-current-density water splitting must combine favorable intrinsic activity with mass transport, surface chemistry, electrical conductivity, morphology, and stability under demanding operational conditions. These factors show that laboratory-scale catalytic activity does not automatically translate into sustainable industrial performance. Researchers need to evaluate catalysts across multiple scales, from electronic structure to reactor conditions. Such multiscale relationships make coordination chemistry especially relevant because the coordination environment surrounding a catalytic center often determines how molecules bind, react, and leave the catalytic cycle.

At the molecular level, many catalytic systems depend on interactions among metal centers, ligands, substrates, solvents, and surrounding functional groups. Wiedner et al. [5] demonstrate that molecular catalysts containing diphosphine ligands with pendant amines can facilitate proton and electron transfer through carefully organized coordination environments. Reek et al. [6] further show that hydrogen-bonding interactions within the

second coordination sphere can regulate substrate positioning, activity, and selectivity. These findings indicate that coordination chemistry should not be reduced to static representations of metal-ligand bonds. Coordination environments function dynamically because they influence electronic distribution, substrate access, intermediate stabilization, and reaction pathways.

This molecular perspective also challenges simplistic definitions of a green catalyst. High catalytic activity does not necessarily guarantee high sustainability performance. Researchers must consider catalyst composition, critical-metal dependence, synthetic routes, operational lifetime, recovery, solvent requirements, energy use, and waste generation. Hessel et al. [21], for example, show that even solvents commonly labeled as green require broader life-cycle and circularity assessment before researchers can judge their sustainability. Reyes et al. [17] likewise argue that chemical decision making benefits from combining green chemistry principles, life-cycle assessment, and systems thinking. These perspectives support a broader interpretation of catalytic sustainability that extends beyond single performance metrics.

The relationship between molecular design and sustainable production directly connects with Sustainable Development Goal 12 on Responsible Consumption and Production. SDG 12 emphasizes resource efficiency, waste minimization, sustainable management practices, and responsible use of materials. Chemistry contributes to these goals when scientists improve reaction efficiency, reduce unnecessary transformations, select safer materials, and design catalysts that minimize resource losses. However, this contribution begins at the molecular level. Decisions about metal centers, ligand structures, reaction media, and reaction conditions can determine downstream energy consumption, selectivity, waste formation, and catalyst recovery. Molecular chemistry therefore provides an important scientific foundation for understanding responsible production.

Education must make these relationships visible. Chemistry curricula often divide bonding, inorganic chemistry, kinetics, catalysis, environmental chemistry, and sustainability into separate topics. This fragmentation can lead students to memorize chemical representations without understanding their technological or environmental significance. Tümay [7] argues that chemistry education should develop systems thinking because chemists routinely analyze dynamic systems whose properties emerge from interactions among multiple components. Paschalidou et al. [8] also identify strong conceptual connections between systems thinking and green chemistry education. Their review demonstrates that sustainability-oriented chemistry requires students to understand relationships across molecular, process, environmental, and societal levels.

Several studies support this educational shift. Jovero and Picardal [9] report that green chemistry education has developed across emerging Asian economies, particularly at secondary and tertiary levels, but implementation still faces limitations related to teacher

knowledge, resources, and pedagogical support. Mitarlis et al. [10] demonstrate that chemistry learning can integrate green chemistry principles with Sustainable Development Goals through discussions, concept mapping, laboratory activities, and project-oriented learning. Eilks and Linkwitz [15] argue that chemistry curricula should respond more directly to green and sustainable chemistry because changes in scientific practice should also influence what and how students learn. Kanapathy et al. [20] similarly develop a framework for integrating sustainable development into chemistry curricula through a qualitative study involving academic experts.

Despite these developments, a conceptual gap remains. Catalysis studies frequently explain molecular structure, electronic effects, activity, selectivity, and reaction mechanisms. Education studies more frequently address green chemistry, systems thinking, sustainable development, teaching strategies, and learner engagement. Researchers rarely integrate these domains into one explicit pathway that begins with coordination chemistry and continues through catalytic function, sustainable production, SDG 12, and chemistry learning. As a result, students may encounter sustainability as an external context without understanding how molecular-level decisions actually contribute to environmental outcomes.

This study addresses this gap by analyzing the conceptual relationships among coordination bonding, catalyst structure and function, green chemistry, SDG 12, systems thinking, and sustainability-oriented chemistry education. The study aims to construct an integrated framework that explains how molecular interactions influence catalytic performance, how catalytic performance affects responsible production, and how educators can translate these relationships into meaningful learning. The study therefore asks how coordination chemistry can serve as a molecular foundation for understanding sustainable catalysis and how chemistry education can use this relationship to develop sustainability reasoning.

Research Methodology

Research Approach and Design

This study used a qualitative research approach through qualitative document analysis, narrative literature review, and thematic synthesis. The researcher selected this design because the study aimed to interpret conceptual relationships rather than calculate pooled effects or compare quantitative performance measures. The analysis focused on meanings, assumptions, relationships, and patterns across research on coordination chemistry, sustainable catalysis, green chemistry, and education.

Flemming and Noyes [12] explain that qualitative evidence synthesis can generate deeper interpretive understanding by bringing together findings from multiple studies. Maeda et al. [13] similarly argue that qualitative synthesis can identify conceptual patterns

that individual studies may not reveal independently. These methodological positions support the present study because its research problem crosses disciplinary boundaries.

The study adopted an interpretive orientation. The researcher did not assume that sustainability, green catalysis, or systems thinking possess one fixed meaning across all publications. Different disciplines use these concepts within different analytical boundaries. The researcher therefore interpreted how each field constructs the relationships among molecules, technologies, environmental consequences, and education.

Data Sources and Selection

This study did not involve human participants or a physical research site. Peer-reviewed scholarly documents served as the units of analysis. The researcher prioritized articles published between 2020 and 2025 to maintain relevance to contemporary scholarship. The selected literature included international journals indexed in major academic databases and relevant national journals with established academic standards.

The researcher used purposive criterion sampling. The inclusion criteria required each source to address at least one major area of the study: coordination chemistry, green catalysis, sustainable chemical production, green chemistry, systems thinking, sustainability education, or chemistry pedagogy. Each article also needed sufficient conceptual, empirical, or methodological information to support interpretation.

The researcher excluded documents that lacked peer review, duplicated other records, addressed sustainability only superficially, or did not contribute to the conceptual framework. The researcher also avoided relying on nonacademic websites as primary evidence.

Literature Search and Data Collection

The literature search used several conceptual clusters. The first cluster included “coordination chemistry,” “coordination bonding,” “metal-ligand interaction,” “molecular catalyst,” and “second coordination sphere.” The second cluster included “green catalyst,” “sustainable catalysis,” “electrocatalysis,” “green chemistry,” and “sustainable chemical production.”

The third cluster included “SDG 12,” “responsible consumption and production,” “sustainability assessment,” and “life cycle assessment.” The fourth cluster included “systems thinking in chemistry education,” “green chemistry education,” “sustainability literacy,” “education for sustainable development,” and “Project Based Learning.”

The researcher combined these terms during the document search. Initial screening focused on titles and abstracts. Full-text assessment followed when a publication appeared relevant to the research questions. The researcher then extracted relevant evidence using a structured analytical matrix.

Research Instrument

A document-analysis matrix served as the principal analytical instrument. The matrix recorded bibliographic details, research objectives, methodological design, research context, major findings, chemical concepts, sustainability indicators, pedagogical implications, and relevance to SDG 12.

For catalyst-related studies, the matrix focused on metal-ligand interactions, ligand structure, electronic properties, catalytic activity, selectivity, operational stability, energy requirements, and catalyst recovery. For sustainability studies, the matrix recorded resource use, hazard reduction, waste generation, life-cycle considerations, and circularity. For education studies, the matrix recorded learning models, systems thinking, sustainability literacy, curriculum integration, and student reasoning.

This structured process allowed the researcher to compare evidence without reducing disciplinary differences. The matrix supported systematic interpretation while preserving contextual information from each source.

Trustworthiness

The researcher established trustworthiness through source triangulation, conceptual triangulation, an audit trail, and reflexive analysis. Source triangulation compared evidence from coordination chemistry, catalytic science, green chemistry, sustainability research, and chemistry education. Conceptual triangulation examined similar findings through different frameworks, particularly green chemistry, systems thinking, life-cycle perspectives, and SDG 12.

The researcher maintained an audit trail through documentation of search terms, selection criteria, coding categories, theme development, and conceptual revisions. Yadav [14] emphasizes that qualitative quality requires methodological coherence, transparency, reflexivity, and clear alignment between research questions and analytical procedures.

The researcher also considered contradictory evidence. For example, the researcher did not automatically classify an efficient catalytic system as sustainable. The analysis examined whether increased catalytic activity required scarce materials, hazardous solvents, high-energy preparation, or difficult recovery. This reflexive position prevented the study from equating technological efficiency with environmental sustainability.

Data Analysis

The researcher used thematic synthesis through three stages. First, initial coding identified passages related to coordination interactions, catalyst structure, catalytic function, selectivity, energy use, resource efficiency, waste, sustainability, systems thinking, and education.

Second, the researcher organized related codes into descriptive themes. Codes concerning metal-ligand interactions, proton transfer, electron transfer, and second coordination sphere effects formed a broader category concerning molecular foundations of catalysis. Codes related to energy reduction, selectivity, reuse, and waste formed categories related to green catalytic performance.

Third, the researcher developed analytical themes through cross-study comparison. This stage moved beyond summarizing individual publications. The researcher interpreted relationships among molecular chemistry, technological function, sustainability outcomes, and pedagogy. The analysis generated five major themes that structure the results and discussion.

Results and Discussion

Overview of the Thematic Findings

The thematic synthesis generated five interconnected themes. The first identifies coordination bonding as the molecular foundation of catalytic interaction. The second shows that catalytic performance emerges from multiscale relationships among electronic structure, molecular organization, surfaces, and process conditions. The third interprets green catalysis as a strategy for improving energy and resource efficiency while recognizing sustainability trade-offs. The fourth positions SDG 12 as an evaluative framework for chemical production. The fifth identifies systems thinking and Project Based Learning as mechanisms for translating molecular chemistry into sustainability-oriented education.

These themes form a coherent explanatory structure. Molecular structure affects catalytic interactions. Catalytic interactions influence activity, selectivity, and reaction pathways. Reaction performance affects energy consumption, resource use, waste generation, and catalyst recovery. Sustainability frameworks evaluate those outcomes. Education then transforms this chain of relationships into opportunities for scientific reasoning.

Coordination Bonding as the Molecular Foundation of Catalysis

The first theme reveals that coordination bonding functions as a dynamic molecular relationship rather than a static structural category. Wiedner et al. [5] show that molecular catalysts containing diphosphine ligands with pendant amines depend strongly on local proton-transfer and electron-transfer environments. Changes in ligand architecture can alter catalytic pathways because they change how the active center interacts with substrates and intermediates.

Reek et al. [6] extend this argument through second coordination sphere interactions. Hydrogen bonds near catalytic centers can influence molecular orientation and reaction selectivity without forming direct metal-ligand bonds. These interactions show that catalytic

sites operate within organized molecular environments. The active center cannot explain catalytic behavior independently from its surroundings.

This finding has theoretical importance because it changes the interpretation of coordination chemistry. Traditional teaching may represent coordination bonding through arrows, formulas, coordination numbers, and geometries. These representations provide important foundational knowledge. However, they become more meaningful when students understand how coordination environments affect actual chemical function.

The finding therefore supports a shift from structural recognition toward mechanistic interpretation. Students should not only identify the ligand and metal center. They should also ask how ligand properties change electron density, substrate access, intermediate stability, and selectivity. Such reasoning transforms chemical bonding into an explanatory model.

Catalyst Performance as a Multiscale Phenomenon

The second theme shows that catalyst performance emerges across molecular, interfacial, and process scales. Luo et al. [4] demonstrate that high-current-density water splitting requires appropriate electronic properties, morphology, surface chemistry, charge transport, mass transport, and operational stability. A catalyst that performs well in a small-scale electrochemical test may not necessarily maintain similar performance under industrial conditions.

This observation distinguishes intrinsic catalytic activity from system-level performance. Intrinsic activity describes properties of the active site or material under controlled conditions. System-level performance includes mass transfer, reactor operation, stability, separation, and energy use. Sustainable performance adds further considerations related to material availability, toxicity, recyclability, and waste.

The distinction matters because green chemistry requires researchers to consider consequences beyond reaction rate. Centi and Perathoner [16] emphasize that sustainable chemical production requires integrated technological transformation. Catalysts must operate within energy, feedstock, separation, and infrastructure systems.

The result therefore challenges narrow claims about green catalysts. Researchers should avoid labeling catalysts as sustainable based only on high activity or low reaction temperature. They need multidimensional evidence. Reyes et al. [17] support this position by showing the value of combining green chemistry, life-cycle assessment, and systems thinking in chemical decision making.

Green Catalysis and Sustainability Trade-Offs

The third theme identifies four recurring contributions of catalysis to greener production: lower energy requirements, greater selectivity, reduced waste, and opportunities for catalyst reuse. These characteristics align with established green chemistry principles.

However, the synthesis also reveals trade-offs. A catalyst may reduce reaction temperature but require energy-intensive synthesis. A highly selective catalyst may depend on scarce metals. A recyclable heterogeneous catalyst may require complex preparation or generate environmental burdens during material production. A catalyst that works under mild conditions may still rely on hazardous solvents.

Hessel et al. [21] illustrate why these trade-offs matter. Their analysis of green solvents shows that sustainability labels require life-cycle and circularity assessment. Solvents influence reaction efficiency, separation, waste, and environmental performance. The same principle applies to catalysts. Researchers should evaluate both direct and indirect consequences.

This result extends the meaning of green catalysis. Green catalysis should not describe catalysts that merely improve one reaction parameter. It should describe catalytic systems that provide a defensible improvement when researchers consider the relevant system boundaries.

SDG 12 as an Evaluative Framework

The fourth theme positions SDG 12 as more than a contextual topic. Responsible Consumption and Production provides criteria that can guide chemical evaluation. In chemistry education, educators often use global environmental issues as examples or introductory contexts. However, the present synthesis indicates that SDG 12 can play a deeper analytical role.

Students can evaluate a chemical process by asking several questions. What raw materials does the process require? How much energy does it consume? What substances create hazards? How selectively does the reaction form the desired product? Can the catalyst be recovered? What waste does the system generate? Can another pathway achieve the same outcome with fewer resources?

These questions transform sustainability into chemical reasoning. They require students to connect molecular and process knowledge with material consequences. Sustainability literacy therefore involves the capacity to explain why a chemical choice creates particular benefits or risks.

Mitarlis et al. [10] demonstrate that green chemistry principles can support SDG-oriented chemistry education in Indonesia. Eilks and Linkwitz [15] also argue that green and sustainable chemistry should become more visible within chemistry curricula. The present study extends these positions by connecting SDG 12 specifically with coordination chemistry and catalyst design.

Systems Thinking as the Integrating Epistemic Framework

The fifth theme identifies systems thinking as the main epistemic bridge among the other themes. Tümay [7] conceptualizes chemistry as a systems science because chemical properties and behaviors arise from interactions among system components. Learners therefore need to understand relationships, feedback, boundaries, and emergent behavior.

Paschalidou et al. [8] find that systems thinking and green chemistry education share substantial conceptual ground. Green chemistry requires students to evaluate multiple variables simultaneously. Systems thinking helps them organize those variables and understand their relationships.

Reynders et al. [23] show that systems thinking can be taught and assessed in first-year chemistry. Their work also indicates that developing this competency requires carefully designed tasks. Students need to move beyond linear cause-and-effect reasoning toward interconnected explanations.

Within the present framework, coordination chemistry provides a suitable disciplinary context for systems thinking. Students can begin with metal-ligand interactions, move toward catalytic mechanisms, examine energy and resource implications, and finally evaluate production sustainability. They can also reason in the opposite direction by beginning with an environmental problem and tracing it back to molecular design choices.

From Sustainability Awareness to Sustainability Literacy

The thematic synthesis suggests an important distinction between sustainability awareness and sustainability literacy. Sustainability awareness involves recognizing environmental problems and acknowledging the need for improvement. Sustainability literacy requires deeper analytical capacity. Learners must evaluate alternatives, identify trade-offs, interpret evidence, and justify decisions.

Ballard and Mooring [18] demonstrate that case-based green chemistry can increase students' knowledge and attitudes toward chemistry. Such experiences create an important entry point. However, more advanced sustainability learning requires students to connect environmental concerns with disciplinary explanations.

Reyes et al. [17] address this deeper level through integrated chemical decision making. Their framework combines green chemistry principles with systems thinking and life-cycle assessment. This integration allows learners to compare options rather than simply identify whether a process includes a green chemistry principle.

The present study adds molecular coordination to this reasoning. Students can evaluate not only which process appears greener but also how molecular structure and catalytic mechanisms contribute to the observed performance. This connection strengthens the scientific basis of sustainability literacy.

Project Based Learning as a Pedagogical Translation Mechanism

Project Based Learning provides a practical structure for implementing the conceptual framework. Liu and Zhang [11] demonstrate that students can integrate green chemistry, electrochemistry, synthesis, reactor design, literature review, and scientific communication through project-based learning. Their work shows that sustainability-oriented projects can connect several chemistry topics within a single learning experience.

Howell [22] also demonstrates the importance of active and reflective learning in sustainability education. Students engage more deeply when learning activities require participation, application, reflection, and discussion. These characteristics align with Project Based Learning because projects create opportunities for students to investigate, evaluate, revise, and communicate.

Based on the thematic synthesis, this study proposes the project theme **“From Chemical Bonding to Sustainable Production: Designing Green Catalyst Concepts for the Future.”** The project should begin with an authentic production problem rather than with a predefined chemical formula. Students can investigate a process that consumes substantial energy, produces waste, or requires hazardous reagents.

During the molecular investigation stage, students identify the role of catalysts, ligands, metal centers, electron donation, substrate binding, and relevant reaction mechanisms. They then compare alternative catalytic systems. Students should avoid choosing an alternative merely because the literature labels it green. Instead, they should evaluate energy requirements, material availability, selectivity, hazards, catalyst lifetime, and recovery.

Students can present their analysis through a molecular model, scientific poster, infographic, presentation, or structured technical report. The educational goal does not require students to invent an industrially viable catalyst. The goal requires them to construct a scientifically defensible explanation linking molecular structure with sustainability consequences.

Curriculum and Teacher Implications

Curriculum design strongly influences whether this type of integration can succeed. Eilks and Linkwitz [15] argue that green and sustainable chemistry should reshape chemistry education rather than remain peripheral topics. Kanapathy et al. [20] similarly show that curriculum integration requires deliberate connections among content, teaching methods, and sustainability outcomes.

The present framework supports integration without requiring educators to create an entirely separate sustainability subject. Teachers can connect sustainability with topics that already exist in the curriculum. Coordination chemistry can connect with catalysis. Kinetics can connect with energy efficiency. Solvents can connect with life-cycle considerations.

Organic synthesis can connect with atom economy. Environmental chemistry can connect with process design.

Teacher capacity remains essential. Cannon et al. [19] show that professional development can strengthen the implementation of green chemistry at the school level. Teachers need both content knowledge and pedagogical strategies. Without these competencies, sustainability risks becoming a collection of slogans rather than a disciplinary way of thinking.

Comparison with Previous Studies

The present findings align with Jovero and Picardal [9], who identify green chemistry education as an emerging but unevenly developed field in Asian contexts. Both studies recognize the importance of teacher capacity, curriculum design, and contextual relevance. However, the present study adds a stronger molecular focus through coordination chemistry.

The findings also support Mitarlis et al. [10], who connect green chemistry principles with Sustainable Development Goals in chemistry learning. Their work establishes the relevance of SDG-oriented chemistry in Indonesia. The present study extends this relationship by explaining how molecular catalyst design can provide a specific scientific pathway toward SDG 12.

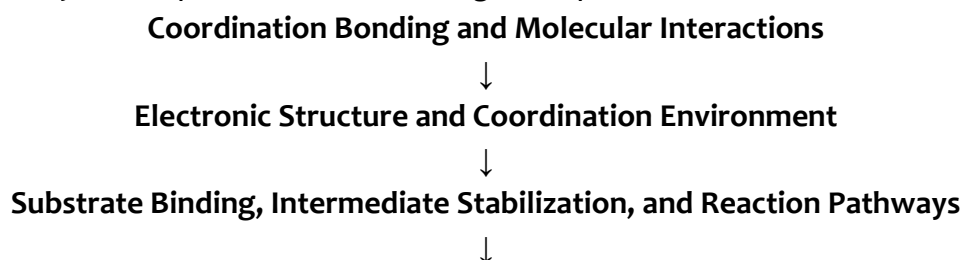
Liu and Zhang [11] provide practical evidence for project-based green chemistry learning. The present study uses their work to support the pedagogical mechanism but develops a broader conceptual model. The framework can support different projects rather than one experimental activity.

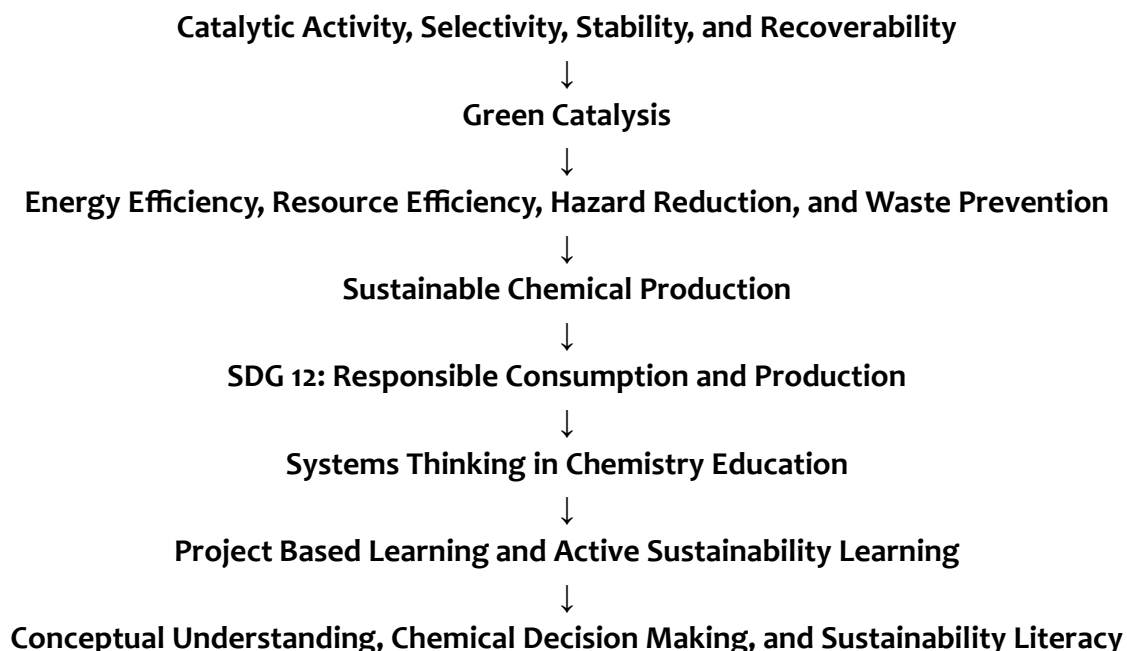
The findings also complement Paschalidou et al. [8] and Reynders et al. [23]. Those studies emphasize systems thinking as an important competency in chemistry education. The present analysis gives systems thinking a specific disciplinary trajectory that begins with coordination environments and ends with sustainability evaluation.

Finally, the findings extend Reyes et al. [17]. Their work integrates green chemistry, systems thinking, and life-cycle assessment for decision making. The present study contributes an additional explanatory layer by showing how molecular coordination and catalyst function can form the scientific foundation of such decision making.

Proposed Conceptual Framework

The thematic synthesis produces the following conceptual framework:





The arrows do not imply a strictly linear causal chain. Systems thinking connects all levels of the framework. Students may begin with molecular structures and move toward environmental consequences. They may also begin with a sustainability problem and trace it backward toward molecular and technological causes.

This multidirectional structure distinguishes the framework from simple contextual teaching. Sustainability does not appear only after students learn chemistry. Sustainability becomes part of the reasoning process used to understand chemistry itself.

Theoretical Implications

The study produces three major theoretical implications. First, it expands the role of coordination chemistry. Coordination bonding should not remain limited to descriptions of complex ions and molecular geometries. It can explain how molecular organization influences catalytic behavior and sustainable production.

Second, the study refines the interpretation of green catalysis. The synthesis shows that catalytic sustainability requires multidimensional evaluation. Activity, selectivity, energy, material choice, stability, toxicity, and recovery interact. Researchers should therefore avoid absolute sustainability judgments based on isolated metrics.

Third, the study strengthens the role of systems thinking in chemistry education. The framework provides a concrete path from molecular interaction to technological and environmental consequence. This path gives systems thinking a specific disciplinary structure.

Practical Implications

Chemistry educators can use the framework to redesign existing lessons. A coordination chemistry lesson can include catalyst case studies. A kinetics lesson can examine energy efficiency. A laboratory activity can compare solvents or catalysts using green chemistry criteria. An inorganic chemistry course can connect ligand design with industrial catalysis and responsible production.

Curriculum developers can also use the framework to map sustainability outcomes onto existing chemistry topics. Such integration may prove more effective than treating sustainability as a separate module because students can observe how sustainability emerges from core disciplinary concepts.

Teacher education programs should include opportunities to analyze sustainability problems using chemical evidence. Cannon et al. [19] show the value of professional development for green chemistry implementation. Educators need practice in facilitating open-ended analysis, managing multidisciplinary questions, and evaluating student reasoning.

Finally, policy and institutional curriculum design should support sustainability-oriented laboratory work. Safer materials, waste minimization, energy awareness, and resource recovery can become learning objectives rather than administrative concerns alone.

Conclusion

This study demonstrates that coordination chemistry can function as a conceptual bridge among molecular interaction, catalytic performance, green chemistry, sustainable production, SDG 12, and chemistry education. The thematic synthesis generated five interconnected findings. Coordination bonding provides a molecular foundation for catalytic interaction. Electronic and structural properties shape catalytic function. Green catalysis can improve energy and resource efficiency but also creates sustainability trade-offs. SDG 12 provides a framework for evaluating responsible production. Systems thinking and Project Based Learning can translate these relationships into meaningful chemistry education.

The findings answer the central research objective by establishing a conceptual pathway from molecular coordination to sustainable production. Catalytic sustainability cannot depend only on activity, reaction rate, or yield. Researchers must consider selectivity, energy demand, material availability, toxicity, stability, catalyst recovery, solvents, and waste. This multidimensional interpretation prevents the concept of green catalysis from becoming a simplistic technological label.

Theoretically, this study extends coordination chemistry from structural knowledge toward a mechanism for explaining sustainability outcomes. It also strengthens systems thinking by giving it a specific chemical pathway from bonding and molecular structure to

technological function and environmental consequence. The framework therefore integrates disciplinary understanding with sustainability literacy.

Practically, educators can use the framework to integrate sustainability into existing chemistry topics. Coordination chemistry, kinetics, catalysis, inorganic chemistry, electrochemistry, and environmental chemistry can provide entry points for sustainability reasoning. Project Based Learning can help students compare chemical alternatives and construct evidence-based arguments concerning responsible production.

Methodologically, the study demonstrates the value of qualitative document analysis and thematic synthesis for integrating research across disciplinary boundaries. The approach allowed the researcher to interpret relationships among molecular chemistry, sustainability science, and education without reducing these fields to a single quantitative measure.

This study has several limitations. The findings depend on the scope and quality of the selected literature. The qualitative synthesis provides an interpretive framework rather than direct evidence of instructional effectiveness. The study does not experimentally compare catalysts or assess student outcomes. The conceptual framework may also require adaptation across educational levels, curriculum structures, and chemical topics.

Future research should test the framework empirically. Qualitative studies can investigate how students reason across molecular, technological, and sustainability levels. Researchers can use interviews, think-aloud protocols, learning artifacts, and classroom observations to examine conceptual development. Mixed-method studies can investigate changes in systems thinking, sustainability literacy, and chemical understanding after project implementation. Future studies should also compare how the framework functions in secondary chemistry, general chemistry, inorganic chemistry, teacher education, and sustainability-focused laboratory courses.

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