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Developing Transferable Skills through Design Thinking - Infused Project-Based Learning In Pre-University Chemistry Education

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Abstract

The development of transferable skills remains a persistent challenge in chemistry education, particularly in pre-university contexts characterised by examination-oriented instruction and procedural laboratory practices. While Project-Based Learning (PjBL) is widely adopted to promote authentic inquiry, evidence suggests that it does not consistently foster higher-order competencies without structured cognitive support. This study explores how Design Thinking–infused Project-Based Learning (DT–PjBL) supports the enactment of transferable skills as epistemic practices in pre-university chemistry learning. Adopting a qualitative, exploratory, multiple-case study design, the research involved 11 students organised into four groups who engaged in electrochemistry-based tasks over a 24-week intervention. Data were collected through classroom observations and document analysis. A theoretically informed analytic rubric was used as a heuristic to examine six dimensions of transferable skills: critical thinking, problem-solving, collaboration, communication, creativity, and decision-making. Data were analysed using deductive coding, within-case analysis, and cross-case synthesis. Findings indicate observable shifts in how students enacted transferable skills, particularly in collaborative problem-solving, the justification of design decisions, and the development of creative solutions within DT–PjBL contexts. Rather than functioning as discrete outcomes, transferable skills emerged as situated epistemic practices shaped by iterative design processes. However, the absence of a comparison condition limits causal interpretation.

Keywords: Design Thinking, Project-Based Learning, Transferable Skills, Chemistry Education, Electrochemistry

Introduction

The landscape of 21st-century science education increasingly demands that learners move beyond the acquisition of procedural and conceptual knowledge towards the development of higher-order competencies required to address complex, real-world problems. In

Chemistry education, this shift is particularly significant, as students are expected not only to understand abstract principles but also to apply them meaningfully within societal and industrial contexts. Consequently, growing attention has been directed towards the development of transferable skills, such as critical thinking, problem-solving, collaboration, communication, creativity, and decision-making, which are essential for academic progression (Asefer & Abidin, 2021; Mishra & Mehta, 2017; Overton & McGarvey, 2017; Sarkar et al., 2016; Smith & Reid, 2018; World Economic Forum, 2023).

On the other hand, increasing concern has emerged regarding the preparedness of graduates to navigate complex and rapidly changing professional environments (OECD, 2023; UNESCO, 2024). Contemporary educational debates increasingly emphasise the importance of transferable competencies, including critical thinking, collaboration, creativity, communication, and adaptive problem-solving, as essential capacities for participation in knowledge-based economies and socially complex workplaces (Future of Jobs Report 2025), since these competencies are frequently associated with graduate employability.

Increasingly, scholars argue that traditional teacher-centred pedagogies may inadequately prepare students for the complex problem-solving and interdisciplinary collaboration required in contemporary professional contexts (Rusmin et al., 2024). Such tensions have generated substantial discussion regarding how educational practices can move beyond procedural instruction towards more authentic, inquiry-driven, and socially situated forms of learning (Zhao, 2023). This is because, despite the recognised importance of transferable skills, numerous studies indicate that students at the pre-university level continue to demonstrate limited proficiency in transferable skills, both globally and within the Malaysian context (Linda et al., 2024; Mat Salleh et al., 2022; Nurul Fatni et al., 2021; OECD, 2023; Sangiemjit & Vázquez-alonso, 2025; Salame et al., 2024; Wan Yunus & Mat Ali, 2018). As in the Malaysian context, this concern is further reflected in national education policies such as the Malaysia Education Blueprint 2026–2035 (The Star, 2026), which emphasises the need to enhance graduate employability through pedagogical innovation and the development of higher-order thinking skills. Recent policy directions continue to prioritise the cultivation of creativity, problem-solving, and collaborative competencies as key outcomes of science education.

Nevertheless, classroom practices in Chemistry remain largely examination-oriented, with instructional approaches often centred on content delivery and procedural laboratory work (Karpudewan & Kulandaisamy, 2018; Seery et al., 2024). Such approaches provide limited opportunities for students to engage in authentic inquiry, articulate reasoning, or participate in collaborative knowledge construction, thereby constraining the development of transferable skills. To address these conceptual limitations, this study adopts the framework of epistemic fluency. Epistemic fluency refers to the capacity to engage with knowledge in multiple ways, including generating, evaluating, and applying knowledge across contexts. It emphasises the integration of different forms of knowing and doing, rather than the possession of isolated skills. Within this framework, what are often labelled as transferable skills, such as critical thinking or problem-solving, are reconceptualised as epistemic practices. These practices include interpreting data, constructing arguments, negotiating meaning, and making informed decisions. Importantly, these practices are not independent; they are interdependent and co-occur within authentic learning situations. This perspective provides a coherent theoretical basis for this study.

Project-Based Learning (PjBL) has been widely advocated as a pedagogical approach to address authentic, inquiry-driven tasks that require the application of disciplinary knowledge in real-world contexts. Through PjBL, learners are encouraged to work collaboratively, investigate complex problems, and produce tangible outcomes. However, evidence suggests that PjBL alone does not contribute to the development of transferable skills, but it needs a scaffolding (Li & Zhu, 2023). Systematic reviews further highlight persistent limitations in the development of 21st-century skills through PjBL, including insufficient innovation skills and lack of holistic skill development (Larsen, 2025; Rozan et al., 2024). Studies by Hariyanto et al., (2025) show that authentic PjBL produces better skill development than simulated PjBL, indicating that not all PjBL environments are equally effective, so PjBL must be carefully designed to be impactful. These findings suggest that while PjBL provides a promising learning environment, it requires structured cognitive frameworks, such as Design Thinking, to effectively support the development of transferable skills.

Design Thinking (DT) has increasingly emerged as a powerful pedagogical approach to address these limitations. Conceptualised as an iterative, human-centred problem-solving process encompassing the stages of empathise, define, ideate, prototype, and test (d.school, 2010), DT provides a structured yet flexible framework for navigating complex, real-world challenges. Recent research highlights that DT fosters key 21st-century competencies, particularly creativity, collaboration, and problem-solving, through hands-on, inquiry-driven learning experiences (Muneer et al., 2025). Within educational contexts, DT promotes active engagement, reflective inquiry, and iterative knowledge construction, enabling learners to generate, test, and refine ideas in meaningful ways (Henriksen et al., 2017; Leem & Lee, 2024; Lor, 2017). Similarly, Guaman-Quintanilla et al., (2023) found that design-oriented learning environments enhanced collaborative engagement and innovative thinking among university students. Importantly, DT is strongly aligned with social constructivist principles, as it situates learning within collaborative environments where knowledge is co-constructed through dialogue, experimentation, and shared problem-solving. Studies further demonstrate that Chemistry students exposed to design thinking demonstrate heightened creativity and greater openness to generating unconventional solutions (Ananda et al., 2023). The collaborative and iterative nature of DT also facilitates deeper interaction among learners, strengthening communication and teamwork skills essential for complex problem-solving (Leem & Lee, 2024).

Although these studies provide important insights, existing research remains limited in three significant ways. First, many studies conceptualise transferable skills as isolated competencies rather than interconnected epistemic practices. Second, there is limited exploration of the mechanisms through which Design Thinking structures students' engagement with disciplinary knowledge. Third, relatively few studies have examined DT–PjBL within pre-university chemistry contexts, particularly in relation to epistemic fluency and transferable skill enactment.

Hence, the present study investigates how Design Thinking–infused Project-Based Learning can support the development of transferable skills as epistemic practices rather than discrete

competencies. Drawing on the notion of epistemic fluency, learning is understood as the capacity to engage with knowledge in multiple ways, including generating, evaluating, and applying knowledge within disciplinary contexts. From this perspective, skills such as critical thinking, problem-solving, collaboration, and decision-making are not independent attributes, but integrated practices that emerge during participation in knowledge-building activities. The six dimensions examined in this study are not treated as isolated skills but are analytically grouped into three interrelated epistemic domains:
(1) analytical practices (critical thinking, problem-solving),
(2) social practices (collaboration, communication), and
(3) generative practices (creativity, decision-making).

This structuring reflects how learners engage with knowledge cognitively, socially, and productively within DT–PjBL environments. This study contributes to the growing body of research on STEM education by providing empirical evidence on the role of Design Thinking as a pedagogical scaffold for developing transferable skills. It also offers practical insights for educators and curriculum designers seeking to implement innovative instructional approaches that align with national and global educational priorities.

Methods

Research Design

This study employed a qualitative exploratory multiple case study design to explore students' development of transferable skills within the DT-infused PjBL framework. Each project group was treated as a distinct case, enabling both within-case and cross-case analysis.

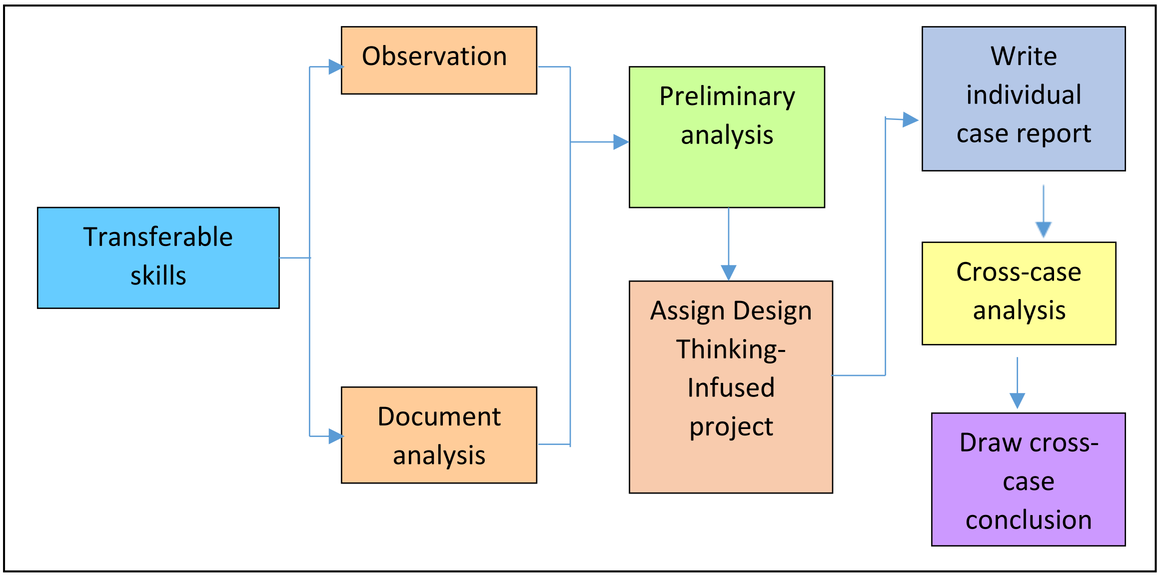

Figure 1: Research Design

Participants and Topics

The study involved 11 pre-university chemistry students organised into four groups (Arrhenius, Bohr, Charles, Dalton) as shown in Table 1. The intervention was conducted over 24 weeks within the topic of electrochemistry.

Table 1
Topics of the Project According to the Group

Group Name	***Participant***	***Topics***
Arrhenius	*Student 1, 2 & 3*	*Enzymatic Fuel Cell*
Bohr	*Student 4, 5 & 6*	*Fruits Battery*
Charles	*Student 7, 8 & 9*	*Purification of Metals*
Dalton	*Student 10 & 11*	*Galvanisation to Prevent Corrosion*

Intervention Design
Students engaged in PjBL tasks structured around Design Thinking phases: empathise, define, ideate, prototype, and test. Projects focused on the usage and application of electrochemistry. Figure 2 shows the flow of activities during the project intervention.

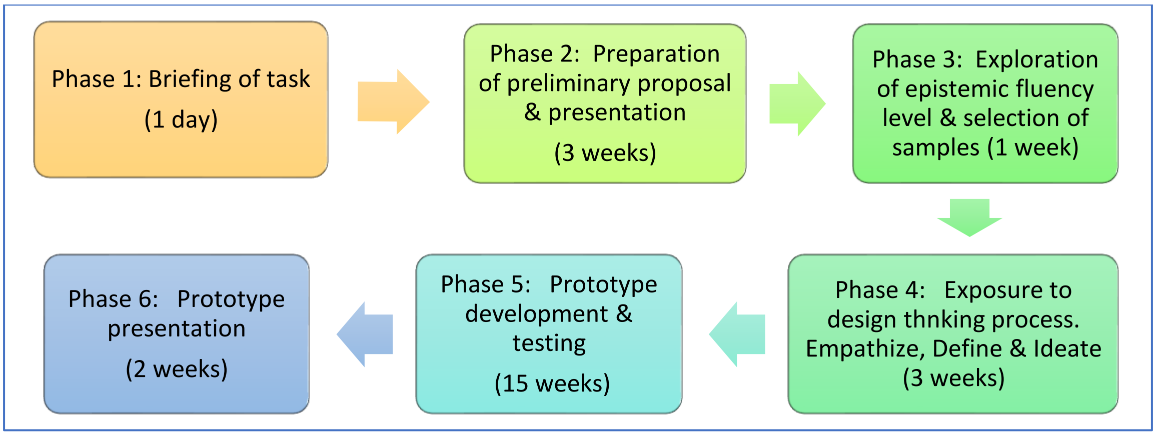

Figure 2: Design Thinking-Infused Project-Based Learning Activity

Data Collection
Data were collected using two methods: observation and document analysis. Project observations were done based on the following transferable skills: 1. critical thinking, 2. problem-solving, 3. collaboration & teamwork, 4. communication, 5. creativity & innovation, 6. decision making. Document analysis was conducted using their preliminary proposals and project final reports.

Each epistemic practice was operationalised through observable behaviours derived from the literature and adapted to the DT–PjBL context, as shown in Table 2. These indicators guided both observation and document analysis.

Table 2
Indicators of Epistemic Practice

Epistemic Practice	Observable Indicators
Critical Thinking	Questioning, Evaluating Evidence
Problem-Solving	Troubleshooting, Testing Solutions
Collaboration	Role Negotiation, Shared Decisions
Communication	Explaining, Arguing Scientifically
Creativity	Generating Alternative Ideas
Decision-Making	Justifying Choices

Data Analysis

Data were analysed using deductive content analysis guided by transferable skill constructs. A three-level rubric (Low–Moderate-High) was applied, as shown in Table 3. The rubrics were drawn from the literature review (Henriksen et al., 2020; Sowinski & Taylor, 2018) and aligned theoretically with the aims of assessing transferable skills.

Table 3
Document Analysis Rubrics for Development of Transferable Skills

Indicator	Level 3 – High Performance	Level 2 – Moderate Performance	Level 1 – Low Performance
EF2: TRANSFERABLE SKILLS			
Evidence for Critical Thinking	Deep analysis; evaluates assumptions; conclusions strongly supported by Chemistry concepts and evidence.	Logical reasoning with some evaluation; conclusions supported.	Limited or no analysis; conclusions weakly supported or incorrect.
Evidence for Problem-Solving	Systematic, creative approach; identifies root causes; develops innovative and feasible solutions.	Structured approach; solutions generally practical.	Inconsistent or weak approach; solutions lack depth or feasibility.
Evidence for Collaboration & Teamwork	Highly effective teamwork; clear roles; respectful communication; strong contributions.	Good teamwork; contributes consistently.	Uneven participation; occasional conflict; limited contribution.
Evidence for Communication	Clear, persuasive communication; strong chemical reasoning; well-designed visuals.	Adequate communication; explanations generally clear.	Unclear or poorly structured explanations; communication is weak.
Evidence for Creativity & Innovation	Highly original ideas; strong creative integration of Chemistry concepts.	Some creativity; attempts at novel ideas.	Minimal creativity; conventional or repetitive ideas.
Evidence for Decision-Making	Decisions are justified using Chemistry principles, user insights, and testing data.	Decisions are mostly reasonable and justified.	Decisions unclear or poorly justified.

Ethical Considerations

This study was conducted in accordance with established ethical guidelines for educational research involving human participants. Informed consent was obtained from all 11 pre-university students prior to data collection. Participants were fully briefed on the purpose of the study, the nature of their involvement, and their right to withdraw at any stage without any academic consequences.

To ensure confidentiality and anonymity, no personally identifiable information (including names, gender, or ethnicity) was collected or reported. All participants were assigned numerical identifiers (e.g., Student 1, Student 2) for the purpose of data analysis and reporting. Similarly, all project-related documents, including proposals and reports, were anonymised and coded prior to analysis to prevent identification of individuals or groups.
Data collected through observations, and document analysis were used solely for research purposes and were securely stored. Interpretations of students' work were conducted using coded data, and no raw identifiable materials are disclosed in this publication. The study adhered to principles of voluntary participation, confidentiality, and responsible data handling throughout the research process.

Results

Preliminary Transferable Skills (Pre-DT)

The findings of this study indicate that, prior to the Design Thinking–Project-Based Learning (DT–PjBL) intervention, the pre-university students demonstrated limited proficiency in transferable skills, particularly in tasks requiring independent reasoning, collaborative sense-making, and adaptive problem-solving.

Initial observation data indicated that many students approached laboratory work as a procedural exercise, adhering strictly to instructions without questioning underlying rationales. This "cookbook" approach to experimentation has been widely critiqued in Chemistry education literature for constraining students' epistemic engagement and limiting opportunities for critical thinking (Abels et al., 2020; Cetin-Dindar & Geban, 2017). Consistent with Mennani et al. (2023), the present study found that students rarely justified experimental steps, evaluated assumptions, or reflected on sources of error prior to the intervention.

The students' problem-solving abilities were also notably underdeveloped. Many relied heavily on textbook guidance and showed reluctance to engage with problems independently. This aligns with findings by Trivić and Milanović (2018), who noted that students accustomed to algorithmic problem-solving often struggle when confronted with open-ended or unfamiliar tasks. Similarly, early observation data in this study indicated that students lacked confidence in selecting appropriate project topics, identifying relevant variables, and predicting experimental outcomes. Furthermore, collaborative practices were initially limited, with group work characterised primarily by task division rather than meaningful collective sense-making. Other transferable skills, including communication, critical thinking, and decision-making, were minimally evident in both observational data and preliminary proposal documents.

Development During DT-PjBL Project Implementation

Transferable skills, including critical thinking, problem-solving, collaboration, communication, creativity, and decision-making, represent a central dimension of epistemic fluency and are increasingly recognised as essential outcomes of contemporary chemistry education (Abelha et al., 2020; Overton & McGarvey, 2017). Following the intervention, substantial improvements were observed across all four case groups, suggesting that these competencies can be systematically cultivated when chemistry learning is embedded within authentic, design-oriented pedagogical frameworks. The findings indicate that the integration of Design Thinking within Project-Based Learning not only enhances students' engagement with disciplinary content but also supports the development of higher-order cognitive and collaborative capacities necessary for addressing complex, real-world problems.

Within-Case Analysis: Arrhenius Group (Enzymatic Fuel Cell)

Their project report's organisation, division of tasks, and cohesive presentation indicate coordinated teamwork. They troubleshoot voltage inconsistencies by conducting repeated trials and controlling variables. The report uses a clear structure, reflecting purposeful internal communication. They identify limitations (enzyme degradation, pH sensitivity, porosity issues) and propose logical future improvements. Decision-making is evident in variable selection, choice of enzyme concentration levels, and temperature conditions. Their idea, turning festive food waste into renewable energy, demonstrates originality. Observation notes (Table 4) show clear growth in transferable skills, where these behaviours represent strong skill development.

The Arrhenius group demonstrated notable development across multiple dimensions of transferable skills during the DT–PjBL intervention. Their critical thinking was evident when students actively questioned fluctuations in voltage readings, with one student proposing that "the enzyme could be breaking down when it's too warm," reflecting analytical reasoning grounded in scientific understanding. This was closely linked to their problem-solving approach, as the group systematically investigated inconsistencies by reviewing concentration values, verifying dilution accuracy, and consulting relevant literature to diagnose potential enzyme denaturation.

Collaboration and teamwork were also strongly demonstrated through effective self-organisation, with members taking on specific roles such as enzyme extraction, apparatus setup, and data recording, while maintaining consistent cooperation throughout the project. In terms of communication, students articulated their ideas clearly using appropriate scientific terminology, including concepts such as oxidation and enzyme activity, facilitating shared understanding within the group.

Creativity and innovation were reflected in their ability to conceptualise the conversion of food waste into a renewable energy source, indicating an application of chemistry knowledge to real-world sustainability challenges. Furthermore, their decision-making skills were evident in their evaluation of alternative approaches, such as piezoelectric energy harvesting, before justifying the selection of an enzymatic fuel cell as the most feasible solution. Collectively, these behaviours indicate a high level of transferable skill development within the Arrhenius group.

Table 4
Arrhenius Group Observation Data

Group Observed	*Arrhenius*
Number of Students Present	*3 (Student 1, 2 & 3)*
Project title	*Enzymatic Fuel Cell*
TRANSFERABLE SKILLS	*Observer Notes / Description*
Evidence of Critical Thinking	*Students repeatedly questioned why voltage readings fluctuated and discussed the biochemical stability of the orange enzymes. Student 1 suggested, "Could the enzyme be breaking down when it's too warm?" showing analytical reasoning about biochemical variables.*
Evidence of Problem-Solving	*When the enzymatic cell produced unexpectedly low voltage, the group reviewed their concentration values and modified the dilution ratio. They cross-checked literature to identify possible enzyme denaturation factors.*
Collaboration & Teamwork	*Students distributed tasks voluntarily—one prepared enzyme extract, one managed apparatus, another recorded data. High levels of cooperative communication and mutual support were observed.*
Communication	*During discussions, they articulated scientific reasoning clearly and corrected each other constructively. Student 3 explained oxidation processes to others, demonstrating peer teaching.*
Creativity & Innovation	*The group explored a secondary idea—piezoelectric energy harvesting—even though it was not fully developed. They creatively repurposed fruit waste as a renewable energy source.*
Decision-Making	*Decisions were made collectively. For instance, when determining which variables to test first, they debated feasibility and chose concentration over pH due to a shorter preparation time.*

Within-Case Analysis: Bohr Group (Fruit Battery)

Their report is cohesive, consistently uses "we", and presents coordinated experimental procedures and analyses, suggesting effective teamwork and shared responsibility. They plan and execute systematic measurements of voltage across five fruit conditions, deal with variation between fruits, and interpret non-linear graph behaviour (not a straight line due to different ion compositions). The structure of the report is clear and logically sequenced. Explanations of voltage trends are written in accessible, scientifically sound language.

Their discussion explains why different fruits, despite similar acidity ranges, yield slightly different voltages; they attribute this to other ions affecting the electrochemical system. They also interpret the non-linear graph by acknowledging that "*there are some ions, not only the H^+ ions, will affect the voltage produced,*" indicating reflective reasoning. They appropriately decide on measurable variables (type of fruit, pH, ripeness) and justify their focus on acidity as a driver of voltage.

However, they do not document many alternative experimental pathways beyond changing fruits and ripeness. The idea of fruit waste to electricity is creative and environmentally relevant, and they extend this further by suggesting future research using fruit compost as a renewable energy source.

The Bohr group exhibited substantial development in transferable skills throughout the DT–PjBL intervention, as evidenced by observational data (Table 5). Their critical thinking was demonstrated through continuous comparison of acidity levels using pH paper and their inquiry into why certain fruits, particularly lemons, produced higher voltage outputs. Students reasoned that increased acidity contributes to greater ion availability, reflecting an emerging ability to link chemical properties to observed outcomes.

In terms of problem-solving, the group responded effectively to inconsistent voltage readings by proposing and implementing adjustments, such as repositioning electrodes at equal depths across all fruit samples, which successfully improved measurement consistency.

Collaboration and teamwork were clearly evident through the structured division of responsibilities, including electrode insertion, voltage measurement, and sample management, with observational notes highlighting smooth coordination and equitable participation among members. Communication skills were also strongly demonstrated, as students consistently employed appropriate scientific terminology, including references to H^+ concentration and electrode potential, to articulate their ideas and reasoning.

Creativity and innovation were reflected in their decision to extend the scope of the experiment beyond conventional fruit battery tasks by comparing different fruit types and ripeness levels, as well as proposing future exploration of fruit compost as a renewable energy source. Furthermore, the group's decision-making processes were systematic and collaborative, with students evaluating multiple options and justifying their final selection of fruits based on factors such as pH levels and material availability. Collectively, these findings indicate a high level of transferable skill development within the Bohr group.

Table 5
Bohr Group Observation Data

Item	
Group Observed	*Bohr*
Number of Students Present	*3 (Student 4,5 & 6)*
Project title	*Fruits battery*
TRANSFERABLE SKILLS	*Observer Notes / Description*
Evidence of Critical Thinking	*Students compared fruit acidity levels using pH papers and questioned why lemons produced higher voltage. Their reasoning connected acidity to ion availability, showing conceptual analysis.*
Evidence of Problem-Solving	*When the electrode placement resulted in inconsistent readings, Student 5 suggested repositioning electrodes at equal depth across all fruits. This adjustment stabilised readings.*
Collaboration & Teamwork	*Members took turns inserting electrodes, measuring voltage, and handling different fruit samples. Discussions were cooperative, and disagreements were resolved calmly.*
Communication	*Students actively verbalised observations such as "This fruit is too soft; the electrode wiggles". They used scientifically appropriate terms (electrode potential, H^+ concentration).*
Creativity & Innovation	*The group experimented with ripeness levels of fruits, showing curiosity and innovative extension beyond instructions.*
Decision-Making	*When choosing fruit samples, students voted between five available fruits. They justified choices based on expected pH and availability, indicating rational group decision-making.*

Within-Case Analysis: (Purification of Copper and Zinc)
This group's report is coherent and jointly authored, implying coordinated planning and shared roles in experimental work and analysis. The group designs a comparative study between zinc and copper purification, collects mass data before and after electrolysis, and calculates percentage changes, demonstrating structured problem-solving. Methodology and results are presented in a clear, ordered manner; calculations and tables are well organised. In discussion, they interpret why zinc appears more efficiently purified than copper, linking back to oxidation/reduction tendencies and typical uses (e.g., galvanising steel).

They choose a reasonable experimental design (two metals, constant conditions) and focus on comparing outcomes. However, decisions about alternative methods (e.g., different purification techniques) are not explored. Creativity here is more analytical than inventive because they apply a standard technique (electrolysis) but use comparative reasoning to deepen understanding.

The Charles group demonstrated meaningful development in transferable skills during the DT–PjBL intervention, as reflected in observational data (Table 6). Their critical thinking was evident through frequent analytical discussions, particularly when students questioned the differing behaviours of copper and zinc during electrolysis and linked these observations to oxidation–reduction tendencies. This analytical approach was complemented by their problem-solving skills, as the group engaged in systematic troubleshooting when faced with inconsistent mass changes. They reviewed their procedures and identified inadequate electrode cleaning, specifically the incomplete removal of oxide layers, as the source of error.

Collaboration and teamwork were also clearly demonstrated, with roles rotated among members, including electrolyte preparation, electrode measurement, and data recording, while students actively reminded one another about safety and procedural consistency. In terms of communication, the group consistently employed appropriate scientific terminology, such as oxidation, crystal lattice, electrolyte, and impurities, to articulate their reasoning and observations.

Creativity and innovation were reflected in their curiosity-driven exploration, as students discussed experimenting with different electrolyte concentrations and considered how metal purity influences industrial applications, indicating emerging innovative thinking within the scope of their project. Furthermore, their decision-making processes were purposeful and evidence-based, exemplified by their choice to conduct the zinc trial first due to its higher reactivity, allowing observable changes to occur more readily. Collectively, these findings indicate a proficient level of transferable skill development within the Charles group.

Table 6
Charles Group Observation Data

Item	
Group Observed	*Charles*
Number of Students Present	*3 (Student 7,8 & 9)*
Project Title	*Purification of metals*
TRANSFERABLE SKILLS	*Observer Notes / Description*
Evidence of Critical Thinking	*Students examined why zinc showed more mass loss than copper. Student 7 proposed examining electrode stability and metal reactivity. They engaged in structured reasoning using electrochemical series.*
Evidence of Problem-Solving	*When their zinc plate darkened, they hypothesised contamination. Student 9 checked the cleaning procedure and repeated the sandpapering step to ensure surface consistency.*
Collaboration & Teamwork	*The group divided electroplating tasks—solution preparation, electrode cleaning, mass measurement—with strong coordination and minimal conflict.*
Communication	*Frequent scientific dialogues occurred, e.g., "If impurities migrate, conductivity changes…" Students corrected each other respectfully and clarified each scientific step.*
Creativity & Innovation	*They tested purification on two metals (zinc and copper), showing initiative beyond the basic requirement. They brainstormed various impurity types during discussion.*
Decision-Making	*Students decided to use 1.0 M $CuSO_4$ due to availability and consistency with literature. The decision was justified through group reasoning about solubility and stability.*

Within-Case Analysis: Dalton Group (Galvanisation to Prevent Corrosion)

The report is coherent and systematically organised, suggesting coordinated work and negotiated understanding between group members. They design an experiment with two concentrations, conduct two full trials, and interpret differences in mass change and plating quality. This shows structured and systematic problem-solving.

The methodology, tables, and discussion are presented clearly, with appropriate technical detail and logical flow. They make sense of their data by relating higher zinc sulfate concentration to more efficient galvanisation and improved corrosion protection, and they discuss efficiency and operational conditions rather than only restating results. Their choice to vary only concentration, keeping other variables constant, reflects sound experimental control and purposeful decision-making aimed at optimising galvanisation.

While they adopt a standard industrial method (galvanisation), they extend it by considering optimisation through concentration variation and suggesting broader ranges of concentrations in future work.

The Dalton group demonstrated notable development in transferable skills throughout the DT–PjBL intervention, as evidenced by observational data (Table 7). Their critical thinking was reflected in their ability to explain how varying concentrations of $ZnSO_4$ influence plating thickness, with students reasoning that higher Zn^{2+} concentrations increase the rate of deposition due to greater ion migration to the cathode.

This conceptual understanding supported their problem-solving processes, as the group actively diagnosed and corrected procedural issues. For instance, when uneven plating was observed, students identified that the iron nail was not fully submerged, prompting them to restart the trial and adjust the electrode orientation accordingly.

Collaboration and teamwork were evident through a clear division of responsibilities, enabling the group to work cohesively and efficiently during experimental tasks. In terms of communication, students articulated their ideas using precise scientific terminology, as illustrated when one student explained that zinc acts as a sacrificial metal due to its more negative reduction potential.

Creativity and innovation were also apparent in their exploratory thinking, particularly when students considered whether combining $ZnSO_4$ with another salt could enhance plating quality. Furthermore, their decision-making was purposeful and evidence-informed, demonstrated by their choice to test the 1.5 M solution first based on the expectation of achieving faster deposition. Collectively, these findings indicate a proficient level of transferable skill development within the Dalton group.

Table 7
Dalton Group Observation Data

Item	
Group Observed	*Dalton*
Number of Students Present	*2 (Student 10 & 11)*
Project Title	*Galvanisation to Prevent Corrosion*
TRANSFERABLE SKILLS	*Observer Notes / Description*
Evidence of Critical Thinking	*Students questioned why thicker zinc layers formed at higher concentrations. Student 10 analysed how ion concentration affects deposition rate, showing scientific evaluation.*
Evidence of Problem-Solving	*When uneven plating occurred, the group repositioned the cathode, checked current stability, and repeated trials. They analysed process errors systematically.*
Collaboration & Teamwork	*Clear role division was observed: one monitored the power supply, another measured mass, and another recorded results. They supported one another during safety procedures.*
Communication	*Students used electrochemical terminology correctly ("oxidation at anode", "electron flow"). Their explanations were concise and comprehensible.*
Creativity & Innovation	*The group experimented with different $ZnSO_4$ concentrations beyond the standard method. Student 11 suggested trying 1.5 M to observe a steeper electroplating gradient.*
Decision-Making	*When choosing concentration values, decision-making was collective and based on prior readings and predicted efficiency, showing logical justification.*

Cross-case Analysis

The Arrhenius and Bohr groups demonstrated increasingly enacted epistemic practices, characterised by strong teamwork, systematic planning, effective troubleshooting, reflective reasoning, and well-justified decision-making. Evidence from both project reports and observational data indicates that these groups engaged in clear and purposeful communication, coordinated task distribution, and critical interpretation of data trends, reflecting a more integrated and adaptive approach to problem-solving.

In contrast, the Charles and Dalton groups also exhibited solid collaborative and communication practices but demonstrated comparatively lower levels of sophistication in creative idea generation and iterative decision-making. While both groups engaged in systematic problem-solving, their approaches tended to be more linear and procedure-driven, with limited exploration of alternative strategies or design iterations. This suggests that, although transferable skills were present, their design flexibility and innovative thinking remained at an emerging stage rather than fully developed. Table 8 presents a cross-case synthesis of transferable skill development across all four groups.

Table 8
Cross-Case Analysis of Transferable Skills

Transferable Skill Dimension	**Arrhenius Group**	**Bohr Group**	**Charles Group**	**Dalton Group**
Critical Thinking	High: Students questioned fluctuating voltage readings, hypothesised enzyme degradation due to temperature, and linked observations to biochemical stability.	High: Students analysed voltage differences across fruits, linking acidity (H^+ concentration) to electromotive force.	Moderate–High: Students reasoned using the electrochemical series to explain mass loss and electrode behaviour.	Moderate–High: Students analysed effects of ion concentration on deposition rate and plating thickness.
Problem-Solving	High: Adjusted enzyme concentration, reviewed literature, and modified dilution ratios after low voltage outcomes.	High: Repositioned electrodes to stabilise readings after identifying experimental inconsistency.	Moderate–High: Repeated electrode cleaning and adjusted procedures to address contamination issues.	High: Systematically adjusted cathode positioning and current stability to resolve uneven plating.
Collaboration & Teamwork	High: Clear voluntary task distribution and strong mutual support throughout experimentation.	High: Turn-taking in experimental roles and cooperative resolution of disagreements.	High: Coordinated task division with minimal conflict and shared responsibility.	High: Explicit role allocation (monitoring power supply, measuring mass, recording data).
Communication	High: Students articulated scientific reasoning clearly and engaged in peer explanation and correction.	High: Frequent verbalisation of observations using appropriate electrochemical terminology.	High: Continuous scientific dialogue, clarification of concepts, and respectful peer correction.	High: Concise explanations using accurate electrochemical language.
Creativity & Innovation	High: Repurposed fruit waste into enzymatic fuel cells and explored secondary energy ideas.	Moderate–High: Extended task by exploring fruit ripeness as a variable beyond instructions.	Moderate: Tested purification on multiple metals and brainstormed impurity types.	Moderate–High: Proposed additional concentration levels (e.g., 1.5 M $ZnSO_4$) to explore efficiency.
Decision-Making	High: Collective decisions prioritised feasibility and time constraints when selecting variables.	High: Group voting with scientific justification for fruit selection based on pH and availability.	Moderate–High: Decisions justified using literature consistency and chemical stability considerations.	High: Decisions based on predicted efficiency and prior readings.
Overall	**High**	**High**	**Moderate–High**	**Moderate–High**

Pre-Intervention Patterns: Limited Epistemic Engagement

Prior to the DT–PjBL intervention, students' engagement with chemistry tasks was largely procedural. Observational data indicated that laboratory work was approached as a sequence of prescribed steps, with limited evidence of questioning or interpretation. Students rarely articulated the reasoning behind their actions, and decision-making was often based on following instructions rather than evaluating alternatives. For example, during early project discussions, one group stated, "We just follow the experiment first, then see what happens," reflecting a compliance-oriented approach rather than an inquiry-driven one. Such responses indicate minimal engagement in epistemic practices such as hypothesis generation or evaluation of assumptions. Collaboration during this phase was also limited. Group work was characterised by task division rather than collective reasoning, with students completing assigned roles independently. Communication tended to be descriptive rather than analytical, focusing on reporting actions rather than explaining underlying concepts.

Emergence of Analytical Epistemic Practices

Following the introduction of DT–PjBL, students began to demonstrate more sophisticated analytical engagement. This was particularly evident in their increasing tendency to question unexpected results and propose explanations. In one case, students working on an enzymatic fuel cell project questioned fluctuations in voltage output. A student remarked, "Maybe the enzyme is affected by temperature, that's why the reading drops," indicating an emerging ability to link observations to underlying chemical principles. This shift reflects the enactment of critical thinking as an epistemic practice, where students move beyond observation to interpretation and explanation. Problem-solving practices also became more iterative. Rather than accepting initial results, students engaged in cycles of testing and refinement. For instance, when inconsistent readings were obtained in a fruit battery experiment, students adjusted electrode placement and repeated measurements, demonstrating adaptive problem-solving.

Development of Social Epistemic Practices

Collaboration and communication evolved significantly during the intervention. Students increasingly engaged in shared decision-making and collective reasoning, rather than working in isolation. In several groups, students negotiated roles dynamically, with responsibilities shifting based on task requirements. Discussions became more dialogic, with students building on each other's ideas. For example, one student suggested modifying a variable, prompting another to respond, "If we change that, we also need to control the temperature, otherwise the result is not fair." Such exchanges indicate the co-construction of knowledge through interaction. Communication also became more analytically oriented. Students used discipline-specific language more consistently and engaged in explaining and justifying their reasoning. This shift suggests that communication functioned not merely as information exchange but as a tool for thinking and reasoning.

Development of Generative Epistemic Practices

Creativity and decision-making practices became increasingly evident as students progressed through the DT phases. During the ideation stage, students generated multiple possible solutions, often extending beyond initial task requirements. For instance, a group exploring corrosion prevention proposed testing different concentrations of zinc sulfate and suggested future experimentation with alternative electrolytes. This reflects generative thinking, where students move beyond reproducing known solutions to exploring new possibilities. Decision-making also became more evidence-based. Students justified their choices using experimental data, feasibility considerations, and theoretical reasoning. In one discussion, a student argued, “We should test this first because it is easier to control, and we can compare later,” demonstrating strategic reasoning in selecting experimental approaches.

Cross-Case Patterns of Epistemic Engagement

Across all four groups, collaboration and communication emerged as the most consistently enacted epistemic practices. Analytical practices such as critical thinking and problem-solving were particularly evident during the prototyping and testing phases, where students encountered and addressed unexpected challenges. Generative practices, including creativity and decision-making, varied across groups and were most prominent when students extended beyond prescribed procedures. Groups that engaged more deeply in iterative design cycles demonstrated more sophisticated enactment of these practices. Overall, the findings indicate a shift from procedural engagement to more integrated epistemic participation. Rather than demonstrating isolated skills, students increasingly engaged in interconnected practices involving reasoning, collaboration, and decision-making within the DT–PjBL environment.

Discussion

The findings suggest that DT–PjBL functions as a mechanism for structuring epistemic engagement. Rather than directly causing skill development, it creates conditions where transferable skills are enacted through participation in iterative design processes. These findings align with epistemic fluency, highlighting that transferable skills emerge through engagement with disciplinary practices.

Analytical and Creative Thinking Skills

The findings of this study reveal a clear progression in students’ transferable skills following the implementation of Design Thinking–infused Project-Based Learning (DT–PjBL). Following the DT–PjBL implementation, a notable shift towards analytical and creative thinking was observed. Students are increasingly engaged in interpreting data, explaining anomalous results, and justifying design decisions using chemical principles. These practices were particularly evident during the Prototype and Test phases, where learners were required to iteratively refine their solutions. This transition reflects the development of epistemic fluency, where knowledge is no longer treated as static content but as a dynamic resource to be questioned, evaluated, and applied. This supports Markauskaite and Goodyear’s (2017c) assertion that epistemic fluency emerges when learners engage with knowledge as something to be interrogated, evaluated, and refined, rather than passively consumed.

Problem-Solving Skills

Similarly, problem-solving skills evolved from reliance on algorithmic procedures to more adaptive and iterative processes. Prior to the intervention, students demonstrated hesitation in tackling open-ended problems and showed limited confidence in identifying variables or predicting outcomes independently. Through DT–PjBL, students began to engage in systematic troubleshooting, hypothesis testing, and evidence-based refinement of solutions. They shifted from seeking predefined “correct answers” to navigating complex problem spaces, demonstrating increased autonomy and resilience in addressing real-world Chemistry challenges.

These findings align with Ahmad, Ammar, Siby, et al., (2023) whose meta-analysis demonstrated that PjBL has a significantly stronger effect on students’ problem-solving performance compared to traditional instructional methods. The study highlights the range of differences in students' capacities to develop these skills, underscoring the significance of a nurturing learning environment and efficient teaching approaches. This is strengthened by studies conducted by Guaman-Quintanilla et al., 2023; Hashim et al., 2019; Henriksen et al., 2017; Hyunjin, 2019; Norliyana et al., 2024; Tu et al., 2018 that combining Design Thinking in Chemistry education had a substantial impact on students' critical thinking and problem-solving skills.

Collaboration and Communication

The development of collaboration and communication skills was also highly pronounced. Early group interactions were characterised by simple task division, with minimal collective reasoning. In contrast, DT–PjBL fostered sustained dialogue, shared decision-making, and collaborative interpretation of data. Students negotiated roles, resolved disagreements constructively, and co-constructed understanding through discussion. These findings highlight the inherently social nature of design thinking, which develops collaborative knowledge construction. These findings are also consistent with the research conducted by Veerasinghan et al., (2021), which emphasised the significance of employing innovative teaching approaches, such as Design Thinking, to improve students' capacity for collaborative work and conflict resolution.

Communication skills also improved markedly, as evidenced by students’ written reports, oral presentations, and group discussions. Students became more adept at articulating scientific reasoning, explaining design choices, and justifying conclusions using appropriate chemical terminology after DT-PjBL intervention. Evidence shows that research courses, improve students' communication abilities by fostering their capacity to collaborate with information and successfully deliver their findings (Bitemirova et al., 2023; Overton & McGarvey, 2017). This also aligns with Prins et al., (2018), who emphasised that authentic scientific practices such as argumentation, explanation, and peer critique are essential for developing disciplinary literacy and epistemic competence in Chemistry. Dai, (2023), too, found that discipline-specific knowledge and the negotiation process are essential for effective communication. Findings from Yuan & Liu, (2023) further supports the notion that persuasive communication is crucial for fostering epistemic agility across disciplines.

Creativity, Innovation, and Decision-Making

Creativity and innovation, often marginalised in traditional Chemistry classrooms, became prominent through the DT–PjBL approach. Students were encouraged to generate ideas, explore alternative materials or methods, and design artefacts that addressed real-world problems. All groups produced functional prototypes grounded in electrochemical principles, indicating a shift from reproductive to productive forms of knowledge use. This finding resonates with Orosz et al., (2022) and Ahmad, Ammar, Sellami, et al., (2023), who reported that creativity flourishes when students are engaged in project-based and design-oriented learning environments.

Decision-making skills were also strengthened, as students were required to select variables, justify methodological choices, and prioritise feasible solutions within practical constraints. These decisions were increasingly informed by chemical reasoning, empirical data, and collaborative deliberation, reflecting a move towards epistemic agency. Such developments support McLaughlan and Lodge’s (2019) argument that design thinking fosters learners’ capacity to make informed, context-sensitive judgements.

Synthesis of Findings

Overall, the findings of this study demonstrate that transferable skills in Chemistry are not ancillary outcomes but integral components of epistemic fluency that can be deliberately cultivated through DT–PjBL. The observed progression from procedural compliance to critical, collaborative, and creative engagement underscores the transformative potential of design-oriented pedagogies. By embedding project-based, transferable skills within authentic scientific practices, the DT–PjBL approach aligns Chemistry education with the demands of the 21st century and prepares students to navigate complex academic, professional, and societal challenges.

Conclusions and Implications

This study provides compelling evidence that Design Thinking–infused Project-Based Learning (DT–PjBL) is an effective pedagogical approach for enhancing transferable skills in pre-university Chemistry education. The findings demonstrate that Design Thinking functions as a powerful epistemic and pedagogical scaffold, enabling students to move beyond procedural engagement towards deeper critical thinking, collaborative reasoning, and creative problem-solving. Through structured engagement in iterative phases of ideation, prototyping, testing, and evaluation, students developed the capacity to justify design decisions, interpret experimental data, and refine solutions based on evidence.

Importantly, the study highlights that transferable skills such as critical thinking, communication, collaboration, creativity, and decision-making are not developed in isolation, but emerge as integral epistemic practices embedded within disciplinary learning. The DT–PjBL framework creates a learning environment in which students actively construct knowledge, negotiate meaning, and engage in reflective inquiry, thereby strengthening both conceptual understanding and skill development simultaneously.

From a pedagogical perspective, the findings suggest that integrating Design Thinking within Chemistry instruction can transform traditionally procedural and examination-oriented practices into more student-centred, inquiry-driven experiences. By foregrounding real-world relevance and authentic problem contexts, DT–PjBL fosters learner agency and prepares students to engage with complex scientific and societal challenges.

In terms of implications, this study offers a structured framework that can guide educators, curriculum designers, and policymakers in implementing innovative instructional approaches aligned with national and global STEM education priorities. The DT–PjBL approach has the potential to bridge the gap between academic knowledge and workforce readiness, supporting the development of scientifically literate, adaptable, and innovative learners equipped for the demands of the 21st century.

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