

Developing Epistemic Fluency: Bridging Theory and Practice in Pre-University Chemistry Education through Design Thinking

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ABSTRACT

Epistemic fluency, understood as the capacity to navigate, integrate, and apply multiple forms of knowledge, is increasingly recognised as a critical outcome of science education. Despite this, many students continue to experience difficulty in transferring theoretical knowledge to practical contexts, highlighting a persistent disconnect between conceptual understanding and application. This study investigates how design thinking, conceptualised through a sociocultural lens, supports the development of epistemic fluency among pre-university chemistry students. Adopting a qualitative case study approach, data were collected from six students through project proposals, written reports, and classroom observations during a design thinking intervention. The data were analysed thematically to examine shifts in students' epistemic practices. Findings indicate that students initially demonstrated fragmented understanding and limited ability to apply disciplinary knowledge. However, through collaborative engagement, iterative problem-solving, and interaction with authentic tasks, students progressively developed the capacity to move between theoretical, procedural, and experiential knowledge forms. The study highlights the role of social interaction, guided participation, and artefact construction in mediating learning, supporting the view that epistemic development is socially situated. It contributes to the literature by positioning design thinking as a sociocultural pedagogical approach that fosters epistemic fluency and enhances meaningful learning in chemistry education.

Keywords: Epistemic fluency, design thinking, sociocultural learning, chemistry education

INTRODUCTION

The increasing demand for graduates who are capable of applying knowledge flexibly across contexts has intensified attention on the development of higher-order competencies in education. Within science education, and particularly chemistry, a persistent concern is the gap between students' theoretical understanding and their ability to apply this knowledge in practical or real-world situations (Wan Yunus & Mat Ali, 2018). Students frequently demonstrate proficiency in algorithmic problem-solving, yet struggle when confronted with open-ended, context-rich problems that require integration of multiple forms of knowledge (Abelha et al., 2020; Karpudewan & Kulandaisamy, 2018).

This gap reflects a deeper issue related to epistemic fluency. Epistemic fluency refers to the ability to recognise, navigate, and integrate different ways of knowing, including theoretical, procedural, and experiential knowledge (Markauskaite & Goodyear, 2017). In chemistry education, this involves not only understanding scientific concepts but also applying them in meaningful ways, making informed decisions, and constructing knowledge through inquiry and practice.

Traditional instructional approaches often privilege decontextualised knowledge acquisition, limiting opportunities for students to engage in authentic problem-solving. As a result, students may develop fragmented knowledge structures that are difficult to mobilise beyond examination settings. Addressing this

issue requires pedagogical approaches that support knowledge integration and application within socially meaningful contexts (Lombardi et al., 2021; Nzomo et al., 2023; van Dinther et al., 2023).

Design thinking has emerged as a promising pedagogical approach that emphasises empathy, problem framing, ideation, prototyping, and testing (Markauskaite & Goodyear, 2017b; McLaughlan & Lodge, 2019). Importantly, design thinking is inherently collaborative and iterative, making it well-aligned with sociocultural perspectives on learning. From a sociocultural standpoint, learning is not an individual cognitive process alone but is mediated through interaction, tools, and participation in meaningful activities, as theorised by Lev Vygotsky.

This study seeks to explore how design thinking, conceptualised as a sociocultural learning process, supports the development of epistemic fluency among pre-university chemistry students. The study is guided by the following research questions:

- i. What are the initial characteristics of students' epistemic practices in chemistry learning?
- ii. How does engagement in design thinking mediate the development of epistemic fluency?

LITERATURE REVIEW

Epistemic Fluency in Science Education

Epistemic fluency has been increasingly recognised as a critical educational goal in contemporary learning environments. It encompasses the ability to understand and utilise different forms of knowledge, as well as the capacity to move flexibly between them. In science education, epistemic fluency involves integrating conceptual understanding with procedural skills and experiential insights (Markauskaite & Goodyear, 2017). Students who lack epistemic fluency often rely on rote memorisation and algorithmic procedures, limiting their ability to engage in authentic scientific practices (Abelha et al., 2020). This results in difficulties when applying knowledge to unfamiliar or real-world contexts (Kranz et al., 2022). Developing epistemic fluency, therefore, requires learning environments that encourage knowledge integration, critical reflection, and application.

Sociocultural Perspectives on Learning

This study is grounded in Sociocultural Theory, which conceptualises learning as a socially mediated process. According to Lev Vygotsky, knowledge is constructed through interaction with others and with cultural tools. Learning occurs within the Zone of Proximal Development (ZPD), where learners can perform beyond their independent capabilities with appropriate support (Vygotsky, 1999). Key concepts in sociocultural theory include mediation, social interaction, and the use of artefacts. Tools and artefacts, whether physical or symbolic, play a crucial role in shaping cognitive processes. Learning is therefore not confined to the individual but is distributed across people, tools, and contexts. From this perspective, epistemic fluency can be understood as emerging through participation in socially mediated activities that require learners to engage with multiple forms of knowledge.

Design Thinking as a Sociocultural Pedagogy

Design thinking is characterised by iterative problem-solving, collaboration, and engagement with authentic challenges. It involves stages such as empathising, defining problems, ideating, prototyping, and testing (Brown, 2008; Razzouk & Shute, 2012). These processes require learners to actively construct knowledge, engage with others, and apply concepts in context. From a sociocultural perspective, design thinking can be seen as a form of mediated activity that supports learning through interaction and tool use. The collaborative nature of design thinking fosters dialogue and shared understanding, while the creation of artefacts externalises thinking and supports reflection (Wrigley & Straker, 2022). This study positions design thinking as a pedagogical approach that facilitates epistemic fluency by enabling students to move between different forms of knowledge within socially meaningful contexts.

Conceptual Framework

The study is guided by a conceptual framework in which design thinking functions as a mediating process that supports the development of epistemic fluency. Through collaborative engagement, interaction, and artefact construction, students are enabled to integrate theoretical, procedural, and experiential knowledge. This process is socially situated and aligns with sociocultural perspectives on learning.

METHODOLOGY

Research Design

This study adopts a qualitative case study design to explore students' epistemic development within a design thinking intervention. The approach allows for an in-depth examination of learning processes within a real educational context.

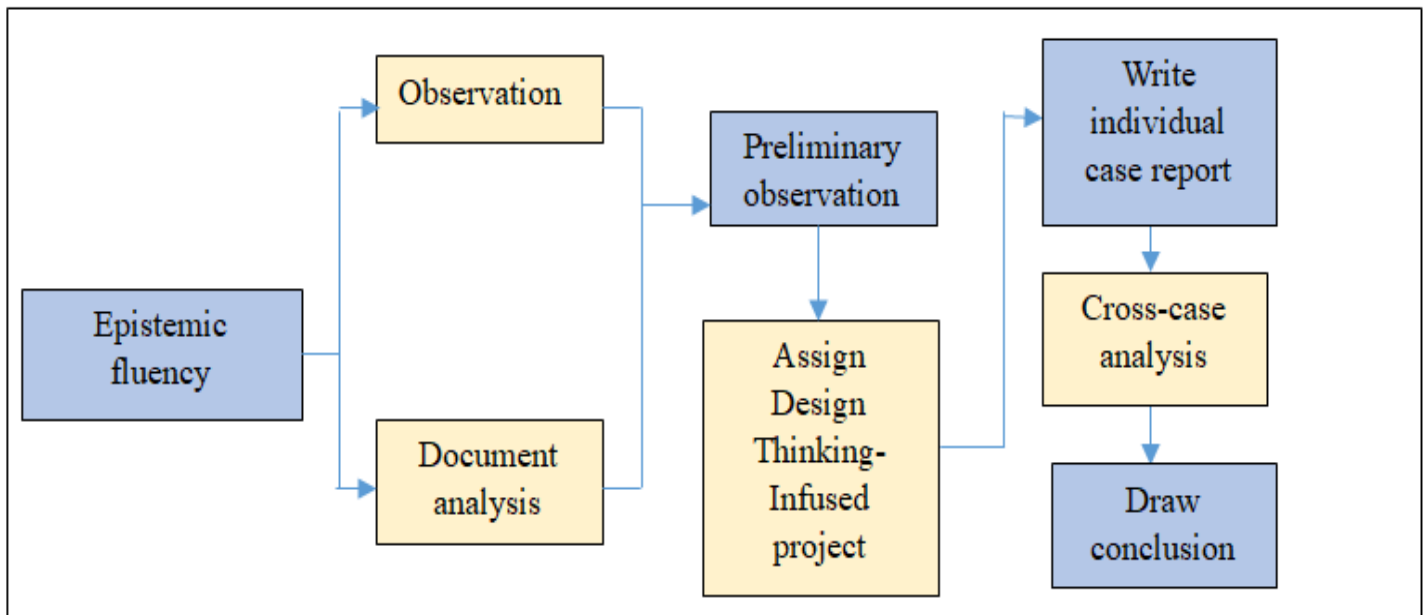


Figure 1 Research Design

Participants and Context

The participants consisted of six pre-university students enrolled in a chemistry programme. The study was conducted within a classroom setting where design thinking was integrated into project-based learning activities. The students were organised into two groups (Arrhenius and Bohr) 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

Data Collection

Data were collected through multiple sources: 1. Students' project proposals, 2. Final project reports. These data sources provided insight into students' thinking processes, interactions, and knowledge application. Validity was ensured through data triangulation and prolonged engagement. Participants' identities were anonymised, and informed consent was obtained. Data were coded to protect confidentiality. Figure 2 below shows the activities and duration during each stage.

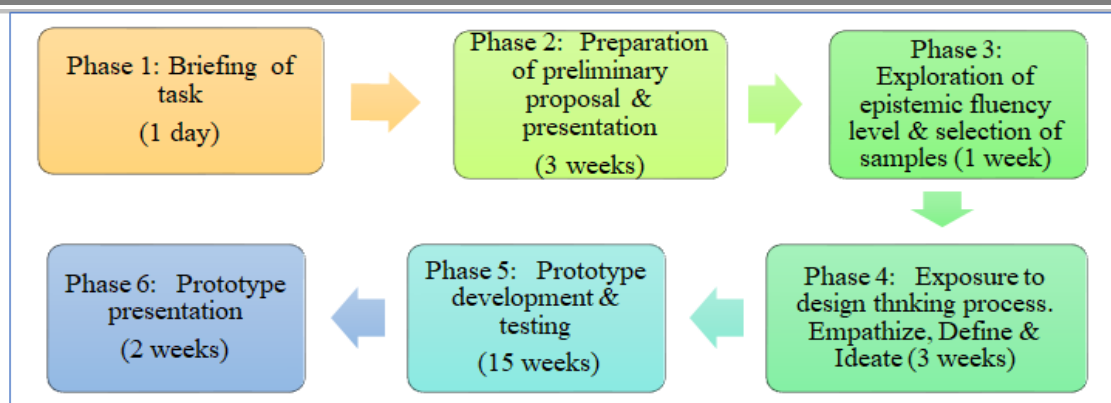


Figure 2: Design Thinking phases

Data Analysis

Data were analysed using a structured qualitative content analysis approach, guided by deductive coding aligned with the theoretical constructs of Design Thinking (DT) and Epistemic Fluency (EF). Two complementary instruments were used:

1. Design Thinking Process Checklist (Section 4.2)
2. Epistemic Fluency Development constructs (Section 4.3)

The analysis focused on identifying patterns related to students' epistemic practices and their development over time.

Findings

Initial Fragmentation of Knowledge and Limited Epistemic Fluency

At the initial stage of the study, students largely depended on memorisation and routine procedures, showing limited capacity to apply chemistry concepts to unfamiliar situations. Their knowledge appeared segmented, with little evidence of integration across different forms of understanding. For example, in their early project proposals, students often restated textbook definitions without extending them to relevant contextual applications.

Arrhenius group

The Arrhenius group exhibits a partially developed understanding of electrochemical principles in their proposal. Although they refer to oxidation and reduction processes, these are largely presented as reproduced textbook statements rather than applied explanations. The proposal does not clearly explain the chemical mechanism underlying their chosen approach of sacrificial protection, nor does it establish any meaningful real-world relevance, as reflected in the general statement, "*Corrosion causes damage to metals.*"

Furthermore, no specific real-life context, such as pipelines, bridges, or vehicles, is connected to their proposed investigation. This suggests that their understanding remains at a surface level, without effective integration into practical application. In addition, while the issue of corrosion is identified, the group does not propose any concrete design of a device, tool, or model (e.g., corrosion-resistant coatings or a galvanic protection system). This indicates an absence of intention toward artefact creation and applied problem-solving.

Bohr group

In their proposal, the group discussed concepts related to corrosion and purification, and made reference to industrial relevance, stating that:

"The presence of impurities in chemical substances will cause dangerous issues such as fire and explosion... purification of metals can be carried out."

However, this discussion is not clearly connected to corrosion, indicating a degree of conceptual inconsistency. Although the group demonstrates awareness of real-world implications, particularly through references to industrial hazards, this is not well aligned with their selected focus on corrosion. Such misalignment reflects weak coherence between theoretical understanding and practical application. Despite the proposal being well organised, it does not introduce any concept of an artefact. The project remains framed as a conventional laboratory experiment rather than a solution-oriented or application-driven approach.

Cross-case analysis

Findings from the preliminary project proposal from both groups' analysis indicate that pre-university students in this study generally exhibit low levels of epistemic fluency. Across both cases, integration between theory and practice is limited, characterised by a strong reliance on memorisation, insufficient real-world contextualisation, and superficial conceptual reasoning. Artefact creation emerged as the weakest aspect across all groups, with initial proposals largely procedural and lacking any indication of prototype development or innovative outcomes.

A consistent pattern became evident: students' epistemic practices were predominantly shaped by rote learning and constrained application of concepts in real-world contexts. This baseline diagnosis underscores the need for an instructional intervention, thereby justifying the implementation of design thinking as a pedagogical approach.

Social Mediation through Collaborative Design Thinking Processes

Arrhenius group

As students engaged in design thinking activities, there was a notable shift in their interactions. Table 2 shows the Arrhenius Group's project report that focuses on the use of design thinking in addressing the problem of waste by converting orange waste into renewable energy sources.

Table 2 Design Thinking Process: Arrhenius Group

DT Phase	Indicator	Evidence From Project Report
Empathize	Identifies a real-world problem	Problem: "mass purchase of mandarin oranges during Chinese New Year leads to waste" (Problem Statement)
	Considers user/environment needs	Highlights "global warming," "depleting crude oil," and "need for renewable energy" (Introduction)
	Collects background info	Extensive literature on enzymatic fuel cells, enzymes, oxidation principles (1.1 Theory)
Define	Clear problem statement	"To avoid wastage... mandarin oranges will be used to make enzymatic fuel cells" (Problem Statement)
	Clear research objectives	Three objectives: produce electricity, study concentration, study temperature (1.4)
Ideate	Generates multiple ideas	Mentions alternative idea "Piezoelectric Energy Harvesting using dried/powdered peel" but not developed.
Prototype	Prototype constructed	Detailed electrochemical cell setup, diagrams, step-by-step preparation (Section 2.3)
	Scientific justification	Electrochemical principles clearly discussed; citations included.
Test	Systematic testing	Voltage-Temperature & Voltage-Concentration trials; tables and graphs provided.
	Iteration/Refinement	Experiments repeated, but no redesign of prototype.
	Reflection & limitations	Mentions enzyme degradation, pH effects, porosity, limitations, and future improvements.
	Suggested improvements	Suggests adding pH variable and improving enzyme stability.

Evidence from the project report shows that the group achieved a well-developed empathise phase. They carried out contextual research on environmental concerns linked to the high consumption of mandarin oranges during the Chinese New Year. The report highlights that “the mass purchase of mandarin oranges during Chinese New Year leads to excessive waste,” and connects this issue to wider challenges such as global warming, depletion of crude oil resources, and the growing need for renewable energy alternatives.

The group also demonstrated strong background inquiry, providing a comprehensive synthesis of literature on enzymatic fuel cells, enzyme activity, glucose oxidation, and the environmental impact of fruit waste. This depth of investigation indicates a high level of engagement with both user needs and environmental considerations within the local context.

Bohr group

Following their exposure to design thinking strategies, the Bohr group proposed a new direction. Their approach to chemistry problem-solving involved the use of fruits as a source of energy, effectively treating them as batteries. This reflects strong engagement with the design thinking process, where their project represents a chemistry-focused, experiment-driven adaptation of the approach. Table 3 presents supporting evidence from their project report illustrating the design thinking process undertaken by the Bohr group.

Table 3 Design Thinking Process: Bohr Group

DT Phase	Indicator	Evidence from Project Report
Empathize	Identifies real-world problem	Report states fruit waste is common and “a lot of fruits is wasted every day... fruit battery can be used to prevent the depletion of fossil fuel resources”
	Considers user/environmental needs	References global electricity demand, depletion of fossil fuels, environmental issues (Introduction, p.5)
	Collects background information	Extensive literature review on redox chemistry, fruit acidity, electrode reactions, bioelectrochemical systems (pp. 5–8)
Define	Clear problem statement	“As the idea of using fruits as a battery has been discovered... investigate the pH level of fruit affects voltage produced.” (p.8)
	Clear objectives	Three objectives provided: probability of fruits generating electricity, effect of pH, effect of ripeness (p.8)
Ideate	Generates multiple ideas	Only one idea explored: fruit battery. No alternatives or comparative solutions (no brainstorming section).
Prototype	Prototype described & constructed	Step-by-step procedure for setting up fruit battery, inserting electrodes, and measuring voltage (pp.10–12) with photos (p.11)
	Scientific justification	Explanation of redox reactions, ion movement, H ⁺ concentration, electrode potential (pp.6–7).
Test	Systematic testing	Data table showing voltage vs pH for 5 fruit types; consistent procedure across samples (p.13)
	Iteration / refinement	No evidence of changes to prototype; only one trial per fruit documented.
	Reflects on results & limitations	Discussion explains why acidity affects voltage, influence of ripeness, structural differences in fruit (pp.14–17).
	Suggests improvements	Suggests future research using fruit compost as renewable energy source (p.3).

This group demonstrated a strong awareness of the environmental significance of their project, situating their investigation within global concerns such as rising electricity demand and the depletion of fossil fuels. In their introduction, they note that “more than 85% of the total power consumed globally is obtained by the combustion of oil, coal, and natural gas,” underscoring the urgency of developing renewable energy alternatives.

They effectively linked core chemistry concepts, particularly redox reactions and ion conduction, to a real-world sustainability issue by proposing the use of fruit waste as a renewable energy source. Their problem statement further highlights that “a lot of fruits is wasted every day,” positioning fruit-based batteries as a potential solution. The literature review is comprehensive, reflecting strong engagement with electrochemical principles, redox processes, and bio-electrochemical fuel cells.

Cross-case analysis

Across both cases, the empathise phase emerged as a key indicator of how design thinking supports socially constructed knowledge. The Arrhenius group grounded their project in a culturally specific and environmentally relevant issue, mandarin orange waste during Chinese New Year, and the associated need for renewable energy, while the Bohr group addressed broader global concerns related to energy consumption and fossil fuel depletion.

In summary, students in both cases utilised design thinking as a structured, inquiry-driven extension of the scientific method. They demonstrated notable strengths in the empathise, define, prototype, and test phases, with developing capabilities in ideation. Design thinking enabled students to reframe chemistry tasks as real-world problems and to articulate clear, investigable objectives. They also showed the ability to design and implement scientifically sound prototypes, translating electrochemical and corrosion concepts into functional experimental systems. This progression highlights how guided participation supported students in connecting theoretical knowledge with practical decision-making.

Emergence of Epistemic Fluency through Iterative Problem-Solving

The epistemic fluency (EF) levels of each group were analysed using three (3) constructs: EF1: Theory–Practice Integration, EF2: Transferable Skills, and EF3: Artefact Creation.

Arrhenius group

EF1: Theory–Practice Integration

The Arrhenius group demonstrated a high level of integration between chemistry theory and real-world application. Their problem framing explicitly linked a socio-environmental issue, “*the mass purchase of mandarin oranges during Chinese New Year leads to waste*,” to a scientific objective of converting this waste into renewable energy through the use of enzymatic fuel cells.

Their project report reflects accurate application of biochemical and electrochemical concepts, including oxidation-reduction reactions, enzyme catalysis and denaturation, as well as the effects of temperature and substrate concentration on reaction kinetics and electron transfer within electrochemical systems. These principles were not only described but also applied in data interpretation. For instance, students explained observed voltage variations by relating them to enzyme degradation at elevated temperatures, demonstrating meaningful application of theoretical knowledge.

EF2: Transferable Skills

The Arrhenius group exhibited strong transferable skills, as evidenced by the organisation of their report, clear division of responsibilities, and coherent presentation of findings, all of which indicate effective teamwork. They addressed inconsistencies in voltage readings through repeated trials and careful control of variables, reflecting a systematic approach to problem-solving. The structured nature of the report also suggests purposeful internal communication.

The group identified key limitations, such as enzyme instability, pH sensitivity, and material porosity, and proposed logical improvements for future work. Their decision-making processes were evident in the selection of experimental variables, including enzyme concentration levels and temperature conditions. Furthermore, their idea of converting festive food waste into a renewable energy source demonstrates originality and innovation.

The following specific skills were observed:

- **Critical Thinking:** Students questioned fluctuating voltage readings, attributing them to enzyme instability. Student 1 asked, “*Could the enzyme be breaking down when it’s too warm?*”, demonstrating analytical reasoning.
- **Problem-Solving:** When voltage was inconsistent, they reviewed concentration values, checked dilution accuracy, and consulted literature to diagnose denaturation causes.
- **Collaboration / Teamwork:** They self-organised roles: enzyme extraction, apparatus setup, data recording, with consistent cooperation.
- **Communication:** Students used scientific terminology fluently (e.g., *oxidation, enzyme activity*), explaining processes clearly to one another.
- **Creativity /Innovation:** They turned food waste to renewable energy source
- **Decision-Making:** They explored a secondary concept, piezoelectric harvesting, before selecting enzymatic fuel cell generation.

EF3: Artefact Creation

The Arrhenius group successfully developed a functional enzymatic fuel cell prototype, supported by detailed documentation including procedures, diagrams, and photographic evidence. Their experimental data, such as voltage versus concentration and voltage versus temperature, demonstrate systematic empirical validation.

The prototype development process aligns with the criteria for epistemic artefact creation, although iterative redesign between trials was not extensively documented. Nevertheless, their reflective analysis identified key limitations, including enzyme stability and material porosity, and proposed feasible improvements, indicating a high level of competence in artefact-related practices.

Further evidence of EF3 includes:

- **Scientific Accuracy:** The group accurately explained enzyme-mediated oxidation-reduction processes, effectively linking biochemical and electrochemical concepts, including clear descriptions of oxidation at the anode and reduction at the cathode.
- **Functionality:** The fuel cell consistently generated measurable voltage, supported by multiple experimental trials and graphical representations of results.
- **Innovation:** The use of mandarin orange waste for energy generation demonstrates strong creativity and a focus on sustainable solutions.
- **Theory–Practice Integration:** Students connected enzyme denaturation and catalytic activity to observed voltage outcomes, reflecting applied and interdisciplinary thinking.
- **DT-Based Refinement:** While the physical prototype did not undergo substantial redesign, experimental refinement was achieved through repeated trials and systematic variation of key parameters.

Bohr group

EF1: Theory–Practice Integration

The Bohr group demonstrated a clear and accurate understanding of chemistry concepts, effectively linking them to a relevant real-world issue, fruit waste management. They framed the socio-environmental context by noting that “*a lot of fruit is wasted every day... fruit battery can be used to prevent the depletion of fossil fuel resources,*” reflecting both conceptual understanding and contextual awareness. This represents a notable improvement from their initial proposals, which lacked real-world grounding.

Their project report shows strong theoretical grounding across several key areas:

- **Redox chemistry:** Clear explanation of oxidation at the zinc electrode and reduction at the copper electrode

- Role of acidity: Recognition that pH influences H^+ concentration and, consequently, the potential difference
- Effects of ripeness: Understanding that sugar content affects internal resistance
- Ion mobility: Acknowledgement that ions beyond H^+ also contribute to voltage output

The group explicitly connected theory to experimental outcomes, explaining that fruit acidity affects H^+ availability and thus the electromotive force measured. Their interpretation of the non-linear voltage-pH relationship demonstrates higher-order reasoning, as reflected in the statement: “*there are some ions, not only the H^+ ions, will affect the voltage produced.*” This depth of reasoning indicates a high level of epistemic fluency in theory-practice integration.

EF2: Transferable Skills

The Bohr group’s report is coherent and consistently written using a collective voice (“*we*”), indicating strong teamwork and shared responsibility. Their experimental procedures and analyses were well coordinated, reflecting effective collaboration. They systematically measured voltage across five different fruit conditions, accounted for variation between samples, and interpreted non-linear graphical trends resulting from differing ion compositions.

The report is logically structured, with clear and scientifically sound explanations presented in accessible language. The group demonstrated reflective reasoning by explaining why fruits with similar acidity levels produced different voltages, attributing this to the presence of additional ions influencing the electrochemical system. Their interpretation of the non-linear voltage trend further reinforces this analytical depth.

The group made informed decisions regarding measurable variables, including fruit type, pH, and ripeness, and justified their focus on acidity as a key factor influencing voltage. However, they explored limited alternative experimental approaches beyond varying fruit types and ripeness. Their idea of converting fruit waste into electricity is both creative and environmentally relevant, further extended by proposing future exploration of fruit compost as a renewable energy source.

The following transferable skills were evident:

- **Critical Thinking:** The group consistently compared acidity levels using pH paper and questioned why certain fruits (e.g., lemons) generated higher voltages. Students compared fruit acidity levels using pH papers and asked “*why lemons produce higher voltage...*”, reasoning that acidity leads to ion availability.
- **Problem-Solving:** Evidence shows that when electrode insertion produced inconsistent readings, Student 5 proposed: “*repositioning electrodes at equal depth across all fruits,*” which successfully stabilised measurements.
- **Collaboration / Teamwork:** A clear division of tasks: electrode insertion, measurement, and sample management, indicating smooth teamwork and equitable workload sharing: “*Members took turns inserting electrodes, measuring voltage, and handling fruit samples... disagreements were resolved calmly.*”
- **Communication:** Students consistently used scientific terminology during laboratory work.
- **Creativity / Innovation:** Creativity is evident in their decision to extend the experiment beyond typical school-level fruit battery tasks by comparing ripeness levels, experimenting with five fruit types, and proposing future exploration of fruit compost as a renewable energy source.
- **Decision-Making:** The group’s decision-making process is well-documented: “*voted between five available fruits... justified choices based on expected pH and availability.*”

EF3: Artefact Creation

The Bohr group successfully constructed a standardised fruit battery prototype using various fruit types, electrodes, and measurement tools. The inclusion of photographs and step-by-step procedures satisfies the requirements for artefact documentation. While the prototype itself was not redesigned, the group varied testing conditions such as fruit type, pH, and ripeness.

The artefact represents an innovative application of fruit waste for energy generation, grounded in electrochemical principles rather than mere replication of textbook experiments. Overall, the prototype demonstrates a high level of competence in artefact creation.

Further evidence includes:

- **Scientific Accuracy:** The group accurately explained redox reactions, incorporating concepts such as acidity, H^+ concentration, and electrode potential, with the prototype closely aligned to established electrochemical principles.
- **Functionality:** The fruit battery consistently generated measurable voltage across different fruit samples.
- **Innovation / Creativity:** Although fruit batteries are a familiar experiment, linking the concept to renewable energy and waste reduction adds a meaningful layer of innovation.
- **Theory–Practice Integration:** The artefact directly reflects their theoretical understanding, as demonstrated in the explanation that more acidic fruits produce higher voltage due to increased H^+ concentration.
- **Design Thinking Evidence:** While the prototype did not undergo iterative redesign, it remains scientifically sound, with refinement occurring through variation of experimental conditions.

Cross-case analysis

A comparative analysis of the Arrhenius and Bohr groups reveals both convergences and divergences in the development of epistemic fluency across three key dimensions: theory-practice integration (EF1), transferable skills (EF2), and artefact creation (EF3). While both groups demonstrated substantial epistemic growth following the design thinking intervention, differences in depth, focus, and execution highlight the nuanced ways in which epistemic fluency is constructed through socially mediated activity.

EF1: Theory-Practice Integration

Arrhenius group work demonstrated interdisciplinary integration, combining electrochemistry with enzyme kinetics and biochemical processes. Notably, they applied theoretical concepts directly in interpreting experimental outcomes, such as linking enzyme denaturation at elevated temperatures to observed voltage variations. This reflects a sophisticated level of epistemic integration, where theory informs both design and data interpretation. In contrast, the Bohr group framed their project within a broader global context of energy consumption and fossil fuel depletion. The group demonstrated strong conceptual reasoning, but with less interdisciplinary expansion compared to the Arrhenius group.

Overall, while both groups achieved effective theory-practice integration, the Arrhenius group demonstrated deeper interdisciplinary synthesis, whereas the Bohr group showed strong conceptual clarity within a more focused domain.

EF2: Transferable Skills

Both groups exhibited well-developed transferable skills, particularly in collaboration, communication, and problem-solving, though their approaches differed in complexity and scope. The Arrhenius group demonstrated a high level of analytical and reflective thinking. They systematically addressed inconsistencies in experimental results by conducting repeated trials, controlling variables, and consulting relevant literature. Additionally, their exploration of alternative concepts, such as piezoelectric energy generation, indicates openness to multiple solution pathways.

The Bohr group, on the other hand, exhibited strong procedural organisation and consistency in teamwork. Their experimental design was systematic, involving comparisons across multiple fruit types and conditions. They demonstrated effective problem-solving, particularly in resolving measurement inconsistencies through adjustments in electrode placement.

While both groups displayed strong collaboration and communication, the Arrhenius group's approach was more exploratory and iterative, whereas the Bohr group's approach was more structured and controlled. This suggests that transferable skills may manifest differently depending on how groups engage with the design thinking process.

EF3: Artefact Creation

In terms of artefact creation, both groups successfully developed functional prototypes, though differences emerged in complexity and innovation.

The Arrhenius group constructed an enzymatic fuel cell prototype, supported by detailed documentation and empirical validation through multiple datasets. Their artefact reflected a high level of scientific integration, combining biochemical and electrochemical principles. The prototype demonstrated functionality and originality, particularly in its use of mandarin orange waste as a substrate.

Similarly, the Bohr group developed a fruit battery prototype using various fruit types, demonstrating consistent functionality across multiple trials. Their artefact was well-documented and grounded in sound electrochemical principles. Although the fruit battery concept is relatively familiar, the group enhanced its relevance by linking it to sustainability and waste reduction. As with the Arrhenius group, refinement occurred primarily through variation of experimental conditions rather than structural redesign of the prototype.

Comparatively, the Arrhenius group's artefact reflects greater conceptual innovation and interdisciplinary application, whereas the Bohr group's artefact demonstrates strong execution and systematic testing within a well-established framework.

DISCUSSION

This study aimed to investigate how design thinking, conceptualised through a sociocultural perspective, facilitates the development of epistemic fluency in pre-university chemistry education. The findings indicate that epistemic fluency is not an isolated cognitive outcome, but rather a developmental process shaped through socially mediated engagement in meaningful tasks.

Importantly, the results demonstrate that epistemic fluency does not develop uniformly across learners. Instead, distinct developmental trajectories emerged based on how students engaged with the design thinking process. The Arrhenius group exhibited a trajectory characterised by interdisciplinary exploration and conceptual expansion, integrating biochemical and electrochemical knowledge within a culturally situated problem context. In contrast, the Bohr group followed a trajectory centred on systematic experimentation and empirical reasoning, demonstrating strong conceptual clarity within a more focused electrochemical framework.

From a sociocultural standpoint, these variations can be interpreted as differences in modes of participation within a shared learning environment. While both groups engaged with key mediational elements of design thinking, namely collaboration, dialogue, and artefact construction, they enacted these processes in different ways, leading to varied expressions of epistemic fluency. This highlights that epistemic development is not only shaped by instructional design but also by how learners interact with and appropriate these learning structures.

From Fragmented Knowledge to Epistemic Integration

The initial phase of the study revealed that students' understanding of chemistry was largely fragmented, characterised by a reliance on memorisation and procedural approaches. Although students were able to recall definitions accurately, they experienced difficulty applying this knowledge to unfamiliar or real-world contexts. This finding is consistent with previous research highlighting the persistence of inert knowledge in science education, where conceptual understanding remains disconnected from practical application (Bhola & Parchoma, 2016; Nakiboglu et al., 2023; Orozco et al., 2023).

From an epistemic perspective, this stage reflects limited movement across knowledge domains. Students operated primarily within declarative knowledge, with minimal integration of procedural or experiential dimensions. The inability to connect theory to practice highlights a lack of epistemic coordination, which is central to epistemic fluency (Bernhard et al., 2019; Markauskaite & Goodyear, 2017; McLaughlan & Lodge, 2019).

Social Mediation as the Mechanism for Epistemic Development

A key contribution of this study lies in demonstrating that the transition from fragmented understanding to epistemic fluency was mediated through social interaction. As students engaged in design thinking tasks, their learning became increasingly dialogic, characterised by questioning, negotiation, and collaborative reasoning, especially during empathize, define, and ideate stages. This supports the central tenet of Sociocultural Theory that knowledge is constructed through interaction rather than internalised in isolation (Chen et al., 2023; van Dulmen et al., 2023; Wan & Subramaniam, 2023).

Drawing on the work of Lev Vygotsky, the findings illustrate how learning occurs within socially structured activity, where peers and instructors function as mediators of understanding. The observed peer discussions, where students challenged assumptions and evaluated alternative approaches, can be understood as instances of co-construction of knowledge. These interactions enabled students to articulate reasoning, confront misconceptions, and refine their understanding. Similarly, instructor prompts functioned as scaffolds, guiding students to make connections between theoretical concepts and practical decisions.

Thus, epistemic fluency emerges not merely from exposure to content but through participation in socially mediated practices that require learners to justify, negotiate, and apply knowledge.

Design Thinking as a Mediating Pedagogical Structure

The findings further suggest that design thinking serves as an effective mediating structure that facilitates epistemic development. Unlike traditional instructional approaches, design thinking situates learning within authentic, problem-based contexts that require iterative reasoning and decision-making (Hashim et al., 2019; Kijima et al., 2021). Through stages such as ideation, prototyping, and testing, students were required to continually move among different forms of knowledge. This iterative process created conditions for epistemic movement, where theoretical understanding was repeatedly applied, evaluated, and refined in practice.

Importantly, design thinking did not simply provide tasks but structured the nature of engagement. The emphasis on empathy, problem framing, and testing required students to consider context, constraints, and consequences, thereby extending their engagement beyond procedural correctness toward meaningful application (Calavia et al., 2023; Panke, 2020). From a sociocultural perspective, design thinking can therefore be understood as a form of organised activity that mediates learning by embedding knowledge use within socially and contextually relevant practices.

CONCLUSION

This study demonstrates that epistemic fluency can be developed through design thinking when learning is situated within a sociocultural framework. The findings highlight the importance of collaboration, interaction, and artefact construction in supporting meaningful learning. The study also provides empirical evidence of how design thinking facilitates epistemic development in chemistry education. It suggests that educators should adopt pedagogical approaches that emphasise social interaction and real-world application.

In conclusion, this study contributes to the literature in three key ways. First, it advances the conceptualisation of epistemic fluency as a socially mediated process rather than an individual cognitive trait. Second, it positions design thinking as a mediating pedagogy that supports epistemic development within science education. Third, it provides empirical evidence demonstrating how sociocultural processes: interaction, scaffolding, and artefact construction, facilitate the integration and application of knowledge.

Limitations, Implications, and Future Directions

While this study provides valuable insights into the development of epistemic fluency through design thinking in chemistry education, several limitations should be acknowledged. First, the study was conducted as an exploratory qualitative case study involving a small number of participants within a single pre-university educational context. As such, the findings are not intended to be statistically generalisable to broader populations or educational settings. Instead, the study aims to provide an in-depth understanding of how epistemic fluency may develop through socially mediated learning experiences within a specific context. Future studies involving larger and more diverse participant groups across multiple institutions and subject domains would strengthen the transferability of the findings.

Second, the study did not employ a control group or quantitative pre- and post-intervention measures of epistemic fluency. Consequently, it is not possible to attribute all observed developments solely to the design thinking intervention, as factors such as increased familiarity with tasks, prolonged engagement, and individual academic progression. Future research could incorporate mixed-method approaches, including self-report scales or quantitative assessments of epistemic fluency, to provide convergent evidence alongside qualitative findings.

Third, the interpretation of epistemic fluency constructs (EF1–EF3) involved qualitative judgment and thematic coding by two researchers. Although structured coding procedures and triangulation across observations, project proposals, and reports were employed to enhance credibility, the analysis remains interpretive in nature. Additionally, the researcher's reflexivity must be considered, particularly as the lead researcher was actively involved in facilitating the intervention. To minimise potential bias, reflective memos, peer debriefing, and an audit trail were maintained throughout the analysis process. Nevertheless, the possibility of interpretive bias cannot be entirely excluded, and future studies may benefit from independent external reviewers during data analysis.

Despite these limitations, the study contributes important implications for chemistry education. The findings suggest that design thinking can support the integration of theoretical knowledge with practical application without necessarily replacing existing curricular structures. Rather than functioning as an additional instructional component, design thinking may be embedded within project-based or inquiry-oriented activities already present in chemistry classrooms. By reframing laboratory investigations around authentic socio-scientific problems, educators can create opportunities for students to engage in collaborative reasoning, iterative problem-solving, and artefact construction.

Importantly, the study also clarifies the distinction between epistemic fluency and scientific inquiry skills. While scientific inquiry skills primarily involve the procedural aspects of conducting investigations, epistemic fluency extends beyond procedural competence to include the ability to navigate, integrate, justify, and apply multiple forms of knowledge across contexts. Thus, epistemic fluency encompasses not only “how to investigate” but also “how to think with and apply knowledge meaningfully.”

Overall, the findings highlight the potential of design thinking as a sociocultural pedagogical approach that supports deeper knowledge integration, collaborative learning, and meaningful engagement in chemistry education. Future research should continue to explore how such pedagogical structures may foster epistemic development across diverse educational contexts and disciplines.

Ethical Approval:

Ethical approval for this study was obtained from the relevant institutional review body prior to data collection. The research involved six pre-university students, and all procedures were conducted in accordance with established ethical guidelines for educational research. Informed consent was obtained from all participants before their inclusion in the study. Participation was voluntary, and students were informed of their right to withdraw at any stage without penalty. To ensure confidentiality and anonymity, all identifying information was removed, and participants were assigned coded identifiers (e.g., Student 1, Student 2). Data collected, including project proposals, reports, and observational records, were used solely for research purposes.

Conflicts of interest:

There are no conflicts to declare.

Data availability:

The data supporting the findings of this study are not publicly available due to ethical and privacy considerations, as they involve student-generated work and classroom observations.

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