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Research article

Kitchen science as a pedagogical model: Integrating students-constructed problem-based learning to enhance thermodynamic conceptualisation in physics education

Sizwe Jackson Clement Masuku and Sakyiwaa Boateng*

Department of Mathematics, Science and Technology Education, Walter Sisulu University, Mthatha, South Africa; smasuku@wsu.ac.za, sboateng@wsu.ac.za

* **Correspondence:** Email: sboateng@wsu.ac.za; Tel: +27737586444.

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Abstract: Thermodynamics remains one of the most conceptually challenging areas of undergraduate physics education, largely due to its abstract nature and limited opportunities for contextualised experimentation. This study investigated the effectiveness of a Kitchen Science–Problem-Based Learning (KS-PBL) pedagogical model in enhancing second-year undergraduate students' conceptual understanding of thermodynamic principles and related concepts, while fostering independent learning and scientific reasoning. The study further integrates thermodynamic principles with transport processes, distinguishing between conceptual understanding of thermodynamics and rate-based observations of heat transfer. Guided by an interpretivist qualitative case study design, the study involved a cohort of 50 students enrolled in a Physics II Thermodynamics course. As part of their course structure, students collaboratively designed and conducted problem-based experiments in their home kitchens using readily available household materials to explore real thermodynamic phenomena. Data were collected from students' experimental logs, group presentations, and reflective statements, and were triangulated to ensure trustworthiness. Thematic analysis revealed notable improvements in students' conceptualisation of key thermodynamic concepts. Furthermore, students demonstrated enhanced analytical thinking, problem-solving ability, and appropriate use of scientific terminology, alongside increased creativity and resourcefulness in adapting everyday materials for scientific investigation. The findings suggest that the KS-PBL model effectively bridges the gap between abstract theory and lived experience, promoting deeper conceptual engagement and student autonomy. The study recommends that integrating KS within a PBL framework offers a viable and contextually relevant approach to thermodynamics instruction, especially in resource-constrained educational settings.

Keywords: conceptual understanding, kitchen science, problem-based learning, student-constructed experiments, thermodynamics

1. Introduction

Teaching thermodynamics in a university physics course is challenging, as students often struggle to connect abstract theories with real-world physical phenomena. The primary difficulty faced by students pertains to the abstract nature of concepts in thermodynamics [1,2]. Furthermore, while these concepts are integral to students' daily experiences, they result in misconceptions when presented in science classes [3].

Prior studies have shown that students at the undergraduate level misunderstand fundamental thermodynamics principles and related concepts, such as entropy, the Second Law, thermodynamic potentials, and enthalpy, since more than 80% of students demonstrate inadequate understanding and conceptual difficulties [4–7]. The primary interests of thermodynamics are the viability of physical processes, the conservation of energy, the states of equilibrium, and the irreversibility of energy conversion, as outlined by the laws of thermodynamics [4,5]. Conversely, transport phenomena such as heat conduction, convection, and radiation explain the rate and process by which thermal energy moves between systems. Whereas thermodynamics defines the possibility of a process to take place, transport phenomena define the rate at which a process can take place [6,7]. Both thermodynamic principles and associated transport processes are actively involved in this study, and a conscious effort is made to separate the conceptual knowledge of thermodynamics and rate-based observations of heat transfer.

Brown and Singh [8] investigated college students' understanding of the First and Second Laws of thermodynamics. They administered the Survey of Thermodynamic Processes and First and Second Laws phenomenon to over 1,000 students across six colleges in the United States of America. Their analysis revealed persistent misconceptions among both introductory and advanced physics students regarding fundamental thermodynamic principles. One of their key findings was that conventional lecture-based instruction had minimal impact on student understanding. These results suggest that traditional teaching methods failed to significantly enhance conceptual understanding of thermodynamic laws, underscoring the need for more effective pedagogical strategies. In another study, Wulandari et al. [9] examined first-year undergraduate students' challenges in grasping fundamental thermodynamic concepts. The study found that students had significant challenges with the isobaric process for ideal gases and the concept of mechanical equilibrium. A notable challenge was the high cognitive load required to solve conceptual problems in thermodynamics, suggesting that students struggled to process and apply multiple concepts simultaneously. In addition, the study found that the students demonstrated an inability to integrate various pieces of knowledge effectively, a crucial skill for a comprehensive understanding of thermodynamic principles.

These insights highlight the need for educational strategies that reduce cognitive load, strengthen the integration of mathematical skills, and promote a holistic understanding of thermodynamics to enhance student learning outcomes. Xu et al. [10] propose an instructional approach that emphasises physical interpretations and real-world applications of thermodynamic concepts. Their study suggests that incorporating intuitive explanations and contextualised examples may improve student engagement and comprehension in thermodynamics. In addition, Weber et al. [11] propose adjustments to the teaching approach, allowing more time for student discussions and utilising both theory and practical examples to bridge the gap between abstract concepts and real-world phenomena.

However, despite the advanced strategies being adopted, many students still retain misconceptions and lack a thorough understanding of these concepts, often linked to insufficient contextualisation of material in their daily experiences [9]. This disconnect suggests that employing new teaching methods is not enough; educators must also prioritise connections to practical scenarios to enhance relevance and understanding.

Numerous studies have demonstrated that integrating Problem-Based Learning (PBL) into physics laboratory courses improves student experimental design skills, data analysis abilities, attitudes, performance, problem-solving skills and adaptive learning skills [12–15]. PBL is distinct from traditional teaching methods, fostering an environment where students actively engage in real-world problem solving to enhance their grasp of theoretical concepts [16]. Recent research shows the value of PBL as a practical pedagogic approach to bridge the gap between theoretical concepts and practical applications in physics [17]. A study by Huong [18] was conducted at a Vietnamese university and explored the integration of PBL into general physics education. The findings showed that a hands-on, project-based approach significantly improved students' understanding and application of physics concepts, demonstrating that experiential learning can lead to deeper understanding and retention of theoretical knowledge. Huong's [18] findings align with a previous study that highlights how engaging students in problem-solving activities fosters a stronger connection to theoretical concepts, leading to better academic outcomes [19] and further bridging the theory-practice divide [20]. A similar study was conducted by Sarkingobir and Bello [21] that examined the effectiveness of PBL in enhancing secondary school students' problem-solving skills in Nigeria. A quasi-experimental method divided 58 students into two groups: a PBL instruction group and a traditional teaching control group. These two groups participated in three-month assessments that prioritised problem-solving skills related to force and motion concepts through essay tests conducted before and after the intervention period. The findings demonstrated that the experimental group achieved better problem-solving skills than the control group.

Kitchen Science (KS) serves as an educational tool, highlighting how everyday cooking can illustrate scientific concepts, making them more relatable and engaging for learners. This teaching approach is an instructional strategy that connects physics concepts, environmental science, and chemical knowledge. Kotsis [22] discusses the educational potential of leveraging common kitchen appliances and ingredients to teach physics concepts and posits that practical kitchen experiments can significantly enhance student engagement and improve learning outcomes, as students are more motivated when they see the direct application of their scientific knowledge in daily life. This aligns with Barham's [23] assertion that cooking is an experimental science in which success hinges on understanding the properties of the materials and processes involved in food preparation. According to Rowat et al. [24], teachers who incorporate local culinary practices into thermodynamics instruction create learning spaces that engage students' diverse experiences. By encouraging students to approach cooking as a scientific endeavour, teachers can foster a deeper understanding of theoretical principles through hands-on experience.

The convergence of studies from the literature underscores the effectiveness of PBL and KS as innovative pedagogical approaches in enhancing students' conceptual understanding and problem-solving skills in thermodynamics. Existing studies highlight the benefits of PBL in physics laboratory courses [12,14,15]. Similarly, KS has been recognised as an engaging educational tool [22,23]. Despite these individual advancements, a gap in the literature remains. While previous studies emphasised the merits of each method independently, there is no empirical research on the synergy between KS and student-constructed PBL in physics education; as a result, effective strategies for enhancing thermodynamic conceptualisation are lacking. This study, therefore, departs from existing work by investigating the implementation of KS within PBL to enhance student engagement, critical thinking, and scientific reasoning in thermodynamics.

1.1. Research objectives

The following research questions guided the study:

1. How do students design and conduct thermodynamic experiments using everyday kitchen materials in a classroom setting?
2. In what ways does the use of hands-on thermodynamic experiments enhance student engagement, critical thinking, and problem-solving skills?
3. How do student-constructed thermodynamic experiments influence their conceptual understanding of key thermodynamic principles?
4. How cost-effective and inclusive is the Kitchen Science model when implemented in resource-limited science classrooms?
5. To what extent can the Kitchen Science model be adapted and applied to other domains of physics education beyond thermodynamics?

2. Literature review

2.1. Conceptualising the problem-based learning (PBL) model

PBL is an educational tool that engages students in real-world problem-solving through inquiry-based learning approaches. PBL challenges traditional notions of education by advocating for a student-centred approach where students are not seen as passive recipients of knowledge but as active participants in their learning journey [25]. Unlike conventional lecture-based methods that focus on directly transmitting factual knowledge [26]. PBL recognises that students bring diverse perspectives, prior knowledge, and learning styles into the classroom [27]. At its core, PBL begins with real-world problems, requiring students to collaborate in small groups to explore, analyse, and develop solutions [28]. This approach shifts the role of educators from content deliverers to facilitators, guiding students through an inquiry-driven learning process [28]. Moreover, the emphasis on active participation and cooperative learning enhances problem-solving skills and also encourages students to take responsibility for their own intellectual growth, making learning more meaningful and dynamic.

The principles of PBL integrate two educational theories: constructivism and experiential learning. According to constructivism, students obtain knowledge by interacting with their environment and building their interpretations [29]. According to the experiential learning theory created by Kolb [30], the learning process requires direct experience and reflection. Active participation and practical student engagement support both educational theories, reinforcing the PBL approach. Although critics counter that PBL's effectiveness depends on context (student readiness, teacher expertise, institutional resources, and assessment alignment), without these supports, PBL risks superficial learning, inconsistent outcomes, and inequities. However, according to Yanto et al. [31] PBL provides meaningful problems that spark student curiosity and facilitate deeper investigations into the subject matter. This intrinsic motivation transforms learners from passive recipients of information into active participants in their education. This dynamic engagement aligns with findings by Yusuf et al. [32], who determined that PBL produces substantial improvements in physics students' achievements, attitudes toward learning, problem-solving abilities, critical thinking capacities, and cooperative learning abilities. This indicates that PBL is highly effective in promoting student engagement and retention.

2.2. Kitchen science as a pedagogical approach

The theoretical framework of KS teaching emphasises integrating scientific principles with practical cooking experiences, positioning the kitchen as an effective learning environment for exploring scientific concepts. This approach harnesses everyday culinary practices to engage learners in the scientific method, nurturing a deeper understanding of physics. KS aligns closely with educational theories that advocate for interdisciplinary learning. Nuora et al. [33] emphasise that KS encourages the development of scientific thinking by promoting boundary-crossing skills, which are critical for enhancing students' overall understanding of science and its applications in everyday life. This interdisciplinary approach helps students appreciate the relevance of scientific inquiry across diverse contexts, thereby contributing to a broader understanding of how science informs daily decisions. Godwin et al. [34] point out that KS can foster scientific discourse within family settings, emphasising how out-of-school experiences can complement formal education and deepen engagement with scientific concepts. Students gain a better understanding of the adaptability of scientific concepts through contextual learning enabled by typical kitchen environments [35].

Studies show that KS embraces participatory activities that drive student motivation by conducting experiments to explore scientific knowledge [36,37]. Through KS, learners gain the autonomy to discover scientific material independently as they select topics that interest them and conduct experiments that match their investigative interests [38]. Hence, this study advocates implementing PBL and KS approaches to enable teachers to develop an effective learning system that strengthens students' conceptual learning abilities, develops their analytical and creative thinking capacities, and builds lifelong learning competencies.

2.3. Student design and implementation of thermodynamic experiments

A growing body of research indicates that student-designed experiments play a crucial role in promoting ownership of learning and authentic engagement with scientific practices [39,40]. In inquiry-based and PBL environments, students who actively participate in designing investigations demonstrate deeper engagement with experimental variables, assumptions, and data interpretation [41]. Such practices align with the epistemic goals of physics education, which emphasise content mastery and also the development of scientific reasoning.

The use of everyday materials further enhances this process by situating learning within familiar contexts. Research in kitchen chemistry and informal science education suggests that familiar settings reduce cognitive load and facilitate the transfer of knowledge from everyday experiences to formal scientific concepts [42,43]. Thermal phenomena such as heating, cooling, phase transitions, and energy transfer are routinely encountered in kitchen activities, making them particularly suitable for exploring thermodynamic principles [44]. Recent studies also highlight that student-led kitchen-based investigations democratise experimentation by lowering barriers associated with specialised laboratory equipment [45].

Despite these promising findings, existing literature in physics education largely focuses on teacher-designed demonstrations or structured laboratory activities, with limited attention to student-constructed thermodynamic experiments, especially at the undergraduate level. This gap raises important questions about how students conceptualise and operationalise thermodynamic investigations when given autonomy over experimental design using non-traditional laboratory resources.

2.4. Hands-on learning, engagement, and the development of critical thinking and problem-solving skills

Hands-on learning has consistently been associated with increased student engagement, motivation, and persistence in science classrooms [46,47]. Active learning frameworks emphasise that meaningful cognitive engagement occurs when learners actively construct, test, and refine ideas rather than passively receiving information [48]. Within thermodynamics, experiential learning environments enable students to reconcile mathematical formalisms with observable physical processes, thereby enhancing problem-solving skills [49].

PBL environments further strengthen these outcomes by fostering collaborative reasoning, hypothesis testing, and iterative refinement of ideas [50]. Recent empirical studies indicate that student-constructed experiments require learners to engage in sustained problem-solving and decision-making, leading to improved higher-order cognitive skills and conceptual retention [51,52]. Clugston et al. [53] argue that authentic experimental tasks promote the integration of disparate thermodynamic concepts and their application to real-world situations. However, while the benefits of hands-on and inquiry-based learning are well documented, kitchen-based thermodynamic activities remain underrepresented in physics education research. In particular, there is limited empirical evidence examining how such activities function as a structured PBL model in university physics contexts.

2.5. Influence of student-constructed experiments on conceptual understanding of thermodynamics

Thermodynamics is characterised by persistent student misconceptions [54,55]. Studies using concept inventories consistently reveal that traditional instructional approaches produce minimal conceptual change [49]. These misconceptions are often reinforced by formula-driven teaching that lacks meaningful experiential grounding.

Constructivist theories of learning posit that conceptual change occurs when learners actively confront inconsistencies between their prior knowledge and empirical evidence [56]. Student-constructed experiments create opportunities for such cognitive conflict by requiring learners to make predictions, test them through experimentation, and reflect on discrepancies between expected and observed outcomes [30]. Research suggests that this process is particularly effective when experiments are embedded in familiar contexts [57].

Nevertheless, most existing studies focus on inquiry-based laboratories with pre-defined procedures. There remains limited empirical evidence on whether student-designed kitchen experiments lead to deeper conceptualisation of thermodynamic principles. This represents a critical gap that the present study seeks to address.

2.6. Cost-effectiveness and transferability of the kitchen science model beyond thermodynamics contexts

Access to well-equipped physics laboratories continues to be a significant challenge in many educational settings, especially in developing regions and under-resourced institutions [58]. In response, researchers have advocated for the use of low-cost and improvised instructional materials to support meaningful practical science learning [59]. The Kitchen Science model aligns strongly with these efforts by leveraging readily available household materials to create inclusive and accessible learning environments.

Studies on inclusive science education highlight that contextualised and culturally familiar learning resources enhance participation and engagement among diverse student populations [60,61]. Empirical work suggests that low-cost experimental approaches not only reduce financial barriers but also foster a sense of relevance and belonging in science classrooms [45,62]. However, systematic evaluations of the cost-effectiveness, scalability, and pedagogical robustness of kitchen-based physics models at the tertiary level remain scarce.

While Kitchen Science has demonstrated pedagogical value in chemistry education, its broader applicability across physics domains remains largely unexplored. Physics concepts like mechanics, waves, electricity, and fluid dynamics are similarly grounded in everyday phenomena and may benefit from context-based, hands-on experimentation [63]. Research on context-based science education suggests that pedagogical models rooted in familiar experiences are more likely to support conceptual transfer across content areas [64]. Clark et al. [65] argue that adaptable instructional models are essential for sustainable curriculum reform in physics education. However, empirical studies examining the transferability of kitchen-based PBL approaches beyond thermodynamics are limited, highlighting the need for further investigation into their broader instructional potential.

A convergence of the existing literature strongly supports the pedagogical value of PBL, hands-on experimentation, and contextualised learning in physics education; however, significant gaps remain regarding student-constructed thermodynamic experiments using everyday materials, the availability of empirical evidence at the undergraduate level, the cost-effectiveness and inclusivity of such approaches in resource-constrained contexts, and the transferability of the Kitchen Science model across different fields of physics. This study addresses these gaps by systematically investigating Kitchen Science as a pedagogical model for enhancing thermodynamic conceptualisation among university physics students, with particular emphasis on student-designed problem-based learning in resource-limited settings.

3. Research method

3.1. Case study design

An interpretivist qualitative approach was employed. An interpretive qualitative design is rooted in the philosophical tradition that seeks to understand the meanings individuals assign to their experiences within a specific social or cultural context [66]. The choice of this approach was driven by the need for students to thoroughly explore and understand the processes involved in collaboratively solving thermodynamic problems through KS experiments. This allowed them to make meaning of their activities, interact with the group and solve problems in authentic learning contexts.

A case study design was employed for this study [67]. The case study design allowed the researchers to explore how students collaboratively solve problems, construct scientific inferences, and reflect on their conceptual understanding of thermodynamics while integrating everyday resources. This design also allowed for the use of multiple data collection sources.

3.2. Participants and context

This study was conducted at a local South African university with a predominantly low-resource, rural student population. Conventional access to laboratories is often limited by budgetary and infrastructure constraints. The target population consisted of undergraduate students from the Science Education department within the Faculty of Education, who were purposefully selected. The science department has only one second-year physics class. The students are pursuing a four-year Bachelor of Education degree and range in age from 19 to 22. The sample consisted of fifty (50) students; the entire class enrolled in the Thermodynamics Physics II course. There were 23 females and 27 males with a foundational understanding of physics. The students were assigned to six random groups, each consisting of eight students (and nine students in the last two groups), who were assigned a specific role within the group. These students participated in a KS and PBL integrated activity on thermodynamic concepts.

3.3. Case description

This second-year physics curriculum was designed for science student teachers to enhance their comprehension of essential physics principles fundamental to teaching and scientific literacy. Upon completion of this module, student teachers should be capable of defining and elucidating the fundamental principles of motion in two and three dimensions, exhibiting both conceptual and practical comprehension of thermodynamics, articulating the gas laws and their implications, assessing and applying the quantum theory of light, and demonstrating an understanding of modern and nuclear physics. The central component of this course is thermodynamics, which provides student teachers with a theoretical understanding and practical problem-solving skills. The curriculum involves students generating and manipulating equations, employing mathematical reasoning, and critically assessing real-world thermodynamic events. The objective is to equip student teachers to understand and teach thermodynamics proficiently while promoting inquiry-based, experiential scientific education in their classrooms.

The assessment criteria (AC) for the thermodynamics section correspond with both conceptual profundity and educational implementation as follows: (a) AC1: Students will exhibit proficiency in deriving fundamental equations in thermodynamics, including those pertaining to the First and Second Laws, heat capacity, and the efficiency of thermodynamic systems. This encompasses comprehending the interconnections between work, heat, internal energy, and entropy; (b) AC2: Students will proficiently substitute established physical values and units into thermodynamic equations and resolve issues related to heat transport, specific heat, and energy alterations in systems, exhibiting competence in unit conversion and dimensional analysis; (c) AC3: Students will elucidate the significance of fundamental thermodynamic concepts for temperature, equilibrium, entropy, and energy conservation and delineate their interconnections. Priority will be given to the capacity to articulate these concepts clearly and convincingly for secondary education; (d) AC4: Students will contemplate and assess the ramifications of their computations and theoretical insights. They will evaluate the efficacy of heat, analyse entropy variations in physical systems, and critically address real-world energy issues from a thermodynamic standpoint; (e) AC5: Students will engage in structured practical investigations on basic heat transfer experiments, calorimetry with household instruments, and observational activities related to phase transitions with practical experience in the application of thermodynamic principles. These activities aim to enhance conceptual understanding of thermodynamic principles through low-resource science teaching methodologies suitable for underprivileged educational environments. Upon completing the unit, students will have mastered the scientific principles of thermodynamics and acquired the pedagogical insight necessary for effective teaching in high schools.

3.4. Instruments and implementation phase

As part of the year's course assessment activities, students were required to conduct experiments to complete the practical component of the thermodynamics topic. In 2024, the lecturers assigned students to groups. Each group was tasked with completing a thermodynamics experiment activity using basic household items. The project began with a guiding scenario in which students were asked to imagine themselves as science communicators or physics consultants, tasked with designing a safe, hands-on experiment to teach thermodynamic concepts in a home setting. Drawing on real-world kitchen phenomena, each group formulated a scientific question or hypothesis that connected their chosen phenomenon to at least two core thermodynamic concepts. Each group designed its experiment, collected and analysed data, and documented the process, fostering collaboration and teamwork. They emphasised critical thinking, inference, and collaborative problem-solving, both conceptual and practical.

The implementation was structured into the following phases:

Phase 1: Conceptual Foundation

Students were introduced to fundamental thermodynamic principles, including the First and Second Laws of Thermodynamics, heat transfer mechanisms, and thermal conductivity.

Phase 2: Project Design

In this phase, student groups selected a specific topic, formulated hypotheses, and designed an experiment using readily available materials.

Phase 3: Execution

Student groups conducted their experiments at home or in campus laboratories, systematically collecting data over predetermined intervals.

Phase 4: Presentation

Finally, student groups documented their findings, analysed the collected data, and presented their results, incorporating reflections on the experimental process and its broader implications.

3.5. Data collection

Data were collected from multiple sources for triangulation [68]. The measure of data collection consisted of structured observation rubrics used in group presentations (rating clarity of hypotheses, scientific accuracy, interpretation of data, and creativity) and reflective writing in their journals about conceptual difficulties and observations on learning. The procedures, variables, and measurements were recorded in experiment logs. Each student group documented detailed procedures, recorded data, and noted observations from their experiments in their student experiment logs. They also delivered oral and visual presentations, which were assessed using a structured rubric. Furthermore, they wrote reflective statements on their learning experiences, the challenges they encountered, and the key scientific insights they gained.

Two independent instructors evaluated the projects using a rubric, and the aggregate scores were used to select the top three projects for a comprehensive data analysis. Three groups (25 students) out of the six groups achieved maximum points and were selected based on the following selection criteria:

a) The project's scientific accuracy (30%): Correct application of thermodynamic principles in the project.
b) Project included creativity and innovation (25%): Originality in experiment design and use of low-cost resource materials.
c) Data presentation and analysis (25%): Quality of data collection, use of tables or graphs, and description of data interpretation.
d) Adherence to guidelines (20%): There is clarity in hypothesis setting, project aims, detailed methodology, and overall presentation.

The rationale behind selecting Groups 2, 5, and 7 was that they provided the most complete, information-rich, and analytically relevant data, aligning with the study’s research objectives. While all groups participated in the learning activities, some groups produced limited or repetitive data that did not meaningfully contribute to the emergence of new themes. We acknowledge that focusing the analysis on a subset of groups may raise concerns about potential bias. To address this, we specifically selected groups that provided the most comprehensive datasets across all three sources of evidence: logs, presentations, and reflections, demonstrating particularly rich reflective accounts and showing consistent participation throughout the intervention. This approach ensured that the analysis was grounded in the most information-rich cases while maintaining methodological rigour and transparency. This method enhances the depth of the analysis, ensuring that the results are both manageable and significant within the scope of the study. The data generated were sufficient to identify patterns and formulate credible conclusions. Validity was also ensured by the application of the structured rubrics. Two independent evaluators rated the data, and the inter-rater reliability was found to be acceptable.

3.6. The data analysis

The study employed qualitative descriptive analysis to examine student-generated data, including experiment logs, group presentations, and reflective statements. This method is appropriate for capturing detailed insights into students' conceptual understanding and reasoning processes [66]. Both researchers conducted individual multiple readings of student logs, captured students' presentations, and students' reflections to develop an in-depth understanding of the data [69]. In students' outputs, the researchers identified key thermodynamic principles. Instances where students demonstrated innovative scientific reasoning and problem-solving strategies were classified accordingly.

Triangulation was applied to enhance credibility, ensuring themes were validated only when they appeared consistently across multiple sources [70]. Structured cross-checking of student outputs minimised researchers' bias and strengthened findings [71]. Transparent categorisation methods were systematically used to classify responses, ensuring analytical accuracy between the two researchers [72]. The researchers also conducted an iterative refining process that involved re-examination of themes and cross-source comparisons to ensure coherence and depth in the analysis [73]. The analysis of these data sources uncovered multiple interconnected themes that illustrate the cognitive, practical, and pedagogical aspects of this experiential approach. These themes encompassed: (a) students’ creative designs and experimental practices; (b) active learning and cognitive engagement; (c) conceptual understanding, misconceptions, and shifts; (d) accessibility, cost-efficiency and inclusion; and (e) transferability and broader pedagogical potential.

3.7. Ethical considerations

Permission was sought from the institution’s Faculty Ethics Committee. Ethical approval for the study was granted. Subsequently, informed consent was obtained from the students. This was intended to ensure students' voluntary participation by providing a comprehensive understanding of the study's objectives and procedures, as well as their right to withdraw their data at any time without academic penalty. The researchers supplied explicit, step-by-step instructions to the students and established protocols to guarantee a secure and effective learning environment. The students were likewise provided with guidance and support throughout the lessons and activities, facilitating their confident and effective interaction with their resources. Stringent measures were implemented to protect students' information and maintain confidentiality, ensuring anonymity throughout the study and the dissemination of its results and findings. Safety protocols were strictly adhered to during all experimental preparation stages to ensure that all materials met school safety standards.

4. Findings

The primary themes identified in the study are presented below.

4.1. Theme 1: Students' creative designs and experimentation practices

This theme captured how students selected, adapted, and innovated using kitchen materials to design and conduct thermodynamic experiments. A summary of the top four student group activities is as follows:

Project 1: Group 2 Activity Summary

The group 2 student explored heat conduction as a means of transport to reinforce their study of thermodynamics, specifically energy transfer and thermal equilibrium. This was studied with stainless steel, plastic and wooden spoons. During the experiments, they submerged these spoons in 80 ℃ hot water to measure butter melting times. The student group 2 hypothesised that items with elevated thermal conductivity would conduct heat rapidly, resulting in quicker butter melting. The metal spoon would outperform plastic and wood in butter melting speed because it transfers thermal energy more efficiently. The experimental configuration is shown in Figure 1.

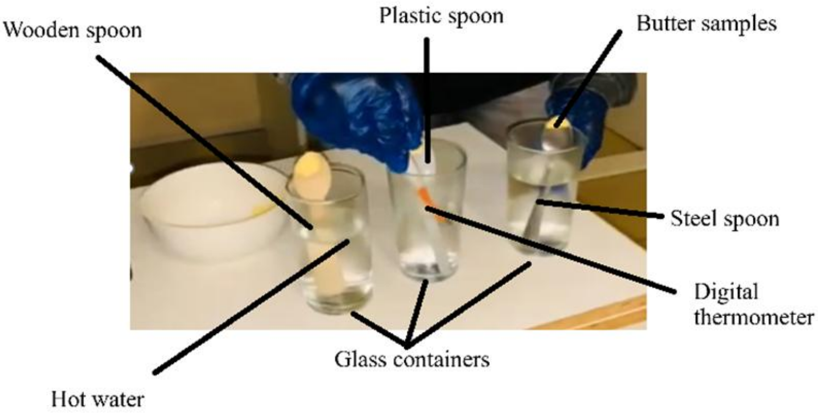

Figure 1. Experimental set-up by group 2.

Group 2 used the following materials: three spoons (stainless steel, plastic, wood), hot water (80 ℃), butter samples, a thermometer, and a stopwatch, under ambient room temperature of 22 ℃, to assess potential heat loss during the experiment. Group 2 made efforts to minimise air drafts by experimenting indoors for consistency.

The procedure group 2 followed was the use of a spoon, with a fixed butter sample (approximately the same amount), which was submerged in hot water for five minutes. Spoon temperatures were recorded before and after immersion. The degree of butter melting served as a qualitative indicator, while the temperature change of each spoon was used for quantitative analysis of the heat transfer rate. The group tabled their result as follows:

Table 1. Heat transfer rate (transport phenomenon) used to illustrate material-dependent thermal conductivity.

Material	**Initial Temp (℃)**	**Final Temp (℃)**	**Temp Change (℃)**	**Time (min)**	**Heat Transfer Rate (℃/min)**
Metal	25	60	35	5	7.0
Plastic	25	35	10	5	2.0
Wood	25	30	5	5	1.0

The observed heat transfer rates can be used to characterise transport behaviour. The pedagogical goal of the given activity was to make students relate the mechanisms of heat flow they have observed to thermodynamic concepts of energy transfer and system interaction. From Table 1, group 2 observed that the metal spoon exhibited the greatest temperature increase, reaching 35 ℃, and that the butter melted rapidly. This confirmed the metal's high thermal conductivity, enabling efficient heat transfer. In contrast, the plastic spoon exhibited a moderate temperature rise of 10 ℃, resulting in only partial butter melting. The lower conductivity of plastic and heat loss to the surrounding air likely influenced this result. Lastly, the wooden spoon displayed minimal heat gain of 5 ℃, with negligible butter melting. This indicated that wood acted effectively as an insulator, preventing significant heat transfer.

A specific time interval allowed the students to determine heat transfer rates through temperature measurements of each spoon material. The students followed the experiment by placing buttered stainless steel, plastic, and wood spoons into hot water kept at 80 ℃ for five minutes and noting each spoon's initial and final temperatures. The calculated rates of heat transfer relied on the formula Heat Transfer *Rate* = $\Delta T/\Delta t$, which used ΔT for defining temperature change and Δt equalled five minutes. Each material’s heat-conducting capacity, shown in Figure 2 through bars, corresponds to the measured heat transfer rates. In Figure 2, metal emerges due to its rapid butter melting, as it shows better heat conduction performance. The thermal conductive capacity of plastic and wood caused slower heating rates, resulting in reduced butter melting compared to metal.

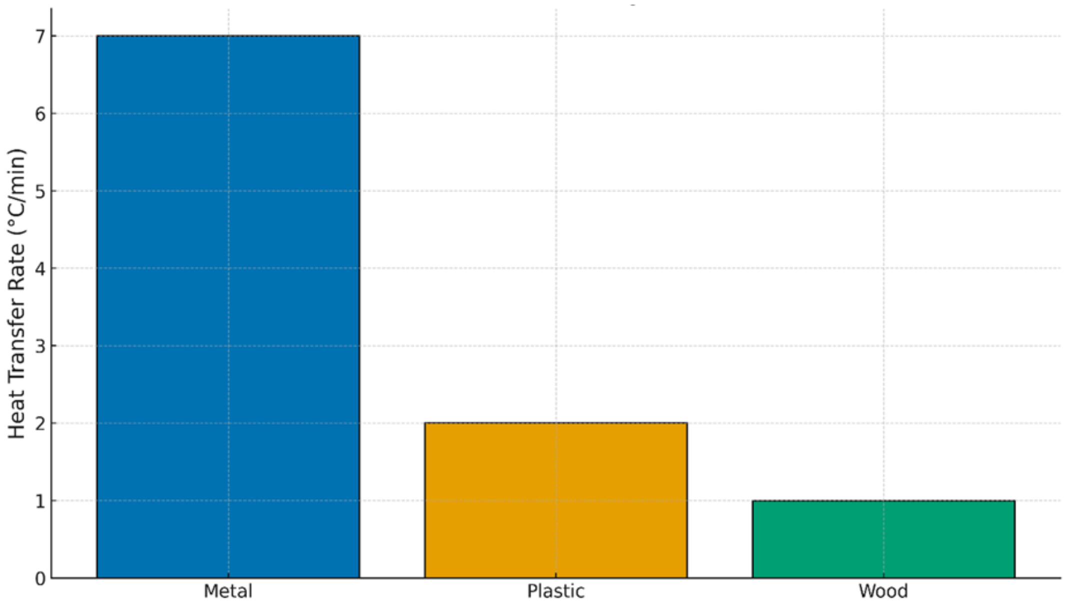

Figure 2. Heat transfer rate (transport phenomenon) used to illustrate material-dependent thermal conductivity.

Group 2 reflected on their activity as follows*:*

> *Different materials exhibited different abilities to conduct thermal energy according to the experimental observations. Our hypothesis indicated that the metal spoon would melt butter the fastest, so it proved the correct assumption. We incorrectly predicted how butter would melt on plastic and wood elements since both materials interacted at room*

temperature and released heat into the environment. Material properties and environmental conditions determine how accurately experiments will produce their results. We will gain better control over these factors to enhance prediction accuracy.

Project 2: Group 5 Activity Summary

Group 5 conducted an activity to track temperature changes in the water of a stainless-steel electric kettle. Group 5 sought to study energy transfer in the kettle heating system while recording how water boiled as they applied thermodynamic rules to explain temperature variations. The experimental design is presented in Figure 3. Group 5 hypothesised that water temperature will increase progressively until the boiling point is reached at 100 ℃. Then, it will decrease when the heat source is cut off due to heat loss to the environment. The Group 5 experimental set-up is shown in Figure 3.

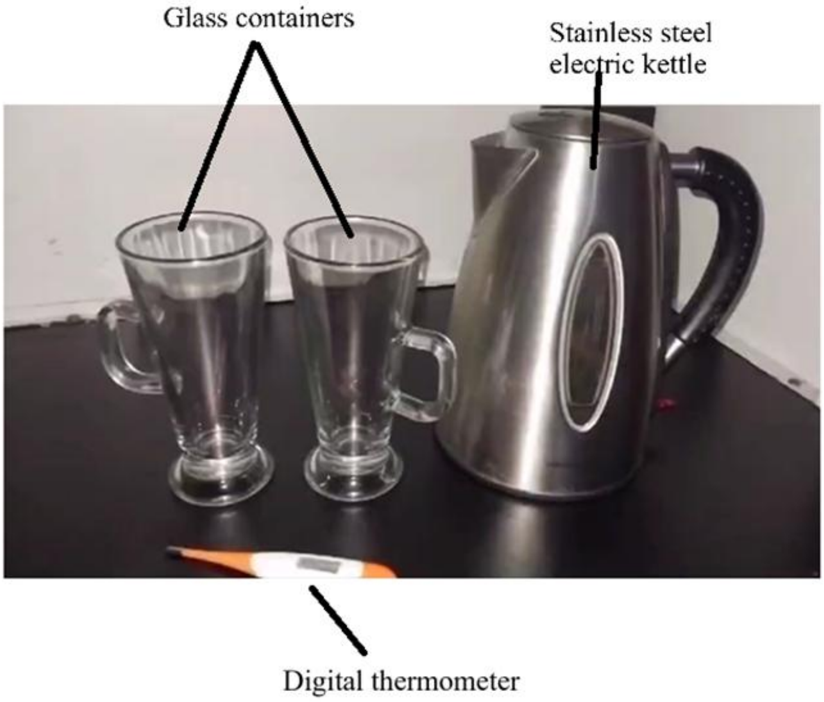

Figure 3. Experimental setup by Group 5.

The members of Group 5 then made a summary of how they carried out their activity, using a stainless-steel electric kettle (1500W), 500 mL of water, a thermometer, a stopwatch, and a container for storing water. They initially filled a stainless-steel kettle with 500 mL of water from a room temperature (25 ℃) tap. The initial temperature was measured. The group activated the kettle to boil the water while recording temperature readings at 30-second intervals until the water reached 100 ℃ boiling point. The boiling process ended by switching off the kettle while recording the temperature for two minutes to monitor the cooling process. The results obtained were tabulated in Table 2.

Table 2. Water temperature change as a function of time.

Phase	**Time (s)**	**Temperature (℃)**
Initial (Room Temp)	0	25
Gradual Heating	30	40
	60	55
	90	68
	120	80
Rapid Heating	150	90
	180	96
Boiling Point Reached	210	100
	240	100
Cooling Begins	270	98
	300	95

Table 2 shows that Group 5 observed a steady increase in temperature to 100 ℃ at 210 seconds, confirming efficient heat transfer. They also noted a temperature plateau at 100 ℃, indicating that latent heat was absorbed during the boiling phase. After the heat source was turned off, the temperature gradually decreased, aligning with the expected heat loss to the surroundings. The data acquired during the cooling phase (starting at 240 seconds) were analysed using Newton's Law of Cooling (Vollmer, 2009).

$$T(t) = T_s + (T_0 - T_s)e^{-kt} \tag{1}$$

where T_s = 25 ℃ (ambient temperature), T_0 = 100 ℃ (initial cooling temperature), and $k \approx 0.0054$ s^{-1} (estimated via curve fitting). The group generated a prediction curve to estimate future temperatures (Figure 4).

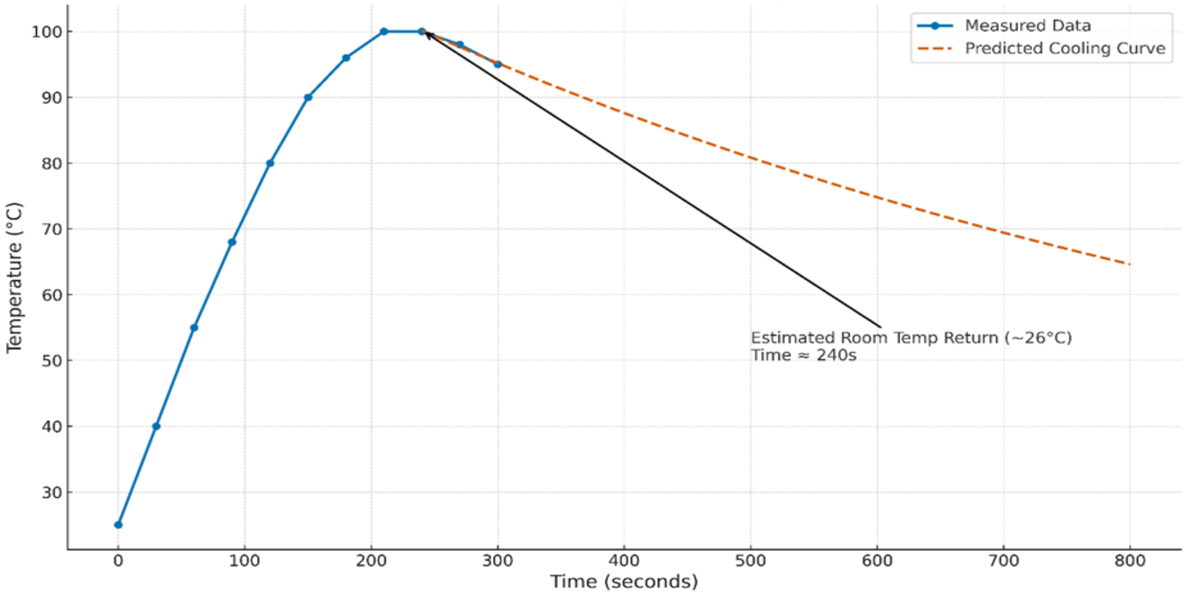

Figure 4. Measured and predicted temperature progression of water.

Group 5 measured and predicted the temperature progression of the water as presented in Figure 4. The collected data recorded the temperature changes during the water heating stages, boiling, and subsequent cooling process. According to the predictive curve model, the heated water would reach 26 ℃ after 750 seconds of boiling. The directionality of the heat flow of equality is given by the Second Law of Thermodynamics and the rate-dependent transport phenomenon is the observed cooling behaviour, as given by the Newton Law of Cooling. The heating and cooling curve diagrams in this activity are primarily associated with the rate of heat transfer, which falls under the category of transport phenomena. The plateau formed at the boiling point and the latent heat uptake, however, directly reinforce the thermodynamic concepts regarding phase changes and energy conservation.

Based on these findings, Group 5 presented their reflections on their activity as follows:

> *The experiment demonstrates that the temperature change of water in a kettle follows a predictable pattern: it increases rapidly as it boils, then decreases as the heat source is removed. The results provide insights into the boiling process and can be applied to various applications such as cooking and industrial processes. We expected the water just to cool down linearly, but the prediction showed it slows down as it approaches room temperature. The cooling equation helped us understand why the temperature change was not constant.*

Project 3: Group 7 Activity Summary

Student group 7 conducted an experiment to demonstrate that boiling water expands the air in a sealed bottle, thereby inflating an attached balloon. The experimental setup demonstrated the application of the First Law of Thermodynamics, which also exhibited gas behaviour during heating, as evidenced by thermal expansion. Figure 5 shows the experimental setup. Group 7 hypothesised that balloon inflation occurs because hot water transfers heat to the bottled air, causing it to expand. The inflation of the balloon demonstrates thermodynamic transformations and energy conversions rather than energy loss, thereby supporting the First Law of Thermodynamics. Group 7 detailed their experimental setup with the use of a plastic bottle (500 mL), a latex balloon, a plastic container, 500 mL of boiling water, a thermometer, a stopwatch and a 30 cm ruler. The room temperature was measured at 22 ℃ to monitor heat exchange and air-cooling effects. They then poured boiling water (approx. 100 ℃) into a container. A plastic bottle with a balloon fitted over its mouth was placed upright in the water. As heat was transferred from the water to the air inside the bottle, balloon inflation was observed and recorded over four minutes at one-minute intervals. The results obtained are tabulated in Table 3.

Table 3. Balloon expansion over time during heating.

Time (minutes)	**Estimated Air Temp (℃)**	**Balloon Diameter (cm)**
0	22	0
1	30	4
2	40	7
3	50	9
4	55	9

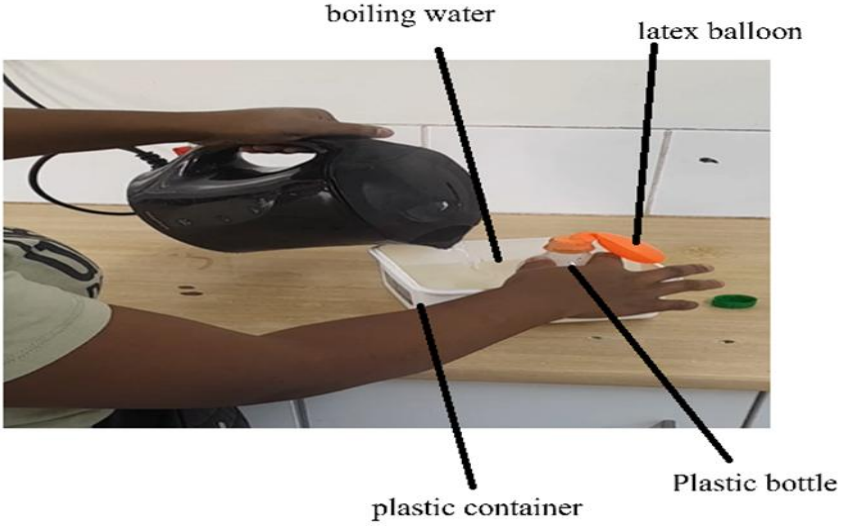

Figure 5. Experimental set-up by group 7.

Group 7 observed that, within the first minute of their experiment, the balloon began to inflate, indicating the expansion of air due to heating. As the experiment progressed, the balloon reached its maximum inflation at approximately three to four minutes. Beyond this point, the inflation plateaued as the system approached thermal equilibrium. The process effectively demonstrated energy conversion, where heat from the water increased the internal energy of the air, allowing it to expand the balloon. Hence, they determined the heat transfer rate by measuring thermal energy (Q) in the sealed bottle during the given time *(dQ/dt)*. The bottle received heat from hot water at about 100 ℃, which increased system pressure and balloon expansion. Group 7 approximated the heat transfer rate through finite differences between consecutive thermal energy values, which were measured at one-minute intervals to evaluate the heat transfer speed during the process. The rate measurement was performed and expressed mathematically as follows:

$$\frac{dQ}{dt} \approx \frac{Q_{i+1}-Q_i}{t_{i+1}-t_i} \tag{2}$$

where Group 7 represented Q_i and Q_{i+1} as thermal energy values at consecutive time points t_i and t_{i+1}, respectively. The experimental trend between heat transfer rate and time during the study appears in Figure 6. Heat transfer reached its highest point when the hot water went into the bottle before it was lowered steadily because the water-air temperature gap decreased. The group reported that their observations matched Fourier’s Law of Heat Transfer because the heat flow rate directly relates to the temperature difference between two connected systems. The balloon stopped growing several minutes after thermal equilibrium because the heat transfer rate experienced a steady decrease. The group illustrated the active energy transfer process, which restricted the balloon inflation by displaying its dynamic properties in Figure 6.

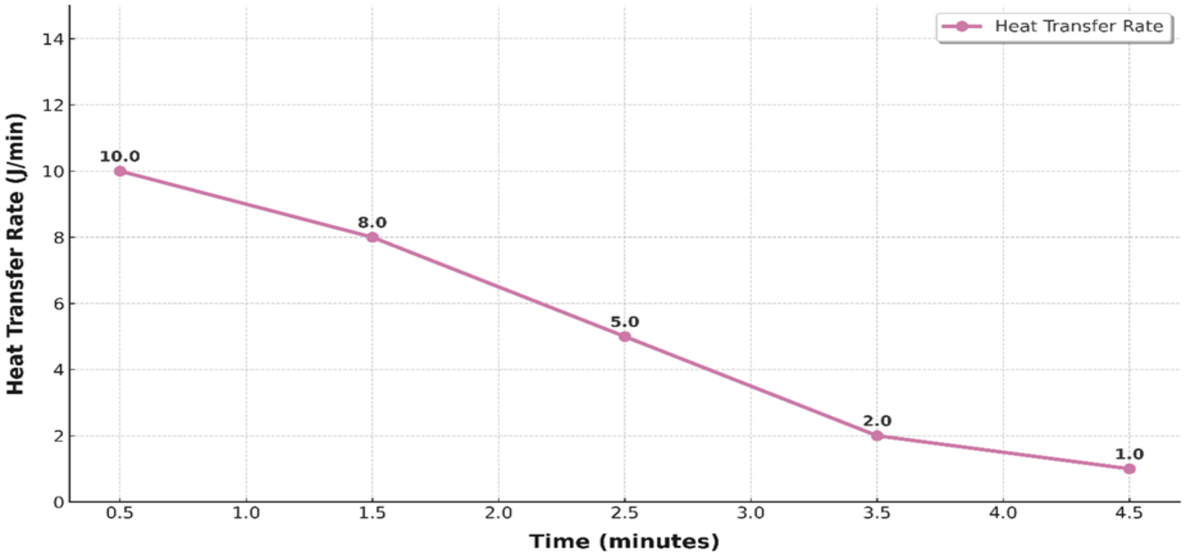

Figure 6. Heat transfer rate during air expansion as a function of time.

The students reflected on their activity by saying:

> *Before the system manages to transform the heat input into work, it is stored inside the system as internal energy. The heat from the waste was transferred to the bottle and balloon system. When the air in the bottle was heated, the balloon inflated. The balloon inflated as the air inside expanded, showing us that heat can do work. We observed that as more heat was added, the air expanded. That was fantastic. This made thermodynamics real to us.*

The balloon inflation exercise does not require a traditional kitchen tool, but it was added because of its conceptual correlation with the heating processes that occur in the home, such as boiling water and gas in closed containers. The experiment involved using everyday domestic materials and was directed towards the phenomena that the students commonly experience at home. For this reason, the activity was termed 'kitchen-near science' and not a culinary discipline.

4.2. Theme 2: Active learning and cognitive engagement

This theme directly addresses Research Question 2, which examines how engagement in hands-on thermodynamic activities within the Kitchen Science (KS) model enhances students' critical thinking and problem-solving abilities through sustained cognitive engagement. Drawing on established frameworks of cognitive engagement, the analysis focused on higher-order thinking processes, including analysis, evaluation, application, and reflective judgment, as evidenced in students' experimental design, interpretation of outcomes, and adaptive problem-solving strategies.

Findings indicate that the KS model significantly increased students' active participation and cognitive involvement, as reflected in student presentations, experimental journals, and reflective laboratory diaries. Students were not merely following prescribed procedures; rather, they were actively engaged in constructing problems, making predictions, and evaluating the validity of their assumptions. One student noted,

> *It was exciting to finally do science that makes sense at home"* (Group 7)

This group highlights how contextualised experimentation facilitated meaningful cognitive engagement.

A key indicator of critical thinking was students' ability to identify, confront, and revise misconceptions through evidence-based reasoning. For instance, Group 2 reflected:

> *Initially, we believed that the water would boil more quickly with salt. However, when this was not the case, we were compelled to revisit our misconceptions regarding boiling points.*

This reflection demonstrates analytical reasoning and evaluative judgment, as students compared predictions with empirical observations and restructured their conceptual understanding accordingly. Such cognitive processes align with higher-order thinking, where learners actively interrogate and refine their knowledge rather than accept outcomes uncritically.

Problem-solving abilities were particularly evident when experimental procedures did not proceed as anticipated. Students demonstrated adaptive reasoning and strategic flexibility by modifying experimental designs in response to emergent challenges. Several groups adjusted variables, altered materials, or revised procedural steps during the experiment, drawing on prior knowledge and real-time observations. For example, Group 5 reported:

> *We were compelled to switch to a metal pot and reconsider the manner in which heat was being transferred.*

after observing the melting of a plastic container. This episode reflects the application of thermodynamic principles to diagnose a problem, evaluate alternative solutions, and implement a more effective strategy under time constraints—core components of scientific problem-solving.

Collaborative engagement further reinforced cognitive processes associated with critical thinking. The division of roles within groups, such as coordinating tasks, recording data, managing time, and leading discussions, supported collective reasoning and distributed problem-solving. Students negotiated decisions regarding variable selection, measurement techniques, and procedural sequences, requiring justification, argumentation, and consensus-building. These interactions revealed not only individual cognitive strategies but also the social dimension of problem-solving, where reasoning is articulated, challenged, and refined through dialogue and discussion.

Evidence of conceptual application was also observed in students' explanations of thermodynamic phenomena. For instance, Group 7 articulated their understanding as follows:

> *"Before the system manages to transform the heat input into work, it is stored inside the system as internal energy. The heat from the waste was transferred to the bottle and balloon system and, when the air in the bottle was heated, the balloon was inflated."*

This explanation demonstrates the application and synthesis of thermodynamic concepts, as students linked heat transfer, internal energy, and work to observable physical outcomes. Such reasoning reflects deep cognitive engagement, where abstract principles are coherently applied to explain real-world phenomena.

Therefore, the findings suggest that the KS model fosters sustained cognitive engagement by positioning students as active problem-solvers and critical thinkers. Through prediction, evaluation, adaptation, and reflection, students engaged in higher-order cognitive processes that underpin effective critical thinking and problem-solving in physics. These outcomes provide empirical support for the role of hands-on, student-constructed experimentation in enhancing cognitive engagement within undergraduate thermodynamics education.

4.3. Theme 3: Conceptual understanding, misconceptions, and shifts

This theme aligns with research question 3, which encapsulates the processes through which students developed and deepened their understanding of thermodynamic concepts as they engaged in hands-on activities using household materials. Findings indicated that student groups exhibited different abilities to conduct thermal energy. However, throughout this process, instances of misconceptions and conceptual shifts also emerged. In the students' reflection logs, some students initially misunderstood key terms such as *latent heat* or *efficiency* and misapplied equations to their scenarios. However, during the process of analysing their experimental outcomes, there was conceptual refinement and a deeper understanding. In this way, the PBL+KS environment acted as a catalyst for cognitive dissonance and resolution.

The use of everyday kitchen settings played a dual role in shaping students' understanding. On one hand, the familiarity of materials and processes (e.g., using pots, stoves, and thermometers) demystified abstract ideas and made physics more accessible. On the other hand, the lack of precision and environmental control occasionally introduced confusion, especially in interpreting results and highlighting how the informal context can both facilitate and complicate the conceptualisation of scientific principles.

4.4. Theme 4: Accessibility, cost-efficiency and inclusion

This theme aligns with research question 4, which examined the cost-effectiveness and inclusivity of the KS+PBL model when implemented in resource-limited science classrooms. An experimental efficiency analysis was conducted across all outcomes to determine the scientific effectiveness of PBL and KS compared to traditional laboratories. The analysis measured how well thermal energy inputs were converted into useful outputs by evaluating operational efficiency across experiments. It also accounted for heat loss due to environmental factors, materials, and design constraints in equipment setup. Experimental efficiency (η) was calculated using the following formula:

$$\eta = \frac{Useful\ \ Energy\ \ Output}{Input\ \ Energy} \times 100\% \tag{3}$$

where: Input Energy was estimated based on the thermal energy transferred from a heat source (e.g., hot water) to the system; and Useful Output was determined through measurable outcomes (such as temperature increase, butter melting, or balloon expansion work). A closer look at each of the projects from the groups indicated the following:

a) Project 1 focused on heat transfer through materials. The efficiency evaluation measured changes in spoon temperature relative to heat input estimates at five-minute intervals. The efficiency in KS decreased due to higher environmental heat loss compared to the insulated, controlled laboratory setups.
b) Project 2 focused on heating and cooling water. Using the standard thermal energy equation enabled the determination of the thermal energy absorbed by water during boiling. The kitchen

setups allowed ambient heat to escape, but the laboratory setups utilised calorimeters, which created higher efficiency.

c) Project 3 focused on gas expansion: The project analysed the work performed by an expanding balloon air volume through the $W = P\Delta V$ relationship against the measured heat input from hot water. The efficiency of the KS model reached 70%, but both sealed gas systems and precise heat control setups in laboratory environments could achieve 90% efficiency.

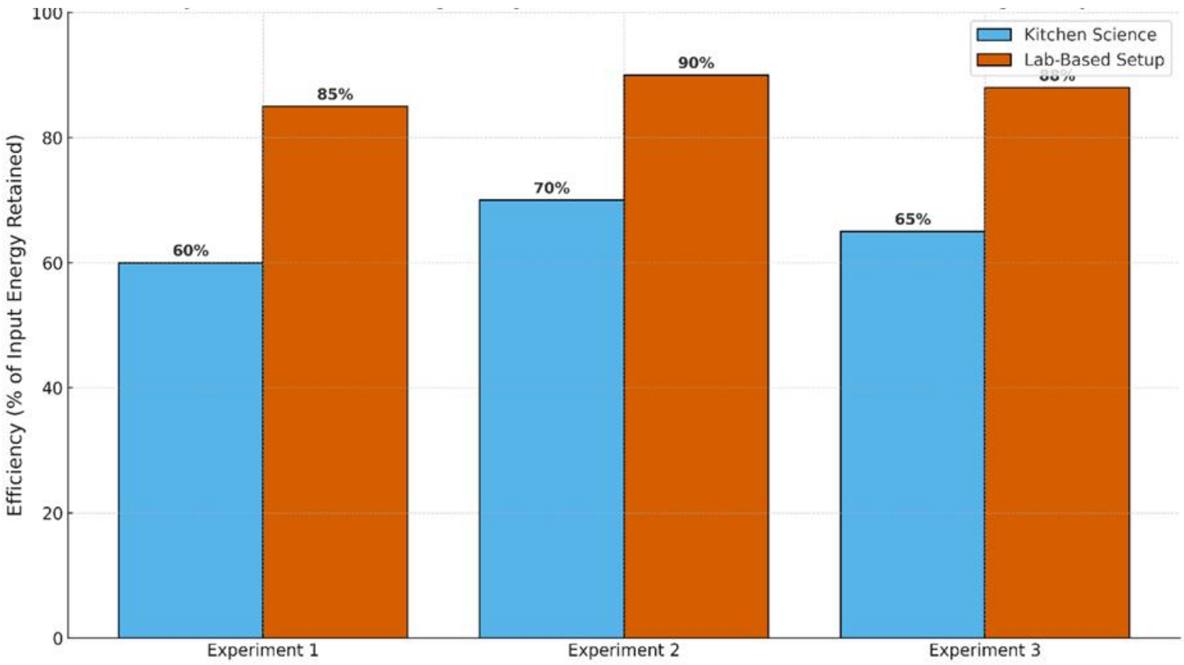

Figure 7. Experimental efficiency comparison: Kitchen vs laboratory setup.

The experimental efficiency of each setup appears in Figure 7 as a percentage. The efficiency of KS setups reached 60–70%, whereas laboratory setups maintained 85–90% efficiency due to improved insulation and heating controls, while minimising laboratory environmental factors reduced energy loss. The lower efficiency levels of KS setups delivered adequate energy transfers for educational experimental objectives, thus proving that educational visualisations of scientific concepts can occur using minimal equipment. According to the study's outcomes, the model demonstrated excellent functionality in various instructional settings.

The setup is cost-efficient compared to conventional laboratory equivalents, while providing estimated price information in South African ZAR. The lists of experimental apparatus show their purposes and estimated South African Rand costs (including VAT) based on 2025 market prices. Standard entry-level physics laboratory equipment costs were obtained from certified educational suppliers, LabTech Instruments, SciLab Suppliers, and Lab Catering Supplies (South Africa), for undergraduate education.

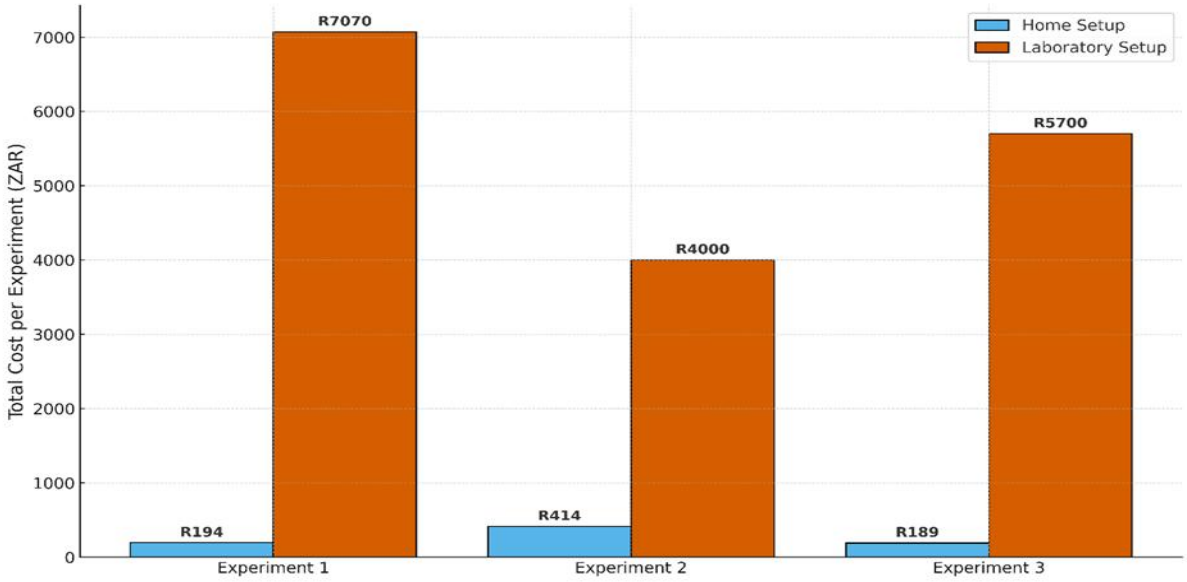

Figure 8. Cost comparison of home vs laboratory setup (ZAR).

The experimentation outcomes demonstrate substantial cost savings from employing the KS tool over conventional laboratory, as Figure 8 indicates. The method produced results that equal conventional thermodynamic knowledge delivery while operating successfully with basic school facilities. The main advantage of the KS model is its highly affordable implementation costs. Common items found at home, substitute expensive laboratory instruments to create an accessible approach suitable for both rural schools and home-based learning programmes and underfunded educational facilities. Students can achieve the same level of conceptual understanding through KS methods with less specialised laboratory equipment than traditional laboratories, thus creating an affordable learning environment.

4.5. Theme 5: Transferability and broader pedagogical potential

This theme aligns with research question 5. The findings show that student groups suggested they could apply this new knowledge to the concepts of mechanics and electromagnetism. In one of their reflective journals, a group suggested designing an experiment on Newton's laws using simple rolling cans and inclined planes made from books and trays. Another group proposed the design of circuits through the use of aluminium foil, batteries, and miniature lights to investigate electrical conductivity and the resistance of materials. These concepts demonstrated students' increasing confidence in utilising PBL+KS approaches to investigate physics principles independently. Despite the apparent enthusiasm, students recognised a number of challenges. One student group noted:

> *Although it is feasible to demonstrate heat transfer using a spoon in hot water, it may be challenging to demonstrate electromagnetic induction in the absence of appropriate equipment. Just thinking, perhaps it could work. Let's try it out and see what happens.*

This concern was also expressed by the other groups, who emphasised that the PBL+KS approach, while it promotes creativity, may not be as reliable in demonstrating quantitative experiments in physics. This implies that KS+PBL inquiry-driven practices may be instrumental in developing students' scientific thinking, resourcefulness, and collaboration skills in under-resourced institutions. As students construct knowledge through these project designs, they also build resilience in physics. This suggests that instructors can foster a spirit of exploration by utilising the resources that students already possess at home. There was a sense of optimism that this model could be integrated with the practical assessment requirements of the CAPS curriculum in high school physics in terms of scalability and curriculum integration.

5. Discussion

This study demonstrates that students gained scientific understanding through their independent data collection initiatives, which validates the principles of conceptual learning in physics education. The implementation of PBL combined with KS provided a transformative approach for students to engage creatively with the principles of thermodynamics. Through experimental tasks, students created their own experimental designs, thereby bridging abstract theoretical concepts with hands-on, real-world observations.

This study's findings suggest that students significantly enhanced their scientific understanding by independently conducting data-collection activities, which aligned well with the principles of conceptual learning in physics education. This finding aligns with the study by Xu et al. [10] study, which suggests that incorporating intuitive explanations and contextualised examples improved student engagement and comprehension. Students gained a more operational understanding of thermodynamic principles. Student-constructed experiments create opportunities for such cognitive conflict by requiring learners to make predictions, test them through experimentation, and reflect on discrepancies between expected and observed outcomes [30]. Research suggests that this process is particularly effective when experiments are embedded in familiar contexts, such as everyday kitchen processes [57]. For example, the students' experiment demonstrated their ability to follow structured procedures and understand how energy moves through open and semi-closed systems. The findings showed that a hands-on, project-based approach significantly improved students' understanding and application of physics concepts, demonstrating that experiential learning can lead to deeper comprehension and retention of theoretical knowledge [18]. Initially, many students struggled with conceptualising heat transfer; however, after experimenting with thermal conductivity samples, they demonstrated a more nuanced understanding of how various factors collectively determine the heat transmission rate.

The students’ reflections on their experimental work revealed noticeable improvements in their ability to employ scientific terminology and take ownership of their experimental designs in thermodynamic concepts. These improvements were evident in both their oral and written explanations. They showed increased proficiency in designing and executing controlled experiments, successfully identifying and manipulating variables, and interpreting quantitative data on temperature changes and heat transfer rates. Furthermore, students were able to reflect on experimental anomalies critically and propose scientifically plausible explanations based on material behaviour and environmental influences, such as ambient temperature and heat loss. These findings emphasise the effectiveness of the PBL and KS models in reinforcing thermodynamic content while simultaneously fostering essential scientific reasoning, data literacy, and real-world problem-solving skills as advocated for by Yanto et al. [31]. Integrating PBL with KS provided students with an active learning environment, prompting them to develop experimental protocols and actively engage in the scientific process, which aligns with Nuora and Valisaari [33] findings. The students' involvement in experimental design, execution, and interpretation sharpened their scientific investigation and iterative problem-solving skills. They were required to analyse different variables, which necessitated a deeper understanding of the underlying scientific concepts.

The findings also showed that students exhibited problem-solving capabilities when encountering unexpected data patterns. Using domestic materials in the experiments also demonstrated the students' creativity and ability to transform everyday objects into useful experimental tools. This aligns with the objectives of scientific literacy, which emphasises skills such as data interpretation, hypothesis testing, and evidence-based learning, which corroborate that a hands-on, project-based approach significantly improved students' understanding and application of physics concepts, demonstrating that experiential learning can lead to deeper comprehension and retention of theoretical knowledge [18]. This finding is also corroborated by Chi and R. Wylie's [48] study which emphasise that meaningful cognitive engagement occurs when learners actively construct and refine ideas rather passively receiving information. Hence, they gradually developed a conceptual understanding and a shift in their mindset regarding misconceptions.

This approach resonates with educational theories that advocate for interdisciplinary learning. Nuora and Valisaari [33] highlight that KS promotes scientific thinking by fostering boundary-crossing skills, which are crucial for enhancing students' understanding of science and its application in real-world contexts. KS thus encourages students to recognise the connections between scientific inquiry and their everyday experiences, expanding their understanding of how science influences daily decisions. The success of this study in using KS and PBL methods aligns with prior research emphasising the benefits of these models in physics education. According to Godwin et al. [34], KS also serves as a platform for informal learning, emphasising student-centred learning, as outlined by Freire [25], which allows students to take responsibility for their own learning, as opposed to the passive receipt of knowledge typical of traditional lecture-based instruction [26].

While previous studies have found that students struggle with fundamental thermodynamic concepts [4,5], this study suggests that incorporating PBL and KS in thermodynamics education can mitigate these challenges. Brown [8] and Wulandari et al. [9] also found that traditional lecture-based methods do not address students' misconceptions. This study supports the assertion that a more interactive, hands-on approach is crucial for enhancing student comprehension and problem-solving skills in thermodynamics. Thus, integrating PBL with KS enhances students' conceptual understanding of thermodynamics and strengthens their ability to apply scientific reasoning to real-world scenarios. Studies on inclusive science education highlight that contextualised and culturally familiar learning resources enhance participation and engagement among diverse student populations [60,61].

6. Limitations of the study

This study has several limitations that should be considered when interpreting the findings. First, the small sample size of 50 students limits the generalizability of the results. Although the sample was sufficient for in-depth analysis within the study context, it may not adequately represent the broader population of students, thereby restricting the extent to which the findings can be generalised to other educational settings. Second, the students were organised into small groups of six, which may have influenced individual participation and performance. Group dynamics, such as unequal participation, dominance by certain members, or interpersonal dynamics, could have affected project outcomes and the data collected, introducing potential bias. Third, only three projects conducted by three groups were selected for data analysis and interpretation. We acknowledge this as a limitation of the study and clarify that the findings are not intended to be statistically generalisable but are analytically transferable to similar educational contexts. As a result, the findings may reflect the characteristics of the selected projects rather than the overall cohort.

This paper recognises that some of the activities of students focused on heat transfer rates, which are technically classified in transport phenomena, but not classical thermodynamics. These activities were purposefully utilised as pedagogical bridges to aid students' conceptual understanding of the laws of thermodynamics, energy conservation, and equilibrium. Additional applications of the KS-PBL model in the future might also elaborate on this difference by explicitly introducing transport phenomena as a complementary teaching module to thermodynamics. Future studies should consider larger sample sizes and the inclusion of all group projects to enhance representativeness and strengthen the validity of the findings.

7. Conclusions

This study proves the originality of using KS and PBL together to provide a low-cost, high-impact model of teaching physics in an environment where resources are scarce. This inclusive model, as opposed to previous models that segregated each of the approaches, fosters an in-depth understanding of concepts, creativity, and scientific investigation. The experimental work produced by students acted as strong evidence supporting the successful implementation of PBL and KS in thermodynamics education. Students demonstrated their understanding of thermodynamic principles when they performed these experiments. Through this teaching strategy, students gained improved conceptual ideas and fundamental scientific abilities relating to data assessment, problem solving, and critical thinking. Home materials serve as economic components for building laboratories, which makes the approach suitable for schools with limited resources, rural communities, and home-based learners. The model achieved its purpose of generating meaningful student learning through real-world applications because students engaged at high levels throughout experimental stages.

Extended assessment methods should be used to determine students' abilities in experimental design and scientific communication, since their critical thinking and problem-solving skills showed marked improvement. The implication is that the use of the PBL combined with the KS model, as an approach for teaching thermodynamics, shows potential for implication in other contexts. This instructional design functions well with various learning spaces and uses everyday resources, enabling its use in traditional classrooms and remote learning platforms. Hence, the model can be effectively extended to other areas of physics, including but not limited to: (a) mechanics (investigating motion, forces, and energy using inclined planes, pendulums, and elastic materials); (b) electricity and magnetism (exploring circuits with batteries and bulbs or magnetic induction with simple coils and magnets); (c) waves and optics (demonstrating sound wave propagation using water surfaces or light refraction through everyday lenses); (d) fluid dynamics (examining buoyancy, pressure, and flow using water containers and simple instruments).

The second implication of this study is that the setup is cost-efficient compared to the conventional laboratory equivalents while providing estimated price information in South African

ZAR. The lists of experimental apparatus show their purposes and estimated South African Rand costs (including VAT) based on 2025 market prices. Standard entry-level physics laboratory equipment costs were obtained from certified educational suppliers, LabTech Instruments, SciLab Suppliers, and Lab Catering Supplies (South Africa), for undergraduate education.

The experimentation outcomes demonstrate substantial cost savings from employing the KS tool over a conventional laboratory. The method produced results that equal conventional thermodynamic knowledge delivery while operating successfully with basic school facilities. The main advantage of the KS model is its highly affordable implementation costs. Common items found at home, substitute expensive laboratory instruments to create an accessible approach suitable for both rural schools and home-based learning programmes and underfunded educational facilities. Students can achieve the same level of conceptual understanding through KS methods with less specialised laboratory equipment than traditional laboratories, thus creating an affordable learning environment.

Hence, this study contributes to the enhancement of science education, as it presents an empirically validated model that can be used by resource-limited schools to establish scientific thinking in an economical and situated manner, by connecting pedagogy with the students' lived environments.

Author contributions

Sizwe Jackson Clement Masuku: Conceptualisation, investigation, methodology, formal analysis and writing the initial draft.

Sakyiwaa Boateng: Methodology, formal analysis, writing original draft, writing review and editing.

Use of Generative-AI tools declaration

The authors declare that they used Artificial Intelligence (AI) tools (Grammarly and Quillbolt) to refine the language and improve the grammar of the text.

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Conflict of interest

The authors declare there is no conflict of interest in this paper.

Ethics declaration

The studies involving humans were approved by the Ethics Committee of the Research Unit of Walter Sisulu University (FEDSRECC014-03-23). The study was conducted in accordance with the local legislation and institutional requirements. Written informed consent for participation in this study was provided by the participants.

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Author’s biography

Mr Sizwe Jackson Clement Masuku just completed his PhD in Materials Science. Masuku is engaged in advanced research in materials science, with a background in physics and a lecturing role at Walter Sisulu University. As a physics lecturer, he is responsible for teaching undergraduate physics modules, supervising practical work, and contributing to curriculum development in the Division of Physics Education at WSU. In his PhD studies, he investigated aspects of material properties, synthesis/characterisation, and their applications. His teaching and research roles complement each other: the lecturing role keeps him engaged with core physics concepts, while his doctoral research added depth to materials-science methodologies and applications.

Dr Sakyiwaa Boateng is a Senior Lecturer in Physics Education at the Department of Mathematics, Science and Technology Education within the Faculty of Education at Walter Sisulu University, Mthatha, South Africa. She specialised in Physics Education. Her research interests include enhancing learner performance in science and teacher professional development, particularly examining the affective aspects that teachers consider essential to making teaching a worthwhile profession. She is also looking to break down the disjunction between science and culture and to focus on 21st-century teaching, science education, and teacher training. Her current research focuses on Mathematics and Science anxiety, and she is investigating interventions to build resilience in mathematics and science among pre-service science teachers and high school science learners.