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International Journal of Education, Technology and Science
4(3) (2024) 2129–2161

IJETS
International Journal of Education Technology and Science

ENHANCING CONCEPTUAL UNDERSTANDING OF ENERGY AND ENTROPY: A STUDY ON THE TRIPOD APPROACH in HIGH SCHOOL CHEMISTRY EDUCATION

(Research article)

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Received: 02.05.2024 Revised version received: 13.08.2024 Accepted: 15.08.2024

Abstract

This study examines the effectiveness of the Tripod Approach developed in previous research, focusing on teaching energy and entropy holistically. The subjects were 11th-grade students from a private school in Turkey, with 15 students in the control group and 19 in the experimental group. Both quantitative and qualitative methods were employed. Quantitative data were collected using the Chemistry and Energy Achievement Test (CEAT). The results revealed a significant difference in favor of the experimental group in both post-test CEAT scores and pre-test-post-test score changes. Qualitative data were analyzed using content and descriptive analysis methods, providing deeper insights into students' conceptual development. The qualitative findings supported the quantitative results, showing that the Tripod Approach not only enhanced factual knowledge but also improved understanding of complex thermodynamic concepts. These findings highlight the potential of the Tripod Approach as an effective teaching strategy in high school science education. By integrating macroscopic and microscopic views of entropy, the approach offers a comprehensive understanding of thermodynamics, making it a valuable tool for educators.

Keywords: Tripod Approach, thermodynamics, energy, entropy, probability, alternative entropy definition

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1. Introduction

Thermodynamics, a cornerstone of science, is essential across various disciplines due to its broad applicability and foundational role in the natural sciences (Meltzer, 2004; Patron, 1997; Sözbilir, 2001). Despite its critical nature, thermodynamic concepts, particularly entropy, have been subjects of extensive debate and challenge in comprehension for centuries (Sözbilir, 2001; Ishida & Chuang, 1997). Consequently, teaching these concepts effectively remains a pivotal area in science education (Johnstone et al., 1977).

A significant challenge in understanding entropy lies in its diverse definitions, which often fail to encapsulate its true meaning. Clausius, a key figure in thermodynamics, introduced an initial definition that led to confusion (Clausius, 1865, 1867). This confusion was further compounded by Boltzmann's (1898) metaphors of "order" and "disorder" to describe entropy microscopically. These metaphors have faced criticism for inadequately conveying the intended scientific concepts (Haglund et al., 2015; Haglund et al., 2010; Lambert, 2002b, 2011; Sözbilir, 2007; Styer, 2000; Wei et al., 2014). A significant issue with the "disorder" metaphor is its concrete connotations in everyday life, which do not align well with the abstract nature of energy dispersion in thermodynamics. Styer (2000) emphasizes that using everyday examples, such as a tidy or messy room, inaccurately represents energy dispersion, hindering teaching the second law of thermodynamics (Wei et al., 2014).

Since 2013, there has been a consensus to exclude the "disorder" concept from educational materials. However, teachers and students continue using this concept out of habit (Haglund et al., 2015). Alternative microscopic approaches focusing on energy dispersion, particle states, and degrees of freedom are recommended for explaining entropy. These molecular approaches, which center on the internal structure of matter, are challenging. For instance, the concept of degrees of freedom, another alternative, can also be misinterpreted through the "disorder" metaphor.

When relying on a single explanatory approach, understanding macroscopic thermodynamic concepts like the energy dispersion index, Gibbs free energy, the second law of thermodynamics, and spontaneity remains risky. While some studies have explored students' conceptual understanding of the second law of thermodynamics, research on conceptual change at the high school and university levels is scarce (Carson & Watson, 2002; Kesidou & Duit, 1993; Sözbilir, 2001; Adomaitis & Meštrović, 2020; Thompson & Bennett, 2021). Developing teaching methodologies that integrate the foundational qualitative ideas of the second law, particularly for concepts such as energy, entropy, heat, and temperature, is essential (Kesidou & Duit, 1993).

Despite recommendations to use metaphors based on microscopic explanations for teaching entropy, such as the energy dispersion index and microstates, these approaches often overlook the macroscopic nature of entropy, which involves changes in energy quality. The challenge is reconciling entropy's macroscopic, statistical average nature with its microscopic characteristics. Thus, a single-approach explanation of entropy poses risks for students' comprehension (Baierlein, 1994).

The core difficulty in teaching entropy is effectively integrating macroscopic (thermodynamic) and microscopic (statistical) approaches (Loverude, 2002; Cochran, 2005). To address these challenges, a new pedagogical strategy, the "Tripod Approach," was developed in a previous study (Akbulut & Altun, 2020, Figure 1). This approach provides a holistic teaching method for energy and entropy, incorporating both macroscopic perspectives (as proposed by Clausius & Kelvin) and microscopic statistical explanations (as articulated by Gibbs). The Tripod Approach is a necessary innovation in teaching thermodynamics because it addresses several critical challenges that traditional teaching methods often fail to overcome. Thermodynamics, particularly the concepts of energy and entropy, are inherently abstract and involve complex, multi-layered ideas that students often struggle to grasp. Traditional approaches tend to focus on either the macroscopic or microscopic perspectives, but rarely integrate the two in a way that fosters a holistic understanding. This can lead to fragmented knowledge, where students understand isolated facts but fail to see the connections between them.

The Tripod Approach innovatively combines macroscopic and microscopic perspectives, allowing students to see the broader picture of how thermodynamic principles operate across different scales. By using this approach, students can better understand the statistical nature of entropy and its macroscopic implications in energy distribution. This method also promotes active learning through hands-on experiments and group activities, which helps students apply theoretical knowledge in practical contexts, deepening their comprehension. Moreover, the Tripod Approach's emphasis on integrating various teaching methods, such as visual aids, interactive simulations, and collaborative discussions, caters to diverse learning styles, making the complex subject matter more accessible to a wider range of students. This comprehensive and student-centered strategy is crucial in fostering a deeper, more connected understanding of thermodynamics, which is essential for mastering the subject and applying it in real-world contexts.

The Tripod Approach has three key components: en(ergy-tropy), unavailability, and probability. Despite their differences, the en(ergy-tropy) component emphasizes the intrinsic relationship between energy and entropy. This component draws from Clausius' foundational work, highlighting how energy transformations and entropy are interconnected. The unavailability component represents the macroscopic meaning of entropy, focusing on the concept of energy that is not available for work, thus introducing an element of uncertainty. The probability component encapsulates the statistical nature of entropy, using various metaphors and approaches to explain how entropy can be understood in terms of the likelihood of different energy dispersions.

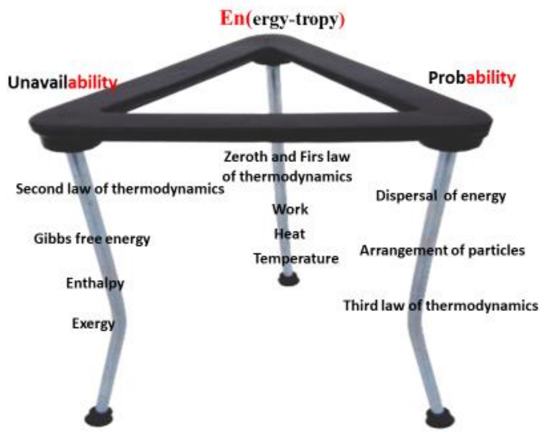

Figure 1. Tripod Approach (Akbulut & Altun, 2020)

First Pod: En(ergy-tropy)

The concept of entropy has its origins in the study of energy, specifically in the conservation and transformation of energy. The term "entropy" was deliberately chosen by Clausius to resemble "energy," reflecting its close physical relationship to energy. Consequently, the first component of the Tripod Approach is centered on the concept(s) of "en(ergy-tropy)." Given that students often confuse the relationships between energy conservation, energy degradation, heat, and temperature, it is crucial to explore these concepts in depth. This first component encompasses two key macroscopic (thermodynamic) concepts, namely work and heat, which are foundational to the birth of the law of entropy. It also includes the zeroth and first laws of thermodynamics, focusing on Clausius's exploration of why not all forms of energy can be converted into work.

Second Pod: Unavailability

The second component of the Tripod Approach, "unavailability," is related to the macroscopic structure of entropy. One of the key concepts in this pod is enthalpy. As illustrated by Clausius's inequality ($dS \geq dQ/T$), the macroscopic change in entropy is influenced by changes in the system's enthalpy and the temperature of the surroundings (Thomas & Schwenz, 1998; Thomas, 1999; Haglund & Jeppsson, 2014; Loverude, 2015). Additionally, this component addresses macroscopic concepts such as the second law of thermodynamics, Gibbs free energy, and exergy, which are essential in explaining the qualitative change in energy resulting from the interaction between a thermal system and its surroundings. Research has shown that students find the concept of Gibbs free energy more comprehensible than entropy, suggesting that it may be beneficial to introduce the relationship between Gibbs free energy and entropy at the outset of entropy instruction (Geller et al., 2014). However, it is recommended to first provide a qualitative and quantitative explanation of entropy in relation to other macroscopic concepts before proceeding with Gibbs free energy. Gibbs free energy is closely related to entropy, heat, work, temperature, and exergy. According to Haglund (2016), Gibbs free energy effectively operationalizes the second law of thermodynamics by integrating the enthalpic and entropic aspects of the interaction between the system and its surroundings into a single formula. Recognizing that the change in energy quality can be understood through entropy, the second law, and the exergy concept, which is grounded in the first and second laws, exergy has been included in the unavailability component of the Tripod Approach (Dincer & Cengel, 2001). Moreover, the use of the exergy concept is believed to enhance clarity and understanding of the second law and entropy (Jones & Dugan, 2003, p. 428).

Third Pod: Probability

The third component of the Tripod Approach, "probability," is based on Gibbs's statistical approach to entropy in the context of probability. The key concepts in this component are the arrangement of particles, dispersal of energy, and the third law of thermodynamics. When introducing the microscopic explanation of entropy, it is suggested to start with the arrangement of particles within the context of probability for beginners, followed by a smooth transition to the metaphor of energy dispersal. This approach is recommended because some students may initially struggle to grasp the abstract and molecular-based concept of energy distribution probability. For example, studies have shown that chemistry students tend to perform better with molecular explanations, while physics students excel with macroscopic approaches (Christensen & Rump, 2008; Haglund et al., 2015).

Several studies have identified the specific problems students face in learning thermodynamics. Meltzer (2004) found that while heat, work, and internal energy are distinct forms of energy, many students need help to differentiate between them and understand their roles. Similarly, Thomas (1998) discovered that while students could define thermodynamic concepts like reversible change, entropy, and equilibrium in everyday language, they needed a deeper scientific understanding. Casulleras (1991) noted that students often need to understand energy conservation and dissipation, leading to difficulties with thermodynamics' first and second laws. Wei et al. (2014) emphasized the need for students to understand spontaneous processes through the second law of thermodynamics.

This study extends our previous work by evaluating the effectiveness of the Tripod Approach (Akbulut & Altun, 2020) on high school students' understanding of energy and entropy concepts within the "Chemistry and Energy" unit. By examining the interrelationships among these concepts, this research aims to provide a more comprehensive understanding of teaching complex thermodynamic principles effectively.

2. Method

This study employed an explanatory sequential mixed methods design, integrating both quantitative and qualitative data to provide a comprehensive understanding of the impact of the Tripod Approach on high school students' comprehension of thermodynamic concepts (Creswell & Plano Clark, 2010, 2014). This design allows for the initial collection and analysis of quantitative data, followed by qualitative data, to explain and elaborate on the quantitative findings.

2.1. Research Questions

This study aimed to address the following research questions:

1. Is there a significant difference between the pre-test scores of the experimental and control groups on the CEAT?
2. Is there a significant difference between the pre-test and post-test scores of the experimental group on the CEAT?
3. Is there a significant difference between the pre-test and post-test scores of the control group on the CEAT?
4. Is there a significant difference between the post-test scores of the experimental and control groups on the CEAT?
5. What are the observed differences in the development of the experimental and control group students' understanding of thermodynamic concepts?

2.2. Working Group

The sample for this study comprised 11th-grade students (ages 16-17) from two branches of a private high school in Turkey. The students were randomly assigned to experimental and control groups. The experimental group consisted of 19 students, including eight females and eleven males, while the control group included 15 students, comprising six females and nine males.

To further ensure a balanced and representative sample within the experimental group, four heterogeneous subgroups were formed based on students' performance on the achievement test and the teacher's classroom observations. Each subgroup included one high-achieving student, one low-achieving student, and two or three students of average ability. The formation of these subgroups was guided by Stahl's (1996) criteria for creating heterogeneous groups, with careful consideration given to ensuring gender balance within each group, in addition to academic performance. This careful structuring of groups was intended to maximize the effectiveness of the Tripod Approach by fostering diverse interactions and perspectives among students with varying academic abilities.

2.3. Quantitative Phase

In the initial quantitative phase, a quasi-experimental design with pre-test and post-test control groups was employed to evaluate the effectiveness of the Tripod Approach. The study participants were 11th-grade students from a private high school, who were randomly assigned to either the experimental group (n = 19) or the control group (n = 15). The experimental group participated in activities structured around the Tripod Approach, while the control group received traditional, teacher-centered instruction.

Quantitative data were collected using the Chemistry and Energy Achievement Test (CEAT), specifically developed for this study to assess students' comprehension of thermodynamic concepts. The CEAT underwent a rigorous validation process, which included item analysis and content validity assessments by subject matter experts (Abraham et al., 1994). The reliability of the CEAT was further established through a pilot test conducted with 80 students, and the item statistics were deemed satisfactory, calculated using the TAP (Test Analysis Program Version 14.7.4) software (Brooks & Johanson, 2003).

Given the distribution of the data, statistical analysis of the CEAT scores for the experimental and control groups was conducted using a non-parametric alternative to the independent samples t-test, facilitated by SPSS 26. Finally, the Chemistry and Energy Achievement Test (CEAT) was finalized, was applied to the experimental and control groups as a pretest at the beginning of the activities and posttest.

2.4. Qualitative Phase

Qualitative data were collected to gain deeper insights into students' experiences and conceptual shifts. This phase involved open-ended questions, classroom observations and video recordings, and semi-structured interviews, providing rich, descriptive data that complemented the quantitative findings.

Open-Ended Questions: Students were asked open-ended questions that were either pre-prepared or shaped according to the implementation process. These questions aimed to gauge students' comprehension of entropy and related thermodynamic concepts. The process began with an open-ended question posed to pre-formed heterogeneous groups. Each group discussed the question collaboratively, synthesizing diverse perspectives to reach a consensus. Group spokespersons then presented their conclusions to the entire class. To document the implementation of the Tripod Approach and its impact on student learning, 28 lesson hours were recorded and later transcribed for analysis. Responses were categorized as correct, partially correct, or incorrect, offering a nuanced view of their conceptual grasp.

Classroom Observations and Video Recordings: Engaging and pedagogically sound activities were designed to align with the research objectives, allowing students to apply theoretical knowledge in practical contexts. Some experiments were teacher-led, while others required active student participation. During these activities, students made observations, recorded findings, and drew conclusions. Each group analyzed their results and shared their interpretations with the class.

Semi-Structured Interviews: To further explore students' perceptions and understanding, semi-structured interviews were conducted. These interviews provided additional insights into their cognitive processes.

The analysis of open-ended questions within this study represents a mixed-method approach, blending qualitative and quantitative elements. Initially, students' responses to open-ended questions were collected to gain in-depth insights into their conceptual understanding of entropy and related thermodynamic concepts. These responses provided rich qualitative data, capturing the nuances of students' thought processes. However, to facilitate a more structured analysis, these qualitative responses were subsequently categorized into three distinct groups: correct, partially correct, and incorrect. This categorization introduced a quantitative dimension, allowing for the numerical analysis of response patterns. By integrating both qualitative and quantitative methodologies, this approach provides a comprehensive understanding of students' conceptual grasp, offering both detailed insights and the ability to identify trends or comparisons within the data.

The other qualitative data were analyzed using thematic analysis based on Miles and Huberman's (1994) framework, which involves data reduction, data display, and conclusion drawing/verification. The data were systematically coded and categorized to identify emerging themes related to students' understanding and the effectiveness of the Tripod Approach.

3. Results

3.1. Normality Assessment of Chemistry and Energy Achievement Test (CEAT) Data

To assess the normality of the data of *Chemistry and Energy Achievement Test (CEAT)* used in this study, both the Kolmogorov-Smirnov and Shapiro-Wilk tests were applied. The data from both groups (Experimental and Control) were evaluated for normality in both the pre-test and post-test phases. The results of these tests are presented in Table 1.

Table 1. Descriptive Statistics for Pre-Test and Post-Test Scores

Group	Test	N	Mean	Std. Deviation	Skewness	Kurtosis
Experimental	Pre-Test	19	9.00	2.67	-0.472	-0.246

	Post-Test		14.00	2.96	-0.731	-0.308
Control	Pre-Test	15	7.53	2.47	0.003	-0.777
	Post-Test		10.47	4.37	0.298	-0.912

Table 1 shows the descriptive statistics for the pre-test and post-test results of both groups (Experimental and Control). The skewness and kurtosis values indicate that the data for both groups are generally close to a normal distribution.

Table 2 summarizes the results of the normality tests. According to the Kolmogorov-Smirnov test, the data for both the pre-test and post-test in both groups are normally distributed ($p > 0.05$). However, according to the Shapiro-Wilk test, the post-test data for theeExperimental group are not normally distributed ($p = 0.017$).

Table 2. Results of the Normality Tests (Kolmogorov-Smirnov and Shapiro-Wilk)

Group	**Test**	**Kolmogorov-Smirnov**		**Shapiro-Wilk**	
		Statistic	**p-value**	**Statistic**	**p-value**
Experimental	Pre-Test	0.142	0.200	0.947	0.347
	Post-Test	0.171	0.145	0.874	0.017
Control	Pre-Test	0.185	0.176	0.923	0.217
	Post-Test	0.119	0.200	0.953	0.568

The results of the normality tests indicate that both the pre-test and post-test data for the Control Group are normally distributed. For the experimental group, while the pre-test data conform to a normal distribution, the post-test data do not meet the normality assumption according to the Shapiro-Wilk test. Consequently, non-parametric tests were employed for the analysis.

3.1.1. Quantitative Findings Related to the First Sub-Problem

Is there a significant difference between the experimental and control group students' Chemistry and Energy Achievement Test (CEAT) pre-test scores related to thermodynamic concepts?

The initial analysis of the CEAT pre-test scores for the experimental and control groups was conducted using the Mann-Whitney U test. This analysis aimed to ensure that any observed differences in post-test scores could be attributed to the intervention rather than pre-existing differences between the groups. As illustrated in Table 3, the Mann-Whitney U test results indicate no significant difference between the pre-test scores of the experimental and control groups.

Table 3. Mann-Whitney U Test for Pre-test Scores of Students' CEAT Achievement

Group	N	Mean Rank	Sum of Ranks	Mann-Whitney U	Wilcoxon W	Z	Asymp. Sig. (2-tailed)	Exact Sig. (2-tailed)
Experimental	19	20.08	381.50					
Control	15	14.23	213.50	93.500	213.500	-1.724	.085	.089
Total	34							

The Mann-Whitney U test was conducted to compare the pre-test scores of the experimental and control groups. The mean rank for the experimental group (Mdn = 20.08) was higher than the mean rank for the control group (Mdn = 14.23). However, the test did not reveal a statistically significant difference between the two groups $U=93.50$, $Z=-1.724$, $p=.085$ (2-tailed). The exact significance value was $p=.089$, which is slightly above the conventional threshold of $p<.05$. These results suggest that there is no significant difference in the pre-test scores between the experimental and control groups, indicating that both groups began with comparable levels of achievement in the CEAT.

3.1.2. Quantitative Findings Related to the Second Sub-Problem

Is there a significant difference between the experimental group students' CEAT pre-test-post-test achievement scores related to thermodynamic concepts?

The Wilcoxon Signed-Rank test was used to compare the pre-test and post-test scores of students in the experimental group (Table 4). The results indicated that there was a significant increase in the post-test scores compared to the pre-test scores, $Z=-3.357$, $p=.001$ (2-tailed). Out of 19 students, 16 showed an increase in their scores, 2 showed a decrease, and 1 student had no change. These results suggest that the intervention had a statistically significant positive effect on the students' achievement in the CEAT, as reflected by the increase in post-test scores.

Table 4. Wilcoxon Signed-Rank Test for Pre-test-Post-test Scores of Experimental Group Students' CEAT Achievement

Comparison	N	Mean Rank	Sum of Ranks	Z	Asymp. Sig. (2-tailed)
Negative Ranks (Post_Test < Pre_Test)	2	4.25	8.50	-3.357	.001
Positive Ranks	16	10.16	162.50		

(Post_Test > Pre_Test)					
Ties (Post_Test = Pre_Test)	1				
Total	19				

3.1.3 Quantitative Findings Related to the Third Sub-Problem

Is there a significant difference related to thermodynamic concepts between the CEAT pre-test-post-test achievement scores of the control group students?

The Wilcoxon Signed-Rank test was used to compare the pre-test and post-test scores of students in the control group (Table 5). The results indicated that there was no statistically significant difference between the pre-test and post-test scores, $Z=-1.572$, $p=.116$ (2-tailed). Among the 15 students, 9 showed an increase in their scores, 2 showed a decrease, and 4 students had no change. These results suggest that there was no significant improvement in the control group's CEAT achievement between the pre-test and post-test, indicating that the traditional teaching method may not have had a substantial impact.

Table 5. Wilcoxon Signed-Rank Test for Pre-test-Post-test Scores of Control Group Students' CEAT Achievement

Comparison	**N**	**Mean Rank**	**Sum of Ranks**	**Z**	**Asymp. Sig. (2-tailed)**
Negative Ranks (Post_Test < Pre_Test)	2	5.00	10.00		
Positive Ranks (Post_Test > Pre_Test)	9	6.22	56.00	-1.572	.116
Ties (Post_Test = Pre_Test)	4				
Total	15				

3.1.4 Quantitative Findings Related to the Fourth Sub-Problem

Is there a significant difference between the CEAT post-test scores of students in the experimental and control groups related to thermodynamic concepts?

The Mann-Whitney U test was conducted to compare the post-test scores of the experimental and control groups. The mean rank for the experimental group (Mdn = 21.26) was significantly higher than the mean rank for the control group (Mdn = 12.73). The test revealed a statistically significant difference between the two groups, $U=71.000$, $Z=-2.497$, $p=.013$ (2-tailed). The exact significance value was $p=.012$, indicating that the experimental group's post-test scores were significantly higher than those of the control group. This suggests that the intervention applied to the experimental group had a positive effect on students' CEAT achievement, leading to a significant improvement in their post-test scores compared to the control group, which did not receive the same intervention.

Table 6. Mann-Whitney U Test for Post-test Scores of Students' CEAT Achievement

Group	N	Mean Rank	Sum of Ranks	Mann-Whitney U	Wilcoxon W	Z	Asymp. Sig. (2-tailed)	Exact Sig. (2-tailed)
Experimental	19	21.26	404.0					
Control	15	12.73	191.00	71.000	191.000	-2.497	0.013	0.012
Total	34							

3.1.5. Quantitative and Qualitative Findings Related to the Fifth Sub-Problem

What are the observed differences in the development of the experimental and control group students' understanding of thermodynamic concepts?

We integrated quantitative and qualitative data to address this research question comprehensively. The quantitative data were derived from the "Chemistry and Energy Achievement Test (CEAT)," while the qualitative data were collected from classroom observations, video recordings, open-ended questions, and semi-structured interviews. The CEAT items were categorized into four primary themes: energy, the macroscopic meaning of entropy, the microscopic meaning of entropy, and disorder. Student responses from the experimental and control groups were compared across these themes.

3.1.5.1. Chemistry and Energy Achievement Test (CEAT) Findings Related to the Fifth Sub-Problem

Chemistry and Energy Achievement Test (CEAT) analysis revealed notable differences between the experimental and control groups across the four conceptual themes. The detailed comparisons are presented in the following sections.

I. Student Development Related to Energy (Heat, Temperature, Work, and Internal Energy)

As illustrated in Table 7, both experimental and control group students exhibited considerable deficiencies in their understanding of the primary concept of energy prior to the intervention. This overarching concept includes sub-concepts such as heat, temperature, work, and internal energy. The pre-test results of CEAT indicate that both groups started with a relatively low level of comprehension in these areas, with the experimental group scoring 42% and the control group scoring 37%.

Table 7. Pre- and Post- Intervention Understanding of the Primary Concept of Energy Among Experimental and Control Group Students

Thermodynamic Concepts	Group	Number of questions	Pre-test (%)	Post-test (%)
Energy (Heat, temperature, work, and internal energy)	Experimental	9	42	78
	Control		37	55

Following the application of the instructional interventions, the post-test results revealed a marked improvement in the experimental group's understanding of energy-related concepts. The experimental group, which engaged in activities based on the Tripod Approach, demonstrated a substantial increase in their scores, achieving 78% in the post-test. In contrast, the control group taught using traditional teacher-centered methods aligned with the 11th-grade chemistry curriculum showed a more modest improvement, reaching 55%.

In the analysis of conceptual development for the experimental and control groups the Wilcoxon Signed-Rank test was applied for the experimental group, and the Mann-Whitney U test was used for comparisons between the two groups (Table 8-Table11).

Table 8. Mann-Whitney U Test for Pre-test Scores of Students on Energy-Related Sub-Concepts (Heat, Temperature, Work, and Internal Energy) in CEAT Achievement

Group	**N**	**Mean Rank**	**Sum of Ranks**	**Mann-Whitney U**	**Wilcoxon W**	**Z**	**Asymp. Sig. (2-tailed)**	**Exact Sig. (2-tailed)**
Experimental	19	20.76	394.50	80.500	200.500	-2.230	0.026	0.030

Control	15	13.37	200.50
Total	34		

The Mann-Whitney U test results indicated (Table 8) a statistically significant difference between the pre-test scores of the experimental and control groups, with the experimental group having a higher mean rank (Z = -2.230, p = 0.026). This suggests that even before the intervention, the experimental group had a slightly better understanding of energy-related concepts.

Table 9. Mann-Whitney U Test for Pre-test Scores of Students on Energy-Related Sub-Concepts (Heat, Temperature, Work, and Internal Energy) in CEAT Achievement

Group	N	Mean Rank	Sum of Ranks	Mann-Whitney U	Wilcoxon W	Z	Asymp. Sig. (2-tailed)	Exact Sig. (2-tailed)
Experimental	19	22.63	430.00					
Control	15	11.00	165.00	45.00	165.00	-3.428	0.001	0.000
Total		34						

After the intervention, the Mann-Whitney U test results (Table 9) showed a more pronounced difference in post-test scores, with the experimental group significantly outperforming the control group (Z = -3.428, p = 0.001). This highlights the effectiveness of the Tripod Approach in enhancing students' comprehension of energy-related concepts.

For the experimental group, the Wilcoxon Signed-Rank test revealed (Table 10) a statistically significant improvement from pre-test to post-test scores (Z = -3.695, p < 0.001), indicating the strong impact of the Tripod Approach on student learning.

Table 10. Wilcoxon Signed-Rank Test for Pre-test-Post-test Scores of Experimental Group Students on Energy-Related Sub-Concepts (Heat, Temperature, Work, and Internal Energy) in CEAT Achievement

Comparison	N	Mean Rank	Sum of Ranks	Z	Asymp. Sig. (2-tailed)
Negative Ranks (Post_Test < Pre_Test)	1	1.00	1.00	-3.695	.000

Positive Ranks (Post_Test > Pre_Test)	17	10.00	170.00		
Ties (Post_Test = Pre_Test)	1				
Total	19				

For the control group, although there was an improvement, it was less pronounced, as shown by the Wilcoxon Signed-Rank test (Z = -2.930, p = 0.003). The gains in the control group (Table 11), while statistically significant, were not as substantial as those in the experimental group.

Table 11. Wilcoxon Signed-Rank Test for Pre-test-Post-test Scores of Control Group Students on Energy-Related Sub-Concepts (Heat, Temperature, Work, and Internal Energy) in CEAT Achievement

Comparison	**N**	**Mean Rank**	**Sum of Ranks**	**Z**	**Asymp. Sig. (2-tailed)**
Negative Ranks (Post_Test < Pre_Test)	1	2.00	2.00	-2.930	.003
Positive Ranks (Post_Test > Pre_Test)	11	6.91	76.00		
Ties (Post_Test = Pre_Test)	3				
Total	15				

The data clearly demonstrate the effectiveness of the Tripod Approach in enhancing students' understanding of energy-related thermodynamic concepts. The experimental group showed a significant improvement in their post-test scores, which can be attributed to the interactive and integrative nature of the Tripod Approach. In contrast, the control group's more modest gains suggest that traditional teaching methods, though covering the same content, lack the depth and engagement provided by student-centered approaches. These findings support the use of holistic and student-centered pedagogies, like the Tripod Approach, as effective strategies for teaching complex scientific concepts, particularly in thermodynamics.

II. Student Development Related to the Macroscopic Meaning of Entropy

The analysis of the Chemistry and Energy Achievement Test (CEAT) revealed that both the experimental and control groups initially had limited understanding of the macroscopic meaning of entropy (Table 12). Pre-test results indicated that the experimental group scored 22%, while the control group scored 23%, highlighting a low baseline comprehension in this area.

Table 12. Conceptual Development Test Results for Experimental and Control Groups

Thermodynamic concepts	Group	Number of questions	Pre-test (%)	Post-test (%)
Macroscopic meaning of entropy	Experimental	4	22	46
	Control		23	20

After the instructional interventions, the experimental group's understanding of entropy improved significantly, with their post-test score increasing to 46%. In contrast, the control group experienced a slight decline, with their post-test score dropping to 20%. This suggests that the traditional teaching methods employed in the control group were less effective in enhancing students' understanding of entropy.

The pre-test scores (Table 13) did not show a statistically significant difference between the experimental and control groups (Z = -1.199, p = 0.231), indicating that both groups started with a similar level of understanding of the macroscopic meaning of entropy. However, post-test results (Table 14) revealed a statistically significant difference between the groups, with the experimental group showing a higher level of understanding after the intervention (Z = -2.487, p = 0.013). This highlights the effectiveness of the Tripod Approach in improving students' comprehension of entropy.

Table 13. Mann-Whitney U Test for Pre-test Scores of Students on the Macroscopic Meaning of Entropy in CEAT Achievement

Group	**N**	**Mean Rank**	**Sum of Ranks**	**Mann-Whitney U**	**Wilcoxon W**	**Z**	**Asymp. Sig. (2-tailed)**	**Exact Sig. (2-tailed)**
Experimental	19	19.24	365.50					
Control	15	15.30	229.500	109.500	229.500	-1.199	0.231	0.256
Total	34							

Table 14. Mann-Whitney U Test for Pre-test Scores of Students on the Macroscopic Meaning of Entropy in CEAT Achievement

Group	N	Mean Rank	Sum of Ranks	Mann-Whitney U	Wilcoxon W	Z	Asymp. Sig. (2-tailed)	Exact Sig. (2-tailed)
Experimental	19	19.24	365.50					
Control	15	15.30	229.500	109.500	229.500	-1.199	0.231	0.256
Total	34							

The Wilcoxon Signed-Rank test (Table 15) revealed a statistically significant improvement in the experimental group's post-test scores compared to their pre-test scores (Z = -2.675, p = 0.007). This indicates that the Tripod Approach had a strong positive impact on their understanding of entropy. For the control group, the Wilcoxon Signed-Rank test (Table 16) did not show a statistically significant difference between pre-test and post-test scores (Z = -0.250, p = 0.802), suggesting that the traditional teaching methods did not effectively enhance their understanding of entropy.

Table 15. Wilcoxon Signed-Rank Test for Pre-test-Post-test Scores of Experimental Group Students on the Macroscopic Meaning of Entropy in CEAT Achievement

Comparison	N	Mean Rank	Sum of Ranks	Z	Asymp. Sig. (2-tailed)
Negative Ranks (Post_Test < Pre_Test)	1	11.00	11.00	-2.675	.007
Positive Ranks (Post_Test > Pre_Test)	13	7.23	94.00		
Ties (Post_Test = Pre_Test)	5				
Total	19				

Table 16. Wilcoxon Signed-Rank Test for Pre-test-Post-test Scores of Control Group Students on the Macroscopic Meaning of Entropy in CEAT Achievement

Comparison	N	Mean Rank	Sum of Ranks	Z	Asymp. Sig. (2-tailed)

Negative Ranks (Post_Test < Pre_Test)	6	7.00	42.00		
Positive Ranks (Post_Test > Pre_Test)	7	7.00	49.00	-0.250	.802
Ties (Post_Test = Pre_Test)	2				
Total	15				

The findings demonstrate that the Tripod Approach significantly improved students' conceptual understanding of the macroscopic meaning of entropy. By integrating both macroscopic and microscopic perspectives, this approach provided a more holistic and nuanced understanding of entropy, moving beyond purely quantitative interpretations. In contrast, the control group's slight decline in understanding suggests that traditional teaching methods, which may rely heavily on statistical calculations, are less effective in conveying complex thermodynamic concepts. These results affirm the value of comprehensive, student-centered teaching strategies in enhancing the understanding of challenging scientific concepts like entropy.

III. Student Development Related to the Microscopic Meaning of Entropy:

The analysis of pre-test and post-test scores for the experimental and control groups regarding the microscopic meaning of entropy revealed important insights (Table 17). Initially, there was no significant difference between the pre-test scores of the experimental (27%) and control (34%) groups, indicating that both groups started with a similar baseline understanding of the concept

Table 17. Comparison of Conceptual Achievement Test Results for Experimental and Control Groups

Thermodynamic concepts	Group	Number of questions	Pre-test (%)	Post-test(%)
Microscopic meaning of entropy	Experimental	6	27	57
	Control		34	42

The pre-test scores (Table 18) between the experimental and control groups did not show a statistically significant difference (Z = -1.378, p = 0.168). This suggests that both groups had a comparable initial understanding of the microscopic meaning of entropy, allowing for a fair comparison of the intervention's impact. Post-test results (Table 19) revealed a statistically significant difference between the groups, with the experimental group showing a higher level of understanding after the intervention (Z = -2.487, p = 0.013). This indicates that the Tripod Approach was more effective in improving students' understanding of entropy at the microscopic level compared to traditional methods.

Table 18. Mann-Whitney U Test for Pre-test Scores of Students on the Microscopic Meaning of Entropy in CEAT Achievement

Group	N	Mean Rank	Sum of Ranks	Mann-Whitney U	Wilcoxon W	Z	Asymp. Sig. (2-tailed)	Exact Sig. (2-tailed)
Experimental	19	15.47	294.00					
Control	15	20.07	301.00	104.00	294.00	-1.378	0.168	0.190
Total	34							

Table 19. Mann-Whitney U Test for Pre-test Scores of Students on the Microscopic Meaning of Entropy in CEAT Achievement

Group	N	Mean Rank	Sum of Ranks	Mann-Whitney U	Wilcoxon W	Z	Asymp. Sig. (2-tailed)	Exact Sig. (2-tailed)
Experimental	19	21.18	402.50					
Control	15	12.83	192.50	72.50	192.50	-2.487	0.013	0.014
Total	34							

The Wilcoxon Signed-Rank test revealed (Table 20) a statistically significant improvement in the experimental group's post-test scores compared to their pre-test scores (Z = -3.591, p < 0.001). This result underscores the strong positive impact of the Tripod Approach on students' understanding of entropy. The Wilcoxon Signed-Rank test for the control group (Table 21) did not show a statistically significant difference between pre-test and post-test scores (Z = -0.320, p = 0.749). This suggests that the traditional teaching methods did not lead to a significant improvement in the students' understanding of the microscopic meaning of entropy.

Table 20. Wilcoxon Signed-Rank Test for Pre-test-Post-test Scores of Experimental Group Students on the Microscopic Meaning of Entropy in CEAT Achievement

Comparison	N	Mean Rank	Sum of Ranks	Z	Asymp. Sig. (2-tailed)

Negative Ranks (Post_Test < Pre_Test)	1	1.50	1.50		
Positive Ranks (Post_Test > Pre_Test)	16	9.47	151.5	-3.591	.000
Ties (Post_Test = Pre_Test)	2				
Total	19				

Table 21. Wilcoxon Signed-Rank Test for Pre-test-Post-test Scores of Control Group Students on the Microscopic Meaning of Entropy in CEAT Achievement

Comparison	**N**	**Mean Rank**	**Sum of Ranks**	**Z**	**Asymp. Sig. (2-tailed)**
Negative Ranks (Post_Test < Pre_Test)	8	6.25	50.00		
Positive Ranks (Post_Test > Pre_Test)	5	8.20	41.00	-0.320	0.749
Ties (Post_Test = Pre_Test)	2				
Total	115				

The findings clearly demonstrate the superiority of the Tripod Approach in enhancing students' understanding of the microscopic meaning of entropy. The experimental group showed a significant improvement, indicating that the activities and teaching methods used effectively deepened their comprehension. In contrast, the control group's minimal improvement suggests that traditional methods, which often emphasize the "disorder" concept, may not adequately support students in grasping the more complex microscopic aspects of entropy. These results highlight the importance of using comprehensive and student-centered teaching strategies to foster a more nuanced and holistic understanding of scientific concepts.

IV. Student Development Related to the Concept of Disorder

In the experimental group, entropy was defined primarily as "a measure of unusable energy or energy dispersion index." In contrast, the control group focused on the definition of "a measure of unusable energy or disorder." At the end of the course, both groups were asked to choose the explanation that best aligned with their understanding of the statement, "Entropy is a measure of a system's disorder." (Table 22)

Table 22. Student Approaches to the Concept of Disorder

Groups	A (%)	B (%)	C (%)	D (%)	Indecisive (%)
Experimental	42	-	5	48	5
Control	-	20	20	33	27

As shown in Table 22, nearly half of the experimental group students (48%) provided the expected answer, indicating a correct understanding of entropy regarding energy dispersion. Conversely, the other half of the experimental group students equated the concept of disorder with chaos or uncertainty (42% and 5%, respectively).

In the control group, 33% provided the expected answer, while a significant portion of the students (20%) associated disorder with chaos or confusion, and another 20% equated the increase in the universe's entropy with an increase in disorder. This suggests that control group students were more inclined to associate macroscopic thermodynamic events with the disorder metaphor, leading to mental confusion. The high percentage of indecisive responses (27%) further indicates a need for more precise understanding in the control group.

Table 23. Chi-Square Test Results for Student Approaches to the Concept of Disorder

Groups	χ^2	df	Sig. (2-tailed)
Experimental	15.36	4	.004
Control	-	-	-

The chi-square test result ($\chi^2(4) = 15.36$, $p < .01$) indicates a statistically significant difference in the distribution of responses between the experimental and control groups (Table 23). This significant difference suggests that the Tripod Approach substantially impacted experimental students' understanding of the concept of disorder.

The initial responses from both groups indicate that disorder is a common source of confusion in teaching entropy. The control group's reliance on the metaphor of disorder, which has been widely criticized for its ambiguity, likely contributed to the students' misconceptions and mental confusion (Styer, 2000; Lambert, 2002; Sözbilir, 2007). The association of disorder with chaos or randomness, as seen in a significant portion of control group responses, underscores the limitations of this metaphor.

In contrast, the experimental group's responses, particularly the high percentage of students providing the expected answer, highlight the effectiveness of the Tripod Approach. By focusing on energy dispersion and providing a more structured and clear explanation, the

Tripod Approach helped students develop a more accurate understanding of entropy. The low percentage of experimental group students mixing thermodynamic and statistical explanations (only 5%) further supports the efficacy of this teaching method.

The findings from this section demonstrate the critical role of clear, energy-based explanations in teaching complex thermodynamic concepts. The Tripod Approach's emphasis on the interrelationship between energy and entropy, devoid of misleading metaphors like disorder, provides students with a more coherent and comprehensive understanding. This approach clarifies the concept of entropy and enhances the overall comprehension of thermodynamic principles.

In conclusion, the data strongly support the Tripod Approach as an effective method for teaching the concept of entropy. By moving away from the problematic disorder metaphor and focusing on energy dispersion, this approach facilitates a deeper and more accurate understanding of entropy and its implications in thermodynamics.

3.1.5.2. Analysis of Responses to Open-Ended Questions Related to the Fifth Sub-Problem

Table 24 summarizes the data collected from the group activities and experiments, including the total number of activities, experiments, targeted thermodynamic concepts, and open-ended questions, as well as the percentages of correct, partially correct, and incorrect answers.

Table 24. Responses of Experimental Groups to Open-Ended Questions in Activities and Experiments

			Open-Ended Questions			
Number of activities	Number of experiments	Number of targeted thermodynamic concepts	Number of open-ended questions	Correct Answers (%)	Partially Correct Answers (%)	Incorrect Answers (%)
7	13	11	143	80	11	9

This analysis provides insight into the effectiveness of the experimental activities and the students' understanding of the thermodynamic concepts taught during the study. As shown in Table 24, one or more experimental studies were performed for each thermodynamic concept during the activities conducted with the experimental group. Following the experiment results, various open-ended questions were posed to students, who generally responded as expected. Key thermodynamic concepts such as heat, and temperature were examined in depth throughout the activities to address potential misconceptions. The careful sequencing of related concepts and the design of various instructional activities for each concept resulted in students mainly providing expected responses to the research questions.

The literature supports the idea that clarity between similar and different concepts, such as heat, temperature, and energy, often arises from a need for more in-depth study (Pinto Casulleras, 1991). Addressing students' preconceptions and misconceptions about basic thermodynamic concepts is crucial to understanding energy and entropy (Akbulut & Altun, 2020).

The data highlights the efficacy of the Tripod Approach in facilitating a deeper understanding of thermodynamic concepts. The high percentage of correct answers (80%) indicates that students could grasp the core ideas effectively. The relatively low percentages of partially correct (11%) and incorrect answers (9%) suggest that the instructional methods used successfully clarified common misconceptions and reinforced accurate scientific concepts.

The experimental group's activities were designed to engage students actively in the learning process, using the Tripod Approach's principles to link macroscopic and microscopic perspectives of thermodynamics. This approach ensured that students could see the connections between different thermodynamic concepts, thereby fostering a more integrated understanding.

Correct Answers (80%): Students demonstrated a strong understanding of thermodynamic concepts, particularly those related to energy and entropy. This high percentage reflects the success of the Tripod Approach in helping students make sense of complex scientific ideas through hands-on activities and guided inquiry.

Partially Correct Answers (11%): Some students provided responses that were partially correct, indicating that they had grasped certain aspects of the concepts but were still struggling with others. These responses highlight areas where additional clarification and reinforcement might be necessary.

Incorrect Answers (9%): A small percentage of responses were incorrect, suggesting that despite the overall effectiveness of the instructional approach, a few students still had misunderstandings or gaps in their knowledge. These findings underscore the importance of ongoing assessment and targeted intervention to address specific learning needs.

The qualitative findings from this study provide valuable insights into how the Tripod Approach can be used to enhance the teaching of thermodynamic concepts. Educators can help students develop a more comprehensive and accurate understanding of these complex scientific ideas by combining macroscopic and microscopic perspectives and using various instructional methods.

In conclusion, the data from the experimental group activities demonstrate the effectiveness of the Tripod Approach in improving students' conceptual understanding of energy and entropy. The high percentage of correct answers and the overall positive response from students indicate that this approach is a promising method for teaching thermodynamics in high school science classes.

I. Qualitative Findings on the Concept of Entropy

In this section, the qualitative findings related to students' understanding of the concept of entropy are presented. These findings were gathered through classroom observations, interviews, and students' responses to open-ended questions during the study. The analysis aimed to capture the depth of students' conceptual grasp and the effectiveness of the Tripod Approach in teaching this complex thermodynamic concept.

Traditional textbooks predominantly emphasize quantitative calculations to explain entropy at the macroscopic level, while the change in entropy during a pure substance's phase transition is often described in terms of disorder. However, in this study, the experimental group received both qualitative and quantitative explanations of entropy framed in terms of energy. Following this instruction, students were asked, "How does the entropy of a pure substance change during the phase transition from solid to liquid to gas?" This question enabled us to observe how students applied their prior knowledge to interpret the statistical meaning of entropy.

The students were divided into four groups to discuss the question and then share their conclusions with the class:

Group 1: "During each transition, energy is converted not just into heat but into other forms of energy. The other forms of energy are not useful to us. Since the unusable energy increases in each phase transition from solid to gas, the unusable energy continuously increases, and thus entropy increases."

Group 2: "As a substance change from solid to gas, it absorbs heat, reducing intermolecular forces and increasing loss. The loss refers to usable energy loss, and therefore entropy increases."

Group 3: "As molecules transition from solid to gas, the distance between molecules and disorder increase while interactions decrease. As disorder increases, entropy also increases."

Group 4: "As a substance transition from solid to gas, temperature and distance between particles increase. As distance increases, so does disorder and entropy."

Examining the responses of the first two groups, they attempted to explain the change in entropy using the macroscopic definition known as a measure of unusable energy. In contrast, the literature primarily adopts a microscopic approach to explain entropy changes during phase transitions, with students often preferring the disorder metaphor. However, in this study, students reached an acceptable conclusion using a different approach, explaining the microscopic meaning of entropy with a macroscopic approach.

These findings suggest that the experimental group students, taught using the Tripod Approach, developed a more comprehensive and accurate understanding of thermodynamic concepts than the control group. The Tripod Approach, which emphasizes energy-based explanations and integrates macroscopic and microscopic views of entropy, facilitated this improved understanding. The results support the effectiveness of the Tripod Approach in teaching complex scientific concepts such as entropy and energy.

Group 1 and Group 2 Responses: The first two groups demonstrated an understanding of entropy by framing it as unusable energy. This perspective aligns with the macroscopic definition of entropy and indicates that students could connect the concept to practical scenarios involving energy transformation and loss.

Group 3 and Group 4 Responses: The latter two groups focused on the disorder aspect of entropy, which, while commonly taught, can lead to misconceptions. Despite this, they correctly identified the relationship between phase transitions and increases in entropy.

Integration of Macroscopic and Microscopic Views: The ability of students to use macroscopic explanations to describe microscopic phenomena suggests that the Tripod Approach effectively bridges the gap between these two perspectives. By framing entropy in terms of energy, students can move beyond the simplistic notion of disorder and develop a more nuanced understanding of the concept.

The qualitative findings indicate that the Tripod Approach fosters a deeper understanding of entropy and energy. This method encourages students to view thermodynamic concepts through multiple lenses, enhancing their comprehension and ability to apply them in different contexts.

In conclusion, integrating macroscopic and microscopic explanations through the Tripod Approach not only improved students' understanding of entropy but also provided them with the tools to approach complex scientific concepts holistically and meaningfully. These findings underscore the value of adopting multifaceted teaching strategies in science education.

II. Qualitative Findings from Researcher-Student Interviews

As part of the research, interviews were conducted with four to five students selected impartially after the first, fourth, and final activities to gather their perspectives and suggestions. The researcher analyzed the students' attitudes and responses during these interviews, leading to the following conclusions:

Adaptation Over Time: Students who initially struggled with the activities showed more acceptable approaches in later sessions.

Increased Engagement: Students who were typically less active in teacher-centered lessons demonstrated significant engagement in the instructional activities, contributing creatively to scientific discussions and facilitating a deeper exploration of the concepts being discussed. Below are some of the students' reflections on the activities:

Student A: "In teacher-centered lessons, words just follow one another. But now my curiosity has been sparked. For example, I started wondering what would happen in the iodine experiment, and the activities stuck in my mind more because I didn't just hear about them—I witnessed them firsthand."

Student B: "When a classmate expresses something I misunderstood, it gets discussed, and I get corrected."

Student C: "Honestly, I don't understand much by just writing things down. But today, through the experiment, we observed how entropy increases based on probabilities. Otherwise, I wouldn't have learned the concept of entropy at all."

Student D: "There is a big difference between the first and the last activity we did. Now we can approach things more scientifically."

The importance of supporting lessons that involve abstract concepts with various observations and experiments is particularly evident. Some student reflections that led the researcher to this conclusion include:

Student E: "I wish they would use such activities to make chemistry less boring."

Student F: "I would like to see more experiments included in lessons."

Student G: "I really enjoy these experiments, and I believe they are beneficial to me."

The qualitative findings from the researcher-student interviews highlight the effectiveness of the instructional activities in fostering a deeper understanding of complex scientific concepts, such as entropy. Over time, students who initially struggled with the activities demonstrated significant improvement, becoming more engaged and active in the learning process. The shift from passive reception in traditional teacher-centered lessons to active participation in experimental activities led to enhanced curiosity, critical thinking, and a more comprehensive grasp of the subject matter. Additionally, the students' reflections underscore the value of integrating hands-on experiments and discussions into lessons, particularly when dealing with abstract concepts. The insights gained from these interviews suggest that the Tripod Approach, which combines both qualitative and quantitative explanations, effectively bridges the gap between theoretical knowledge and practical application, ultimately enhancing students' scientific literacy and engagement.

5. Conclusion and Discussion

Thermodynamics is a critical subject in the curricula of physics, chemistry, and engineering programs. However, it presents significant student challenges, particularly concerning entropy, heat, temperature, and energy. The ongoing debates regarding the definition of entropy further complicate the teaching processes. Moreover, integrating macroscopic and microscopic approaches to entropy in science education remains a topic of discussion in the literature (Baierlein, 1994; Haglund et al., 2016; Kozliak, 2004).

To address these challenges, this study examined the effectiveness of the "Tripod Approach," developed in our previous work, in helping high school students understand thermodynamic concepts, particularly entropy, heat, temperature, and energy. The Tripod Approach provides a holistic teaching method that integrates macroscopic perspectives, as proposed by Clausius & Kelvin, and microscopic statistical explanations, as articulated by Gibbs (Akbulut & Altun, 2020).

In the quantitative dimension of the teaching activities, no significant difference was found between the pre-test scores of the experimental and control group students in the Chemistry and Energy Achievement Test (CEAT). Both groups showed improvement in their post-test scores. However, a significant difference in favor of the experimental group was found when comparing their post-test scores. This indicates that the Tripod Approach-based instruction was more effective than traditional curriculum-based teaching, leading to tremendous success among the experimental group students.

The conceptual achievement test also compared the understanding of critical thermodynamic concepts between the experimental and control group students. Questions were categorized into four themes: energy, heat, temperature, and entropy. The students' pre-test and post-test scores were then compared. Both groups showed similar pre-test performance for energy, heat, and temperature concepts (42% and 37%, respectively). However, at the end of the course, only about half of the control group students (55%) demonstrated the expected understanding, while a significant majority of the experimental group students (78%) did so. This suggests that the activities focusing on the first component of the Tripod Approach (Figure 1) were particularly effective.

Examining student approaches to the macroscopic meaning of entropy revealed that both groups had low pre-test scores, as expected for students encountering the concept for the first time (20%). After explaining the macroscopic meaning of entropy both verbally and mathematically during the course, nearly half of the experimental group students demonstrated the expected understanding in the post-test (46%), while there was no improvement in the control group (20%). A study conducted with undergraduate students reported that most students could not see the relationship between entropy and macroscopic concepts like enthalpy and Gibbs free energy (Haglund et al., 2015). Furthermore, educational programs tend to emphasize the microscopic meaning of entropy, often neglecting its macroscopic aspect. Focusing more on qualitative explanations than quantitative calculations of entropy's macroscopic meaning in the experimental group may have facilitated a better understanding.

For the microscopic meaning of entropy, no significant difference was found between the pre-test scores of the control (34%) and experimental (27%) groups. However, post-test results showed a partial improvement in the control group (42%) and a significant improvement in the experimental group (57%). One of the main reasons for this is that the control group's lessons predominantly explained the microscopic meaning of entropy in terms of disorder, a concept criticized in many studies for causing conceptual confusion (Styer, 2000; Lambert, 2002; Sözbilir, 2007). Supporting this, when asked what they understood by the concept of disorder, both groups lacked a clear understanding, with control group students more inclined to equate disorder with chaos and confusion.

In the qualitative dimension of the study, data obtained from the application activities with the experimental group and the researcher's observations were used as qualitative data collection tools. The activities were designed to guide students toward the targeted learning outcomes through various open-ended questions. Analysis of the students' responses showed that a large majority (80%) provided the expected answers. Additionally, it was surprising that half of the experimental group students could explain the concept of entropy without resorting to the concept of disorder, indicating a significant conceptual understanding achieved through the Tripod Approach. This is noteworthy because even many undergraduate students struggle to explain entropy without referring to disorder.

In summary, the following conclusions were drawn from this study:

- Relating Thermodynamic Concepts: Connecting concepts such as heat and temperature to the zeroth law of thermodynamics, energy to the first law, and mechanical energy to the second law, and explaining concepts like work energy in this context are crucial steps in understanding entropy.
- Focus on Macroscopic Approaches: After understanding the thermodynamic meaning of entropy, it is necessary to focus on its microscopic meaning. This suggests that starting entropy teaching at the high school level with energy-based macroscopic approaches, contrary to the view of starting with the concept of disorder (Haglund, 2017), is more appropriate.
- Avoiding Non-Energy-Based Metaphors: It is possible to understand entropy without using non-energy-based metaphors such as disorder and degrees of freedom.

The findings from the application activities have triggered the need to extend the research and focus on other problem situations related to understanding entropy. Various definitions of entropy have emerged, and the diversity of these definitions has made it difficult for students to understand the concept. However, no definition has deviated from the true meaning of entropy as much as the metaphor of disorder. Many students graduate thinking that entropy is merely about disorder. In this context, an alternative definition of entropy ("Entropy is a probabilistic measure of unavailable energy or energy dispersal") was developed based on the Tripod Approach and the findings from the student activities. This clarified the relationship between the concepts of energy, entropy, and probability, bridging the gap between their macroscopic and microscopic meanings and reducing cognitive confusion.

6. Pedagogical Implications and Future Research Directions

6.1. Pedagogical Implications

The findings of this study have several important implications for teaching thermodynamic concepts in high school settings. The significant improvement observed in the experimental group's understanding of energy and entropy concepts indicates that the Tripod Approach is effective. By integrating macroscopic and microscopic perspectives and focusing on energy-based explanations rather than traditional disorder metaphors, students were able to develop a more comprehensive understanding of these complex concepts.

1. Integration of Macroscopic and Microscopic Approaches: Teachers should consider incorporating explanations of macroscopic and microscopic thermodynamic concepts in their curriculum. This dual approach helps students to see the connection between different levels of analysis and promotes a deeper understanding of the subject matter.
2. Emphasis on Energy-Based Explanations: Replacing the traditional "disorder" metaphor with energy-based explanations can help reduce conceptual confusion. This study supports energy dispersion and the probabilistic nature of entropy as more effective frameworks for teaching these concepts.
3. Use of Interactive and Experimental Activities: The success of the Tripod Approach suggests that interactive and experimental activities play a crucial role in enhancing students' conceptual understanding. Teachers should incorporate hands-on experiments and discussions that allow students to actively explore and internalize thermodynamic principles.

6.2. Future Research Directions

While this study has provided valuable insights into the effectiveness of the Tripod Approach, there are several areas where further research is needed:

1. Longitudinal Studies: Future research should consider longitudinal studies to track the long-term retention of thermodynamic concepts taught using the Tripod Approach. Understanding how well students retain and apply these concepts over time can provide deeper insights into the approach's efficacy.

2. Diverse Educational Settings: This study was conducted with high school students in a specific educational context. Future research should explore the applicability and effectiveness of the Tripod Approach in diverse educational settings, including different grade levels and types of schools (e.g., public vs. private).

3. Comparative Studies: Comparative studies involving other innovative teaching methods for thermodynamics can help identify the most effective strategies. Comparing the Tripod Approach with other pedagogical models can provide a broader perspective on best practices in science education.

4. Cognitive and Affective Outcomes: Investigating the impact of the Tripod Approach on students' cognitive and affective outcomes, such as critical thinking skills, motivation, and attitudes toward science, can provide a more comprehensive understanding of its benefits.

5. Teacher Training: Future research should also focus on the professional development of teachers. Investigating how to effectively train teachers to implement the Tripod Approach and other innovative teaching methods can help scale these practices across educational systems.

In conclusion, the Tripod Approach offers a promising framework for teaching thermodynamic concepts by integrating macroscopic and microscopic perspectives and focusing on energy-based explanations. This study contributes to the ongoing efforts to enhance science education and improve students' conceptual understanding by addressing the pedagogical implications and exploring future research directions.

References

Abraham, M. R., Williamson, V. M., & Westbrook, S. L. (1994). A cross-age study of the understanding of five chemistry concepts. *Journal of Research in Science Teaching*, 31(2), 147–165.

Adomaitis, S., & Meštrović, J. (2020). Teaching Thermodynamics: Concepts, Approaches, and Student Difficulties. International Journal of Science Education, 42(12), 2013-2029.

Akbulut & Altun. (2020). An Integrated Perspective on the Concept of Entropy in Science Education and the Effect of the Tripod Approach Developed in This Context on the Level of Understanding of High School Students. Unpublished Doctoral Thesis. Gazi University, Ankara (Turkey).

Akbulut, F., & Altun, Y. (2020). A Holistic Approach to Entropy in Science Education. International Online Journal of Education and Teaching, 7(4), 1913-1932.

Baierlein, R. (1994). *Thermal Physics.* Cambridge University Press.

Boltzmann, L. (1898). Lectures on Gas Theory. University of California Press.

Brooks, G. P., & Johanson, G. A. (2003). TAP: Test Analysis Program [Computer software].

Carson, J., & Watson, J. R. (2002). Development of a scale to measure knowledge and attitudes toward environmental issues. Journal of Environmental Education, 33(4), 28–35.

Casulleras, J. (1991). Misconceptions in thermodynamics. *International Journal of Science Education*, 13(3), 259-268. https://doi.org/10.1080/0950069910130303

Clausius, R. (1865). The Mechanical Theory of Heat: With Its Applications to the Steam-engine and to Physical Properties of Bodies. J. van Voorst.

Clausius, R. (1867). The Mechanical Theory of Heat: With Its Applications to the Steam-engine and to Physical Properties of Bodies. J. van Voorst.

Cochran, W. D. (2005). The main problem in teaching thermodynamics. Journal of Chemical Education, 82(8), 1187-1190.

Creswell, J. W. (2014). A concise introduction to mixed methods research. Thousand Oaks, CA: SAGE

Creswell, J. W., & Plano Clark, V. L. (2010). Designing and Conducting Mixed Methods Research. SAGE Publications.

Dincer, I., & Cengel, Y. (2001). Energy, entropy and exergy concepts and their roles in thermal engineering. Entropy, 3(3), 116-149.

Haglund, J. (2017). Good use of a 'bad ' metaphor. Science & Education, 26(3-4), pp. 205–214. https://doi.org/10.1007/s11191-017-9892-4

Haglund, J., Andersson, S., & Elmgren, M. (2015). Different senses of entropy—Implications for education. Entropy, 17(3), 124-148.

Haglund, J., Andersson, S., & Elmgren, M. (2016). Language aspects of engineering students' view of entropy. Chemistry Education Research and Practice, 17(3), 489-508.

Haglund, J., Jeppsson, F., & Strömdahl, H. (2010). Different senses of entropy in thermodynamics—Implications for teaching. Entropy, 12(3), 490-515.

Ishida, M., & Chuang, C. Y. (1997). Introductory chemical thermodynamics: The concept of entropy. Journal of Chemical Education, 74(8), 985–988.

Johnstone, A. H., MacDonald, J. J., & Webb, G. (1977). Misconceptions in school thermodynamics. Physics Education, 12(4), 248–251.

Jones, J. B. & Dugan, R. E. (2003). Mühendislik termodinamiği. İstanbul: Beta.

Kesidou, S., & Duit, R. (1993). Students' conceptions of the second law of thermodynamics: An interpretive study. Journal of Research in Science Teaching, 30(1), 85–106.

Kozliak, E. (2004). The second law of thermodynamics: A new approach. Journal of Chemical Education, 81(12), 1757-1763.

Lambert, F. L. (2002). Disorder—A cracked crutch for supporting entropy discussions. Journal of Chemical Education, 79(2), 187–188.

Lambert, F. L. (2002b). Entropy is simple, qualitatively. Journal of Chemical Education, 79(10), 1241–1246. https://doi.org/10.1021/ed079p1241

Lambert, F. L. (2011). The conceptual meaning of thermodynamic entropy in the 21st century. International Research Journal of Pure and Applied Chemistry, 1(3), 65–68.

Loverude, M. E. (2002). Student understanding of basic probability concepts in an upper-division thermal physics course. American Journal of Physics, 70(2), 126–135.

Meltzer, D. E. (2004). Investigation of students' reasoning regarding heat, work, and the first law of thermodynamics in an introductory calculus-based general physics course. American Journal of Physics, 72(11), 1432-1446.

Miles, M. B., & Huberman, A. M. (1994). *Qualitative data analysis: An expanded sourcebook* (2nd ed.). SAGE.

Patron, J. (1997). Thermodynamics and its applications in engineering. Journal of Engineering Education, 86(1), 19–24.

Pinto Casulleras, J. (1991). The importance of the concept of internal energy in teaching thermodynamics. European Journal of Physics, 12(4), 240-243.

Sözbilir, M. (2001). A review of selected literature on students' misconceptions of heat and temperature. Boğaziçi University Journal of Education, 18(2), 131–148.

Sözbilir, M. (2007). First-year Turkish science undergraduates' understanding of thermodynamics and kinetic theory concepts. Chemistry Education Research and Practice, 8(2), 220–227.

Styer, D. F. (2000). Insight into entropy. American Journal of Physics, 68(12), 1090–1096.

Thomas P. L. and Schwenz R. W., (1998), College physical chemistry students' conceptions of equilibrium and fundamental thermodynamics, J. Res. Sci. Teach., 35(10), 1151–1160

Thompson, E., & Bennett, J. (2021). Exploring students' conceptions of the second law of thermodynamics: Teaching implications. Physical Review Physics Education Research, 17(2), 020114.

Wei, B., Sözbilir, M., & Ye, H. (2014). Teaching and learning chemical thermodynamics in university physical chemistry: A review of literature. Chemistry Education Research and