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Impact of STEM on Primary School Students' 21st Century Skills, NOS, and Learning Experiences*

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Abstract

This study examines the influence of STEM activities on fourth-grade students' 21st-century skills, their understanding of the nature of science (NOS), and their overall learning experiences. The research was conducted during the autumn term of the 2021–2022 academic year at a public primary school with a relatively low socioeconomic status. Over six weeks, STEM activities were integrated into the "Earth's Crust and the Movements of Our Earth" unit in the Science curriculum. A mixed-method approach was employed, encompassing a quasi-experimental pretest-posttest control group design for the quantitative phase and a case study approach for the qualitative phase. The sample included 35 fourth-grade students. Data were obtained using the "21st Century Learning and Innovation Skills Scale," the "Ideas About the Nature of Science Scale," and unstructured observation notes. The findings indicated statistically significant improvements in the experimental group's 21st-century skills, particularly creativity, innovation, critical thinking, and problem-solving. Moreover, the activities fostered enhanced cooperation and communication skills. Based on post-test results, the student's understanding of the NOS also improved significantly. Qualitative analysis of teacher observation notes supported these outcomes, showing heightened student engagement, enjoyment, and active participation. Students produced more creative and reflective responses to scientific concepts, while their collaborative and communicative competencies were notably strengthened. In sum, STEM activities embedded within the 5E teaching model enriched the learning process by promoting scientific curiosity, critical thinking, and sustained motivation. Students' requests for similar activities in other courses further underscored these interventions' positive impact and enduring appeal.

Keywords: 21st century skills, learning experiences, nature of science (NOS), primary school students, STEM education

1. Introduction

Today, with rapid technological advancements, the rise of artificial intelligence, and the impact of digitalization, the Fourth Industrial Revolution is unfolding (Turan, 2018). This process underscores the growing importance of individuals' ability to adapt to rapidly changing economic, technological, and social conditions. In response, educational reforms are being implemented to prepare individuals for the demands of the 21st-century economy (National Research Council [NRC], 2012; Next Generation Science Standards [NGSS], 2013). The direct link between these reforms and economic success is evident in international assessments (Organization for Economic

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Co-operation and Development [OECD], 2010). For instance, countries such as South Korea, China, and Japan have enhanced their economic performance through educational reforms.

In modern business and social life, individuals must think creatively and critically, collaborate effectively, use technology proficiently, develop practical solutions to everyday problems, manage information efficiently, and maintain productivity to lead a successful life (TUSIAD, 2014). These abilities, often referred to as 21st-century skills (Partnership for 21st Century Learning [P21], 2009; Yaşar, 2021), are essential for adapting to the rapidly evolving landscape of science, technology, and industry (Keleşoğlu & Kalaycı, 2017). Over the past decade, numerous studies have aimed to identify the life, career, and learning skills necessary in the 21st century (Ananiadou & Claro, 2009; Beers, 2011; Bybee, 2009; P21, 2009).

Cultivating proficiency in science, technology, engineering, and mathematics (STEM) has emerged as a critical educational priority (Bybee, 2010; NRC, 2012). Uluyol and Eryılmaz (2015) categorized 21st-century skills as problem-solving, communication, cooperation, accessing scientific knowledge, evaluating information through technology, and demonstrating responsibility. Sen, Ay and Kiray (2018) emphasized engineering-based collaboration, design, creativity, innovation, and digital literacy competencies. Beers (2011) highlighted essential skills in knowledge management, life skills, communication, career development, problem-solving, cultural awareness, and critical thinking. While definitions and categories vary, the broad consensus is that these skills equip individuals with practical competencies for a knowledge-based, technology-driven, and economically oriented society (OECD, 2012; Trilling & Fadel, 2009; Wagner, 2008). Critical thinking, creativity, collaboration, and problem-solving are frequently emphasized across different frameworks (Belet-Boyacı & Güner-Özer, 2019). These skills are also fundamental for adapting to emerging professions shaped by rapid technological changes, many of which align with STEM careers (Langdon, Mckittrick, Beede, Khan, & Doms, 2011). STEM education thus aims to equip individuals with these competencies, enabling students to research, develop, and analyze information to address real-world problems (Beers, 2011).

With its dynamic and evolving nature, science permeates all aspects of life. Due to its expansive scope, defining science can be challenging. The Turkish Language Association (2022) defines *science* as “organized knowledge that selects a portion of the universe or events as its subject and seeks to draw conclusions using methods based on experimentation and reality.” Science is characterized by rationality and encompasses various branches, including processes for understanding and interpreting data (Hastürk, 2017).

Given the increasing importance of science, understanding scientific knowledge and the nature of science (NOS) has become critical. Turkey’s curriculum reforms in 2005 aimed to enhance students’ understanding of NOS and foster scientific literacy (MoNE, 2005). The concept of NOS includes the framework of science, the organization of scientific research, and the development of scientific knowledge. It is commonly defined as the characteristics of scientific knowledge and the values inherent in its development (Lederman & Zeidler, 1987). It also refers to understanding how knowledge is produced, evolves, and can be reused (MoNE, 2013).

The literature suggests a significant relationship between STEM and NOS. STEM inherently reflects the nature of science, mainly through its interdisciplinary approach (Ozan & Uluçınar-Sağır, 2020). Koştur (2017) emphasized that STEM activities require students to think like engineers or scientists, with NOS as a foundational component of STEM education. Research trends in STEM studies focus on secondary school students, with attitudes and achievements frequently examined variables (Ecevit, Yıldız, & Balcı, 2022). However, there is limited research on STEM activities at the primary school level, especially regarding NOS (Çalışkan & Okuşluk, 2021).

This study contributes to the literature by addressing these gaps and providing practical tools for educators and researchers, such as detailed lesson plans (Appendix 1). Its significance lies in exploring the effects of STEM activities, implemented through the 5E learning model, on primary school students' 21st-century skills and NOS thinking. While related studies have investigated these skills, few focus on the primary level. This research offers valuable insights to guide teachers and researchers, including lesson plans, sample activities, and student feedback.

Research Questions

This study examines the effects of STEM activities on students' 21st-century skills and NOS thinking. The main research questions are:

1. Do STEM activities in science courses enhance primary school students' 21st-century learning and innovation skills?
2. Do STEM activities in science courses improve primary school students' understanding of the nature of science?
3. What are the contributions of STEM activities to primary school students' learning experiences?

2. Method

2.1. Research Model

This study employed a mixed-method research approach combining quantitative and qualitative methodologies to examine the effects of STEM activities on fourth-grade primary school students' 21st-century skills and their understanding of the nature of science (NOS). The quantitative component of the study utilized a quasi-experimental design with a pretest-posttest control group (Karasar, 2004), while the qualitative component adopted a case study design (Yıldırım & Şimşek, 2021).

An embedded mixed-method research design was chosen to investigate students' NOS perspectives and their learning experiences during STEM activities. In this approach, the primary quantitative method addresses the main research questions, while the qualitative method provides complementary insights to explain specific aspects of the data in depth (Creswell & Plano Clark, 2007).

The quantitative dimension, as the main component of the research, employed a pretest-posttest control group quasi-experimental design (Karasar, 2004). Participants were divided into experimental and control groups: STEM activities were implemented for the experimental group, while traditional teaching methods were applied to the control group. Quantitative data were collected using scales measuring 21st-century skills and students' NOS perspectives. These scales were administered as pretests and posttests to evaluate the impact of STEM activities on students' development in these areas.

The qualitative dimension provided a supportive perspective to enrich the research findings. In this dimension, a case study design was employed to explore students' experiences and the effects of STEM activities in depth (Yıldırım & Şimşek, 2021). Case studies focus on detailed examinations of individuals or groups within specific contexts. In this study, unstructured observation notes were collected by the teacher to document the impact of STEM activities on students' learning experiences. These observations occurred naturally during classroom STEM activities, capturing students' behaviors, emotional responses, and overall engagement.

2.2. Study Group

The study group comprised fourth-grade students attending a public school in the central district of Düzce province during the fall semester of the 2021–2022 academic year. A total of 35 students participated in the quantitative component of the study, divided into experimental and control groups. Among these participants, 20 were female, and 15 were male. The experimental group included nine females and six male students, while the control group consisted of eleven female and nine male students.

For the qualitative component, data were collected exclusively from the experimental group to explore their learning experiences during the STEM activities. Observations focused on students' engagement and responses to the activities throughout the implementation process.

2.3. Equivalence of the Groups

To ensure the comparability of the experimental and control groups, a t-test was conducted to analyze their prior science achievement scores, obtained from the e-school system. The average science achievement score for the experimental group was 2.73, while the control group's average score was 2.65. Statistical analysis [$t(33) = 0.512$, $p > 0.05$] revealed no significant difference between the groups in terms of prior science achievement. Thus, it was determined that the experimental and control groups were equivalent with regard to their initial levels of science achievement, ensuring a fair comparison of the impact of STEM activities.

2.4. Data Collection Tools

2.4.1. *Quantitative Data Collection Instruments*

Since the study was conducted with fourth-grade primary school students, the '21st Century Learning and Renewal Skills Scale' developed by Boyacı and Atalay (2016) was employed. In their reliability study conducted with 609 fourth-grade students during the 2014–2015 academic year, the overall reliability coefficient of the scale was calculated as .95. The reliability values for the sub-dimensions were as follows: creativity and renewal (.95), critical thinking and problem-solving (.94), and cooperation and communication skills (.89). Prior to this study, a reliability analysis was conducted with 123 fourth-grade students, yielding reliability values of .87, .75, .67, and .71 for the respective sub-dimensions. According to Büyüköztürk et al. (2010), these values indicate that the scale demonstrates acceptable reliability.

The 'Students' Ideas about Nature of Science (SINOS)' scale, originally developed by Chen et al. (2013) and adapted into Turkish by Cansız et al. (2017), was also used in this study. The Turkish version of the scale comprises seven sub-dimensions: theory-ladenness and subjectivity, creativity and imagination, changeability, durability, consistency and objectivity, science for girls, and science for boys. In its adaptation study, the scale was administered to 380 secondary school students and reported a reliability value of .85 (Cansız et al., 2017). Since the original study group consisted of secondary school students, modifications were made to adapt the scale for primary school students. These adaptations included converting the scale into a three-point Likert-type format based on expert consultations and obtaining the necessary permissions. Additionally, certain sub-dimensions, such as theory-ladenness and subjectivity, creativity and imagination, and consistency and objectivity, were excluded to better align with the developmental level of primary school students. Following these adjustments, the adapted version of the scale consisted of 14 items. In a reliability analysis conducted with 64 primary school students, the revised scale yielded a reliability coefficient of .69, indicating acceptable reliability for this study.

2.4.2. *Qualitative Data Collection Instruments*

In this study, unstructured observation notes, taken by the teacher served as the qualitative data collection tool. These notes documented the behaviors, impressions, and teacher-student interactions observed in the experimental group during their participation in STEM activities. After each lesson, the teacher recorded detailed observations regarding students' responses, levels of engagement, and collaboration throughout the activities. The purpose of these observations was to provide a comprehensive understanding of the impact of STEM activities on students' learning experiences and the overall process. The collected data were analyzed using thematic analysis, which allowed for a deeper exploration of the effects of STEM activities on students' engagement, collaboration, and learning outcomes.

2.5. Implementation Process

The researcher developed the lesson plans and activities used in this study, incorporating expert opinions at every stage of the preparation process. The activities were carefully designed to align with the primary school students' developmental level and the study's objectives. The lesson plans were structured around the 'Earth's Crust and the Movements of Our Earth' unit within the fourth-grade Science curriculum. STEM activities were integrated into the lessons and implemented over eight weeks to ensure alignment with the curriculum and the study's goals.

Table 1

Implementation Process by Weeks

Weeks	Lesson Plan	Activities	Steps of Activities
Week 1		Pre-Test	
Week 2	1.Lesson Plan	Activity 1: Rock Cards	Explore
		Activity 2: Rock Investigation	Explain
		Activity 3: Stone Collecting	Elaborate
Week 3	2.Lesson Plan	Activity 4: Paleontologist Task Fossils	Elaborate
Week 4	3.Lesson Plan	Activity 5: Travelling to Space	Elaborate
Week 5	4.Lesson Plan	Activity 6: Sundial	Elaborate
Week 6	5.Lesson Plan	Activity 7: Building my own Satellite	Explain
Week 7	6. Lesson Plan	Activity 8: Landing on Mars	Elaborate
Week 8		Post-Test	

In the control group, lessons were conducted using a teacher-centered approach, where the teacher primarily assumed the role of a lecturer. The instruction predominantly relied on the question-and-answer technique, and a world model along with a flashlight were used as instructional tools to support the unit content. Lessons were structured around the textbook commonly used in schools, with students expected to take notes on key points as directed by the teacher. At the end of each topic, tests were administered to evaluate students' understanding and retention of the material.

2.6. Data Analysis

2.6.1. *Analysis of Quantitative Data*

Quantitative data obtained from the 21st Century Learning and Renewal Skills Scale were analyzed using dependent and independent samples t-tests, as the data satisfied the assumptions of normality ($p > .05$) and homogeneity ($p > .05$). In contrast, data collected using the Ideas About the Nature of Science Scale did not meet the assumption of normality ($p < .05$). Consequently, non-parametric tests, including the Mann-Whitney U test and the Wilcoxon Signed Rank Test, were employed for analysis.

2.6.2. *Analysis of Qualitative Data*

Qualitative data collected through teacher observation notes during STEM activities were analyzed using thematic content analysis to understand their impact on students' learning experiences. After the coding process, the data were organized into sub-categories, categories, and main themes. To enhance the reliability of the analysis, 10% of the data was independently coded by two researchers, achieving an inter-coder agreement rate of 77%. This calculation followed the reliability formula recommended by Miles and Huberman (1994). Relationships among the derived themes were further examined to develop a comprehensive perspective on the learning process.

2.7. Ethics Committee Permission

All procedures in this research complied with the principles outlined in the Directive on Scientific Research and Publication Ethics of Higher Education Institutions. Ethical approval for the study was obtained from the Düzce University Graduate Education Institute Ethics Committee, with the decision dated 30.09.2021 and numbered 2021-231.

3. Findings

3.1. Findings Related to 21st Century Learning and Renewal Skills

The 21st Century Learning and Renewal Skills levels of students in the experimental and control groups were compared using a t-test. The pretest mean score for the experimental group was 2.34, while the control group had a pretest mean score of 2.31. The analysis results [$t(33) = 0.336$, $p > 0.05$] indicated no statistically significant difference between the groups, suggesting that both groups were at a comparable level in terms of 21st-century skills prior to the intervention.

Table 3 presents the results of the t-test examining the significance of differences between the posttest scores of the experimental and control group students on the '21st Century Learning and Renewal Skills Scale'.

Table 3

21st Century Learning and Renewal Skills Scale Intergroup Posttest T-Test Results

Dimensions	Group	N	X	SS	sd	t	p
21st Century Learning and Renewal Skills Scale	Experiment	15	*2.49*	.189	33	3.387	*.002**
	Control	20	2.28	.169			
Creativity and Renewal Sub-dimension	Experiment	15	*2.51*	.184	33	4.031	*.000**
	Control	20	2.28	.158			
Critical Thinking and Problem Solving Sub-dimension	Experiment	15	*2.37*	.224	33	2.716	*.046**
	Control	20	2.22	.269			
Cooperation and Communication Sub-dimension	Experiment	15	*2.64*	.263	33	2.015	.052
	Control	20	2.62	.242			

The mean posttest score of the experimental group students on the overall 21st Century Learning and Innovation Skills Scale ($\bar{X}$posttest = 2.49) was statistically significantly higher than the mean score of the control group students ($\bar{X}$posttest = 2.28). The t-test analysis indicated that this difference was significant in favor of the experimental group [$t(33) = 3.387$, $p < .05$].

In the Creativity and Innovation sub-dimension, the mean posttest score of the students in the experimental group ($\bar{X}$posttest = 2.51) was statistically significantly higher than the mean score of the students in the control group ($\bar{X}$posttest = 2.28) [$t(33) = 4.031$, $p < .05$].

In the Critical Thinking and Problem-Solving sub-dimension, the mean posttest scores of the students in the experimental group ($\bar{X}$posttest = 2.37) were also statistically significantly higher than those of the control group ($\bar{X}$posttest = 2.22) [$t(33) = 2.716$, $p < .05$].

In the Cooperation and Communication subdimension, the mean posttest scores of both the experimental ($\bar{X}$posttest = 2.64) and control ($\bar{X}$posttest= 2.62) group students were higher than those in other subdimensions. However, the activities did not have a statistically significant effect on improving the students' cooperation and communication skills [$t(33) = 2.015$, $p > .05$].

3.2. Findings Related to Thoughts on the Nature of Science

Since the scale scores of the students in the experimental and control groups did not follow a normal distribution, they were analyzed using the Mann-Whitney U test. The comparison of the pretest rank averages [$U(N_{exp} = 15, N_{control} = 20) = 93.500$, $z = -1.899$, $p > .05$] indicated no statistically significant difference between the groups. This result suggests that the students in the experimental and control groups were similar in terms of their initial thoughts on the nature of science.

The change in the posttest scores of the students in both groups, with respect to their thoughts on the nature of science, was also evaluated using the Mann-Whitney U test, and the results are presented in Table 4.

Table 4

Posttest Mann-Whitney U Test Results of Thoughts on the Nature of Science Scale Between Groups

Group	N	Posttest X	Rank Mean	Row Total	U	p
Experiment	15	2.42	21.63	324.5	95.500	.067
Control	20	2.26	15.28	305.5		

The mean posttest score of the experimental group students ($\bar{X}_{posttest} = 2.42$) was higher than the mean score of the control group students ($\bar{X}_{posttest} = 2.26$). However, the results of the Mann-Whitney U test indicate that this difference is not statistically significant [$U(N_{exp} = 15, N_{control} = 20) = 95.500$, $z = -1.829$, $p > .05$].

3.3. Contributions of STEM Applications to Students' Learning Experiences

Teacher observation notes were recorded in an unstructured format to document students' learning experiences during STEM activities in detail. For instance, notes were taken on students' engagement, prior knowledge levels, curiosity, and peer discussions on topics like the shape of the Earth, space, and rocket design. These observations reflect how students think, learn, and engage in discussions in a natural classroom setting.

To minimize potential bias, the teacher adopted an interactive yet non-intrusive observer role, maintaining the notes in a format that aimed to objectively capture student behaviors and interactions.

When the teacher observation notes were systematically analyzed, the emerging themes, categories, and subcategories are presented as a schema in Figure 1.

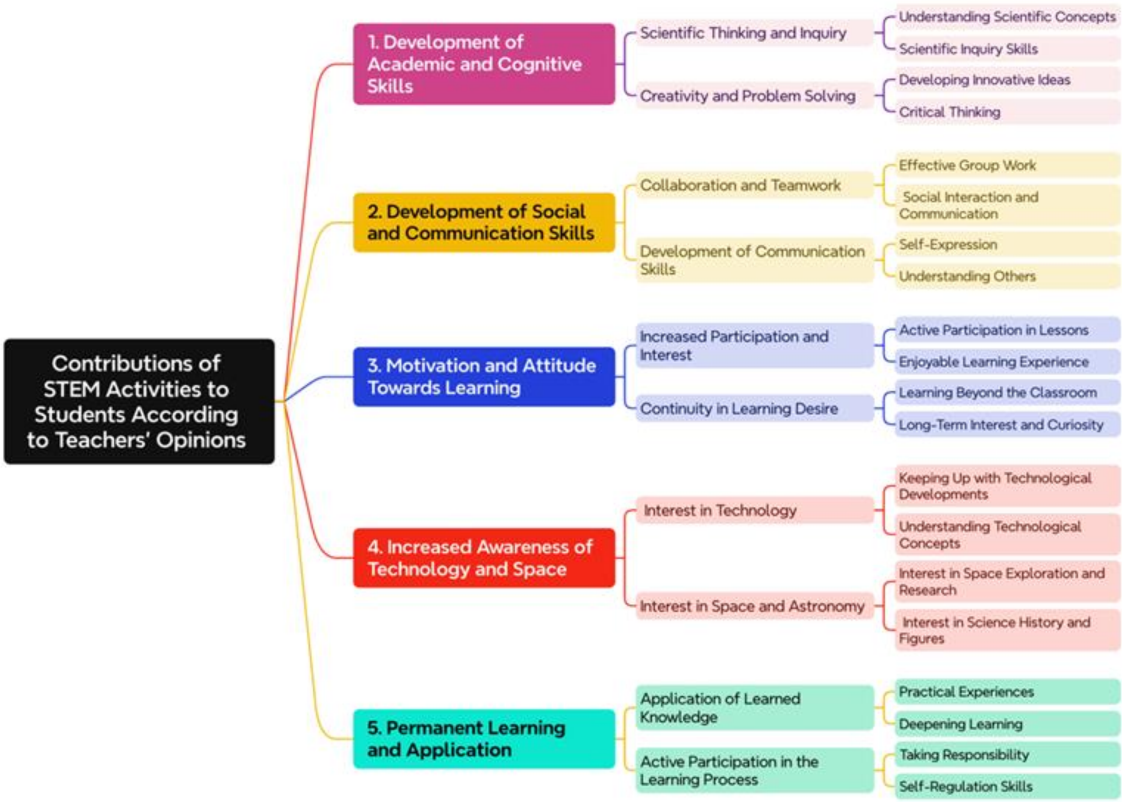

Figure 1. *Contributions of STEM Activities to Students' Learning Experiences: Schema of Themes, Categories, Subcategories*

The findings from teacher observation notes show that STEM activities have a multidimensional effect on students, manifesting in various areas such as cognitive development, social skills, motivation, and technology awareness.

3.3.1. Development of Academic and Cognitive Skills

STEM activities significantly enhanced students' scientific thinking, creativity, and problem-solving abilities. Students demonstrated a deeper understanding of scientific concepts, improved questioning skills, and engaged in creative thinking processes. These activities enabled students to integrate scientific knowledge into daily life rather than simply memorizing course content. For instance, students developed curiosity about fundamental scientific concepts, such as the shape of the Earth and the formation of day and night. They demonstrated their ability to question these ideas. Such scientific inquiry contributes to students' scientific literacy and critical thinking, supporting their future learning processes. Moreover, problem-solving and creativity skills improved as students participated in STEM activities. Through trial and error during experiments, students learned to generate innovative solutions and address practical problems, which increased their confidence in tackling scientific challenges. These enhancements in students' academic and cognitive skills are organized into categories, subcategories, and codes, as illustrated in Figure 2.

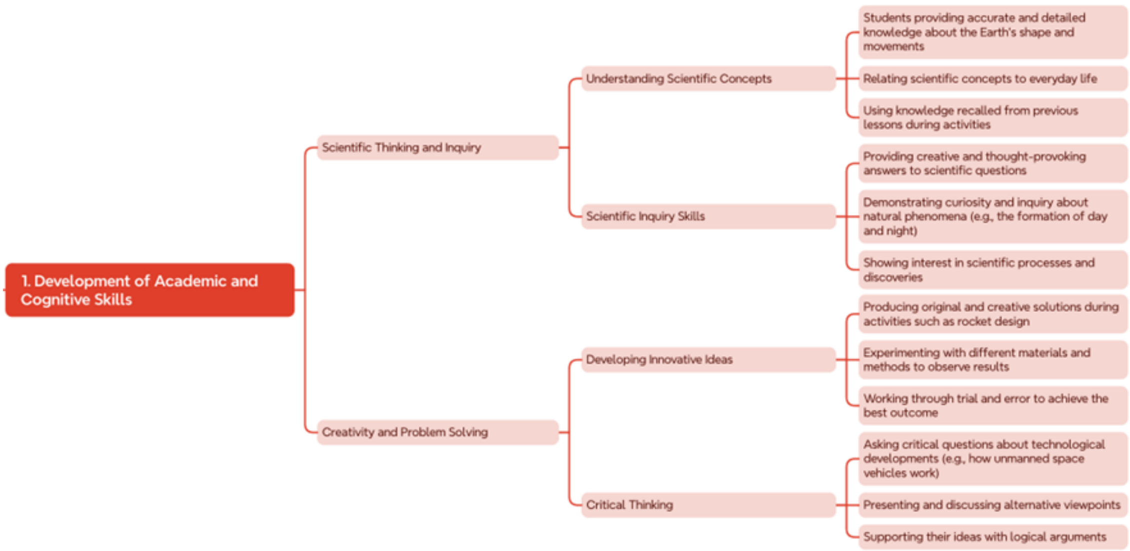

Figure 2. *Categories, Subcategories, and Codes Related to the "Development of Academic and Cognitive Skills" Theme*

3.3.2. Development of Social and Communication Skills

STEM activities also significantly enhanced students' social and communication skills. During group work, students collaborated to produce solutions, improving their communication and social interaction. They exchanged ideas, made decisions, and shared responsibilities within their groups to achieve common goals. This process strengthened their teamwork skills and taught them to take individual responsibility. These social skills enabled students to work more effectively, individually, and collaboratively, providing valuable experience for future projects requiring cooperation. Additionally, improved communication skills empowered students to express their ideas clearly while appreciating the perspectives of others. These observed enhancements in students' social and communication skills are organized into categories, subcategories, and codes, as depicted in Figure 3.

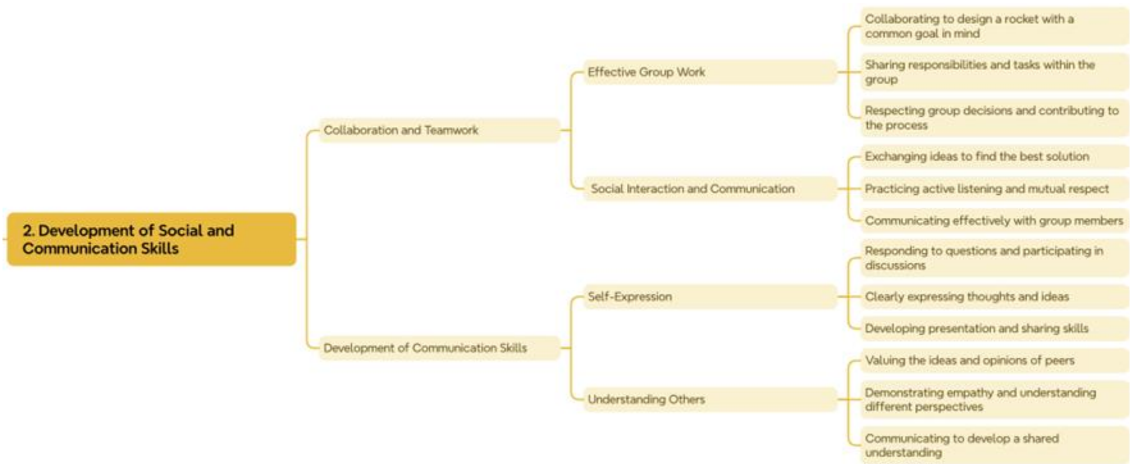

Figure 3. *Categories, Subcategories, and Codes Related to the "Development of Social and Communication Skills" Theme*

3.3.3. Motivation and Attitude Towards Learning

The impact of STEM activities on motivation was evident. Students' interest and participation in lessons increased, with previously disengaged students actively joining the activities. The fun and interactive learning environment fostered positive attitudes toward the subject and cultivated a more favorable perspective on the learning process. Students' willingness to learn outside the classroom also emerged as a long-term effect of STEM activities. Their eagerness to repeat experiments at home or bring objects (e.g., stones) into the classroom for examination demonstrates how the learning process extends beyond the classroom and leaves a lasting impact. Such behaviors maintain students' scientific curiosity and illustrate the sustainability of STEM-based learning. These observed improvements in students' motivation and attitudes towards learning are represented through the categories, subcategories, and codes presented in Figure 4.

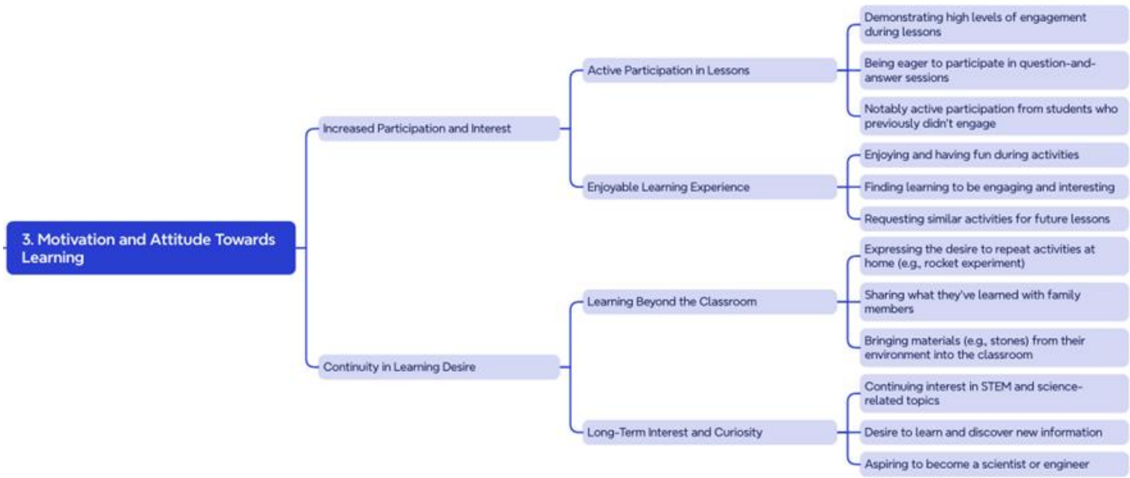

Figure 4. *Categories, Subcategories, and Codes Related to the "Motivation and Attitude Towards Learning" Theme*

3.3.4. Increased Technology and Space Awareness

STEM activities increased students' interest and awareness of technology and space-related topics. For example, their curiosity about Elon Musk's projects and space exploration suggests that STEM activities could inspire some students to pursue careers in these fields. This highlights how STEM activities enhance classroom learning and cultivate a lasting interest in technology and space sciences. This heightened awareness is evidenced by students' desire to learn about current scientific developments and their growing interest in scientific discoveries. Their questions about space exploration and technological advancements demonstrate that these activities deepen students' scientific thinking and increase their likelihood of pursuing careers in STEM-related fields. Figure 5 illustrates the categories, subcategories, and codes associated with the theme of "Increased Technology and Space Awareness," highlighting how STEM activities stimulate students' curiosity about technology and space-related topics, such as space exploration and current scientific advancements.

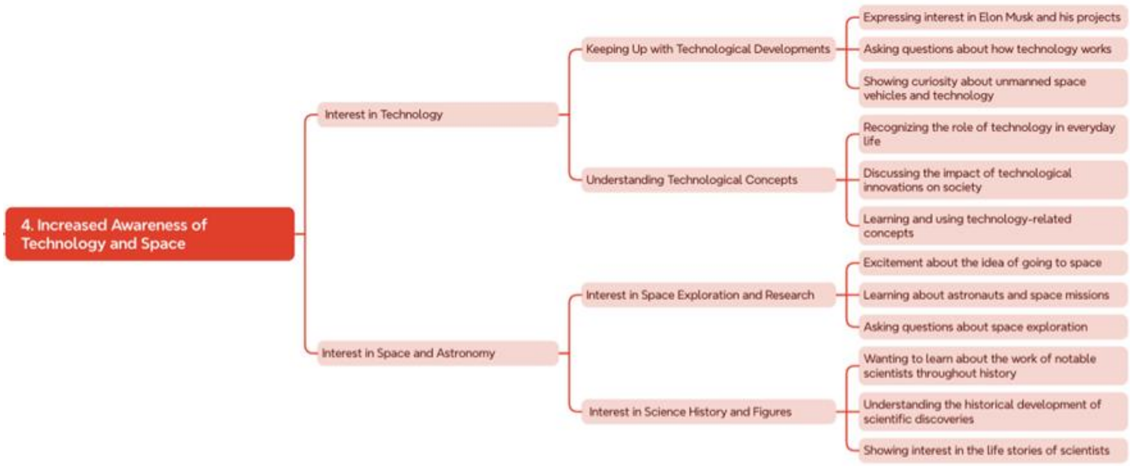

Figure 5. *Categories, Subcategories, and Codes Related to the "Increased Technology and Space Awareness" Theme*

3.3.5. Permanent Learning and Application

STEM activities also profoundly impacted permanent learning. The fact that students revisited and applied the knowledge gained during these activities at home and in daily life suggests that their learning was deepened and more enduring. This permanence indicates that STEM activities are not merely short-term knowledge acquisition exercises but provide students with long-term, practical learning experiences. Following these activities, students often conducted new experiments independently and took greater responsibility for their learning process. Figure 6 presents the categories, subcategories, and codes related to the theme of "Permanent Learning and Application," demonstrating how STEM activities contribute to long-lasting and practical learning experiences that extend beyond the classroom setting.

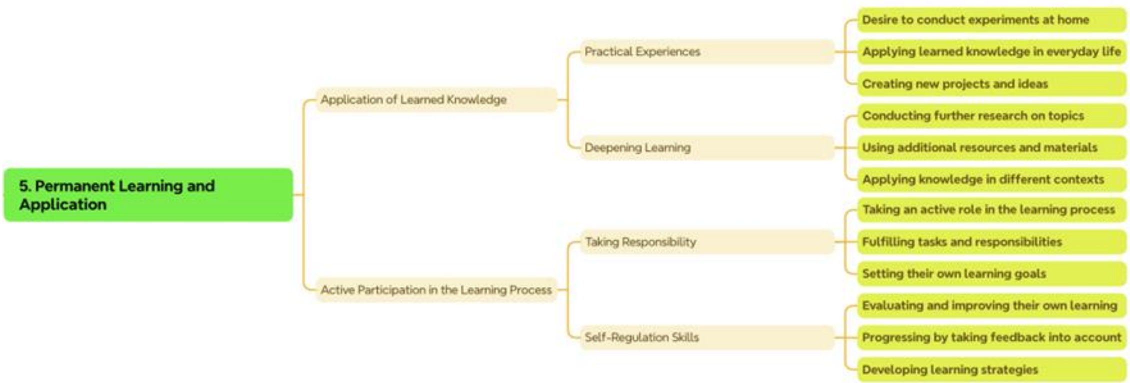

Figure 6. *Categories, Subcategories, and Codes Related to the "Permanent Learning and Application" Theme*

The findings show that STEM activities offer multifaceted benefits to students, fostering scientific thinking, problem-solving, social interaction, and technological awareness. STEM education enhances academic achievement and contributes to students' personal development by improving their social, communication, and motivational skills.

The lasting effects of these activities are reflected in students' positive attitudes toward learning, which extend beyond the classroom. STEM activities equip students with essential skills for advancement in scientific and technological fields while promoting sustained, impactful learning.

4. Conclusion and Discussion

This study evaluated the development of 21st-century skills, understanding of the nature of science (NOS), and learning experiences of fourth-grade primary school students. The effects of STEM applications, which incorporated topics from the 'Earth and Universe' unit in the experimental group and textbook-oriented teaching in the control group, were analyzed.

4.1. 21st-Century Skills

The first sub-problem examined the impact of STEM activities on students' 21st-century skills. Bybee (2010) emphasized that STEM practices enhance productivity and foster 21st-century skills. The results revealed significant differences between the experimental and control groups in favor of the experimental group, underscoring the effectiveness of STEM activities in developing these skills. Post-application analysis of the sub-dimensions of the 21st-century skills scale demonstrated significant improvements in creativity, innovation, critical thinking, and problem-solving among students in the experimental group. While no statistically significant differences were found for collaboration and communication skills, observation notes revealed that these skills were still developed during the STEM activities. Students demonstrated improved communication and a greater tendency to collaborate during group work. These findings align with the literature documenting the positive impact of STEM activities on collaboration and communication skills (Abernathy & Vineyard, 2001; Aydın & Karslı-Baydere, 2019; Dewaters & Powers, 2006; Hiğde, 2018; Karahan, Bilici, & Ünal, 2015; Khanlari, 2013; Morrison, 2006; Özçelik & Akgündüz, 2017; Şahin et al., 2014). Additionally, studies by Yavuz (2019), Capraro and Jones (2013), and Knezek et al. (2013) highlight STEM activities as effective tools for enhancing critical thinking, problem-solving, and creativity. Pekbay (2017) further emphasized the role of STEM activities in improving real-world problem-solving abilities. The results indicate that students in the experimental group outperformed the control group in creativity, innovation, critical thinking, and problem-solving. However, the lack of statistically significant improvement in collaboration and communication suggests that longer-term applications or alternative strategies may be needed to develop these skills further. These findings offer valuable guidance for teachers to effectively design and implement STEM education. The widespread and sustained application of STEM activities could contribute to the balanced development of critical thinking, problem-solving, collaboration, and communication skills.

4.2. Understanding of the Nature of Science (NOS)

The second sub-problem explored students' understanding of NOS. A significant increase was observed in the pretest-posttest scores of the experimental group, indicating that STEM activities contributed to a deeper understanding of NOS concepts and scientific thinking skills. In particular, students recognized that scientific knowledge is evidence-based and scientific processes are multidimensional, highlighting the age-appropriateness of STEM activities for fostering NOS comprehension. While the experimental group's post-test scores were higher than those of the control group, the difference was not statistically significant. This suggests that although STEM activities positively impact NOS understanding, the effect may not be substantial compared to textbook-based teaching. A literature review supports the positive effects of STEM activities on NOS understanding. For example, Bektaş (2011) found that activities designed using the 5E model significantly enhanced NOS comprehension among students. Similarly, Şık (2019) and Eroğlu (2018) documented positive contributions of STEM activities to NOS understanding at the middle and high school levels. Studies with pre-service teachers (Büber-Kılınç, 2021; Yıldırım et al., 2017) also confirmed similar findings. However, research specifically examining STEM's impact on NOS at the primary school level remains limited, indicating a need for further studies to deepen understanding of its effects on younger students.

4.3. Learning Experiences

Qualitative findings from teacher observation notes revealed that STEM activities had multifaceted and lasting effects on students. These activities enhanced scientific thinking, creativity, and problem-solving skills while fostering social interaction, cooperation, and communication. Increased participation and motivation were observed, with the enjoyable and interactive structure of STEM activities promoting positive attitudes toward learning. Additionally, students exhibited a growing interest in technology and space sciences, fostering long-term curiosity and engagement in these fields. This extended learning beyond the classroom and encouraged sustained interest in scientific exploration.

In conclusion, this study's findings suggest that STEM activities are an effective tool for developing 21st-century skills, understanding the nature of science, and enhancing overall learning experiences at the primary school level. STEM activities' positive contributions to both in-class and out-of-class learning processes underscore the necessity and importance of enriching educational programs with these activities.

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Ethics Committee Permission:

In this study, all rules stated in the 'Directive on Scientific Research and Publication Ethics of Higher Education Institutions' were followed. Ethical approval for this study was obtained from the Düzce University Graduate Education Institute Ethics Committee, with the decision dated 30.09.2021 and numbered 2021-231.