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A New Approach to Development of Students' Research Abilities in STEM Education

Yelmurat Dosymov [1], Esim Ergobek [1], Sherzod Ramankulov [1*], Almagul Ualikhan [1], Indira Usembayeva [1], Bakitzhan Kurbanbekov [1]

[1] *Khoja Akhmet Yassawi International Kazakh-Turkish University, Turkistan, Kazakhstan.*

Abstract

The study develops a modern concept of STEM (Science, Technology, Engineering, and Mathematics) education as an essential component for students' research abilities. The study's goal is to enhance students' research skills in STEM subjects by using ionization chambers as a tool for educational research. This aim emphasizes the study's novel use of ionization chambers to improve STEM students' practical skills and theoretical understanding. The research hypotheses were tested using quantitative experimental methods involving pre- and post-experiment assessments. Scientific articles were analyzed using key terms such as "ionization chamber," "STEM," and "research skills" from the Mendeley database to establish a theoretical foundation. A meta-analysis was conducted to elucidate the efficacy of the outcomes. An assessment involving 120 students from the Khoja Akhmet Yassawi International Kazakh-Turkish University was conducted to evaluate the influence on them, with favorable findings. Since both groups had the same dependent variable in control tasks, there was no significant difference before the trial ($t(118) = 0.7749$, $p > 0.05$). The dependent variable was reassessed after 15 weeks of training. Statistics show a significant improvement in the experimental group ($t(118) = 7.8335$, $p < 0.05$), showing that ionization chambers increased STEM students' research abilities. Using ionization chambers in the natural science curriculum may enhance students' research abilities and provide a more effective integration of theory and practice. Kazakhstan uses cutting-edge research tools like ionization chambers to cover STEM teaching gaps and boost student engagement and practical skills. The research recommends integrating these technologies into curricula and teacher training.

Keywords:

Research Abilities;

Students;

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1- Introduction

Instructing students in independent studies cultivates a passion for science and equips them with STEM academic pursuits [1], particularly in physical science courses where understanding abstract concepts such as atomic structure and radiation often requires experiential knowledge. STEM education addresses contemporary challenges and enhances student performance [2] through interdisciplinary integration. Utilizing ionization chambers, which are effective in detecting and quantifying ionizing radiation in physics, chemistry, and biology, can potentially bridge this knowledge gap by elucidating atomic events and facilitating the application of abstract scientific concepts in the laboratory. Empirical learning enhances STEM research competencies [3, 4] and critical thinking [5, 6]. However, compared to technology in education, the use of ionization chambers as educational tools has received less attention despite their potential to conduct scientific research while acquiring theoretical knowledge in STEM [7].

* **CONTACT**: sh.ramankulov.ayu.edu.kz@outlook.com

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This study investigates how ionization chambers can aid STEM students in developing research skills, addressing the necessity highlighted in STEM education research to provide students with real-world challenges to address using their theoretical knowledge [8]. By employing experimentation, observation, and the fabrication of model chambers, this approach can enhance students' comprehension of intricate processes, refine their research abilities, foster critical thinking and problem-solving, and enable the application of theoretical concepts in practical contexts. Furthermore, constructing a replica ionization chamber and observing its use in the laboratory helps to illustrate the real-world applicability of STEM principles, demonstrating how these instructional tools enhance student research. Ionization chambers are valuable for studying various types of radiation and their interactions and also serve as an important tool for online measurements, as evidenced by studies exploring their use in tritium-containing gas detection [9].

Ionization chambers are crucial in dosimetry for radiation therapy, as illustrated by ongoing efforts to standardize protocols for devices such as the MR-linac [10]. Research has explored magnetic field effects on chamber readings and the impact of air gaps in measurement setups, demonstrating the need for corrections to ensure accuracy [10]. Evaluation of various ionization chambers has shown that certain parallel plate designs are suitable for measuring depth-dose data in kilovolt X-rays with limited uncertainty [11]. Moreover, studies have examined the angular dependence of magnetic field correction coefficients in MRgRT systems, revealing a clear angular dependence of the dose response and highlighting the importance of chamber positioning relative to the magnetic field [12]. A study using a small-gap flat-parallel ionization chamber investigated charge multiplication, finding it independent of radiation quality for a given chamber, but chamber-dependent across different proton beams [13]. This highlights the effectiveness of the ionization chamber in explaining atomic phenomena to students and facilitating their mastery of scientific research methods, the combination of theoretical knowledge with practical skills, and a deeper understanding of complex physics.

Using STEM technology [14, 15] to teach ionizing cameras effectively developed students' research and engineering skills. This technology integrates both practical and theoretical physics education. Using STEM elements (science, technology, engineering, and mathematics) to interpret the principles of ionizing chambers helps students develop skills in device design, conduct experiments, and analyze scientific results. For example, by discussing the structure of an ionizing chamber using virtual or real models, exploring its principles, and conducting experiments, students can solve specific problems in physics and engineering. In addition, the ability to process data obtained using STEM technology using mathematical methods statistically analyzes the results and proves that the results increase [16]. This approach develops students' critical thinking and creative problem-solving skills, allowing them to acquire in-depth knowledge in physics and engineering sciences. STEM technology allows students to enhance their practical experience, increase their interest in the subject, and arouse motivation for future scientific research [17-19].

While STEM education has made notable strides in technology integration and hands-on activities, the existing literature reveals persistent limitations in adequately addressing abstract concepts in physical sciences, particularly with resources that translate to hands-on experience. For instance, Potkonjak et al. [20] highlighted the potential of virtual labs in enhancing understanding, but they often fail to provide a tangible experience vital for mastering topics such as radiation. Inquiry-based learning [21] encourages critical thinking but may lack structured experimentation. Although tailored curricula can boost engagement [22, 23], they often lack tools for radiation research and measurement. While digital tools offer promise in STEM [24, 25], some studies show a lack of a hands-on approach. Jiao et al. [26] highlighted the limitations of providing a mix of academic and practical knowledge. These studies lack the ability to be cost-effective and multi-purpose, similar to real-world applications. Khasawneh & Darawsheh [27] showed that even in the presence of makerspaces and 3D printing, they are only good for design thinking and innovation for a very small amount of time. Further expanding on the issues with virtual education, studies have also revealed a lack of peer-to-peer interaction with students, which impacts collaborative learning. While there is an advancement with the current STEM tools, none of these methods have a mix of all these factors and benefits, with the ability of the device to be used to test academic comprehension with the tool. In the realm of collaborative robotics as described by Demetroulis et al. [28], the focus is mainly on collaborative skills in an engineering environment, lacking the scientific aspect, and the tool lacks the combination of both aspects."

This literature indicates that despite advancements, practical skill development, particularly in radiation science, remains under addressed [29]. Virtual physics and inquiry-based methods may be good, but practical and hands-on teaching are underrepresented, particularly in resource-constrained settings. Therefore, the introduction of ionization chambers offers an opportunity to address practical experience and analytical considerations. By investigating the usefulness of ionization chambers, which combine theoretical learning and practical research, this study intends to contribute to the development of novel teaching tools that effectively close the gap between theory and practice, and improve research skills in STEM disciplines. Specifically, this study focuses on hands-on teaching and learning in settings lacking such tools, highlighting their cost-effectiveness and adaptability. Therefore, this study was conducted to answer the following questions:

- What is the effectiveness of understanding the principles of operation of ionizing chambers using STEM technology?
- How do visualization and modeling of the physical characteristics of ionizing chambers using STEM technology affect students?

To address this gap, this study aimed to evaluate the effectiveness of incorporating ionization chambers as a novel educational research tool in STEM education, specifically within the context of atomic physics. The primary objective was to demonstrate the potential of these chambers to enhance students' practical skills, critical thinking, and overall engagement in STEM fields. This research offers a cost-effective and adaptable method for bridging the gap between theory and practice in challenging STEM disciplines, with potential applications in a wide range of educational settings, particularly in resource-constrained environments such as Kazakhstan.

This paper is structured as follows. Section 2 provides the theoretical approaches that underpin the study and develops the research hypotheses. Section 3 details the materials and methods employed, including the research design, sample selection, and data-collection procedures. Section 4 presents the results of the quantitative analysis. Section 5 offers a detailed discussion of these findings in relation to the existing literature and analyzes the study's contributions to the body of knowledge. Finally, Section 6 concludes the paper by presenting the practical implications of this study, summarizing the key findings, and presenting the potential for future research in this area.

2- Theoretical Background and Hypothesis Development

2-1- Theoretical Approaches of the Study

This study is underpinned by several key learning theories that inform the design, implementation, and interpretation of findings related to the use of ionization chambers in STEM education. Constructivism, with its central tenet that learners actively construct knowledge through experience and interaction with their environment, plays a foundational role [30]. Students do not just passively receive knowledge, but instead actively link new data to pre-existing information and engage in productive activities. The focus on "doing" and "discovery" via experiences helps students' knowledge, instead of only memorizing lectures.

In this context, experiential learning theory emphasizes learning through direct experience and reflection. The theory's creator, Kolb, proposes a cycle of experience, reflection, concept formation, and experimentation. Thus, working with ionization chambers allows pupils to engage in this cycle [31]. They had physical experience interacting with the equipment. They studied these observations. They have created new principles based on their understanding and test theories through testing. Using real scientific tools helps STEM students to think critically and generate innovative ideas about physics in Kolb's experiential learning cycle.

Inquiry-based learning (IBL) is another theoretical framework that guides research. It helps students learn through questions, design experiments, and analyze data to draw results [32]. STEM education provides a framework that encourages students to ask questions and solve them. Students take charge of their education in learning, and build a better grasp.

2-2- STEM Education

Science, technology, engineering, and mathematics (or STEM) education emphasizes real-world applications and cross-disciplinary studies in a cohesive curriculum. This approach addresses complex global concerns including climate change, technological innovation, and sustainable development. However, STEM education may be challenging, particularly in under-resourced institutions. STEM programs frequently struggle because of inadequate teacher training, low student engagement, and restricted access to advanced instructional material. Ionization chambers and other hands-on STEM instruments are innovative techniques for addressing these challenges. These tools allow students to create experiments, collect data, and analyze results to apply classroom knowledge to real-world situations. This practical element improves understanding, analytical thinking, and problem-solving. These tools foster collaborative learning, which helps students to develop STEM-related interpersonal and communication skills. Despite these benefits, STEM education has been sluggish in its adoption of new technologies, particularly in developing countries. Expensive costs, inadequate facilities, and improper educational training persist. Policymakers, educators, and corporate leaders must collaborate to create STEM educational ecosystems that can endure these challenges. Public-private partnerships, curriculum modification, and teacher training programs may make STEM learning more accessible and beneficial for children in a changing environment.

2-3- Students' Research Abilities

STEM education emphasizes research skills, including critical thinking, hypothesis generation, experimental design, and data interpretation. These skills are crucial to academic success and job progress in STEM. Traditional classroom techniques emphasize memory and theory over practical experience and discourage students from acquiring these abilities. Ionization chambers and other research equipment in STEM programs may boost students' research skills. These materials allow students to test ideas, study real-world events, and draw conclusions. Students can monitor radiation levels and examine ionizing processes in ionization chambers to learn experimental physics. This practical strategy boosts the research and scientific understanding. Improved research skills improve students' academic and career performance. Through early investigation, the students developed the curious and imaginative mindset needed for STEM success. They learn to overcome challenging problems, adopt new technologies, and expand their 'expertise. Instruments, such as ionization chambers, help students prepare for today's STEM challenges by bridging theory and practice.

2-4- Evaluation of the Effectiveness of Using Ionization Chambers in STEM Education

Ionization chambers in STEM education represent a novel approach for improving traditional teaching methods. This advanced equipment measures ionizing radiation, enabling testing of theoretical notions. Integrating these technologies into STEM classes may provide immersive learning experiences and boost students' engagement. This study analyzes whether ionization chambers work by comparing their impacts with those of a curriculum without them. Users of ionization chambers are more engaged, practical, and academically successful. Ionization chambers may address STEM education's most significant issues, including students' motivation and practical experience. The evaluation process revealed key insights into the larger implications of adopting current technology in STEM instruction. The use of ionization chambers in academia may promote research and increase learning. Due to STEM education budget shortages, this cultural revolution is crucial in underdeveloped countries, such as Kazakhstan. By establishing their benefits, this study supports the inclusion of ionization chambers and other practical equipment for STEM teaching. The ionization chamber was a flat parallel chamber with a 25 mm diameter wide high-voltage electrode and an electrode (collector) with a diameter of approximately 18 mm. The ionization chamber has attracted the interest of many scientists and has become the foundation of important scientific research. With its help, the properties and effects of radiation can be studied, contributing to the development of atomic and nuclear physics.

STEM technology plays an important role in increasing the possibility of using an ionizing camera and providing access to it among students [33]. Due to several advantages of a large effective area for monitoring therapeutic radiation beams, there has been an increased demand for large-area parallel plate ionization chambers (PPIC) or large-area ionization chambers (LAIC) in recent years. In this study, the large effective area of the XY strip PPIC with dimensions of 345.44 × 345.44 mm² and 256 reading channels was investigated. The main results showed that the deviation in the detector response before calibration reached approximately 7% for the test PPIC unit, which is significantly higher than the proposed 1% (IAEA TRS-398) uniform response [34].

2-5- Hypothesis Development

Two hypotheses are formulated from the theoretical background, i.e.;

H_{01}:The use of ionization chambers as an educational research tool in the natural sciences does not significantly affect the effectiveness of STEM-based teaching methods, students' interest in the subject, or the development of practical skills.

H_{02}:If ionization chambers are taught within a STEM education methodology, students' mastery of the subject, practical skills, and interest in the natural sciences will significantly increase.

These hypotheses were tested on student performance to prove that ionization chambers are very effective in STEM education.

2-6- Research Model

This study used a systematic strategy to examine how ionization chambers affect students' research abilities, participation, and academic performance. This approach claims that ionization chambers directly affect students' ability to relate abstract concepts to practical experiments. This model depends on students' participation, practical skills, and academic achievement, and ionization chamber utilization is the independent variable. Ionization chambers may work better with well-trained instructors but less effectively with inadequate budgets. Thus, the model provided a complete overview of the study outcomes. In the research model, feedback loops were used to assess the long-term feasibility of the intervention. By measuring long-term objectives, such as students' STEM interests and advanced research skills, the technique ensures that the results are not limited to immediate advantages. This complete methodology emphasizes the study's distinctiveness and relevance, making it a valuable contribution to STEM education research.

STEM education is increasingly used to develop research skills. Studies have traditionally emphasized experiential learning to assist students in shifting from classroom theory to practice [35, 36]. Students must understand their interests and how they relate to constructing a well-rounded scientific inquiry skill set. Numerous studies have stressed incorporating real-world experiences into STEM curricula to engage students and promote critical thinking, problem-solving, and scientific inquiry [37, 38]. Technology helps students explore complex topics in a more interesting and applicable manner, which has boosted its use in STEM education [39].

Most studies agree that ionization chambers are vital for physics, chemistry, biology, and other research [40, 41]. The development of ionizing radiation detection and measurement tools has advanced several scientific fields. Despite their importance, ionization chambers have not been extensively studied for STEM education. Research shows that lab work improves students' understanding of abstract scientific topics [42-44]. Ionization chambers and other tools help students learn about radiation and atomic behavior by demonstrating theoretical concepts. Prajuabwan & Worapun [45] linked the ionization chamber used in STEM students' research skills. There have been studies on the benefits of lab-based learning [46, 47], but few have examined how ionization chambers can improve scientific research skills [48, 49].

STEM education research has focused on improving students' achievement. Technology in the classroom improves critical thinking and prepares students for careers in science, technology, engineering, and math [50]. Hands-on activities with scientific equipment help students to understand the' practical applicability of academic concepts. STEM education requires students to learn scientific facts, ask questions, evaluate evidence, and apply what should be learned. STEM education in a lab improves scientific literacy and understanding of complex subjects [51]. Ionization chambers and other technologies can assist students in improving their research skills. However, little research has been conducted on this topic. Due to this gap, STEM education should include further research on how ionization chambers improve scientific problem solving, data analysis, experimental design, and other practical research abilities. One lacuna in the literature is the lack of empirical research on ionization chambers as a STEM teaching tool. Few studies on radiation detectors in universities have focused on their research use rather than their impact on education [52, 53]. This study examines how ionization chambers improve student research and proves their efficacy in STEM classes to address these gaps. Ionization chambers in laboratory activities allow students to learn about radiation and atomic phenomena while practicing research methods, experimental design, and data analysis.

In conclusion, the literature praises STEM education and its use of technology and lab experiments, but few studies have examined ionization chambers in the context of improving students' research skills. To address this gap, this study examined how ionization chambers might teach STEM students complex physical processes and research methods. This study adds to the literature by assessing student survey responses and determining whether STEM classroom teaching tactics assist students in becoming independent researchers.

The study used constructivist learning theory, emphasizing how learners actively shape their knowledge and understanding via interactions with their surroundings and experiences [30]. Constructivism holds that hands-on activities that apply classroom knowledge are best for students to learn. STEM education connects theoretical knowledge with practical applications by encouraging student inquiry and problem-solving. The theoretical framework supports these goals. STEM students must understand scientific principles, conduct experiments, assess data, and form conclusions to make the constructivist approach more relevant. Furthermore, the study used experiential learning theory, which states that learning occurs when one acts, thinks, and makes sense of one's own experiences [31]. Ionization chambers can be used for STEM education in hands-on learning. Students use real-life scientific equipment, think critically, and generate new ideas regarding physical processes. Kolb's experiential learning cycle helps explain the' ionization chamber interactions of laboratory students [54]. This cycle includes concrete experience, contemplative observation, abstract conceptualization, and active experimentation. Students monitor the radiation and study the physical concepts in the ionization chamber through each phase. They actively utilize technology, critically evaluate their findings, build new conceptual understandings, and test their theories with other trials. This educational loop helps students to understand abstract scientific concepts and develop analytical, synthesis, and research skills.

Additionally, inquiry-based learning underpins this study. This technique allows students to learn independently by inquiring, discovering, and solving their problems. Since inquiry-based learning stimulates curiosity, engagement, and active participation, it involves questioning, designing experiments, gathering data, and assessing results [32]. STEM education trains future leaders to address complex real-world problems and this technique supports this goal. Ionization chambers in STEM lessons provide students with an actual scientific tool for inquiry-based learning that is relevant to their schoolwork and has real-world relevance. Inquiry-based learning, constructivism, and experiential learning are in line with STEM education trends, which emphasize the necessity for students to master both theoretical and practical research abilities. Ionization chambers are integrated into STEM courses to give students a hands-on inquiry-based approach to science and research. This theoretical view adds to the STEM education literature and illuminates how focused instructional tools can help students improve their research skills, bridge theory, and practice. This study aims to demonstrate that ionization chambers and other STEM education tools can increase students' research, critical thinking, and problem-solving skills.

3- Material and Methods

3-1- Research Methodology

The objective of our study' was to assess the efficacy of ionization chambers in' STEM educational research instruments. This study used a quantitative technique that included a meta-analysis, a survey, and an experimental design. The survey and experiment evaluated the impact of the ionization chamber on students' learning and research abilities, whereas the meta-analysis examined the literature on the effectiveness of STEM tools.

Scientific articles were analyzed during the research and the study was conducted. First, the key terms relevant to the research topic were selected. Using the keywords "ionization chamber," "natural sciences," "STEM," "ionization chamber prototype," and "research skills," research skills, scientific work were gathered from the Mendeley.com database.

We elaborate on the methodology and data collection as well as the data analysis methods used in this study. The methodology used in this study and the process of obtaining the findings are shown in Figure 1.

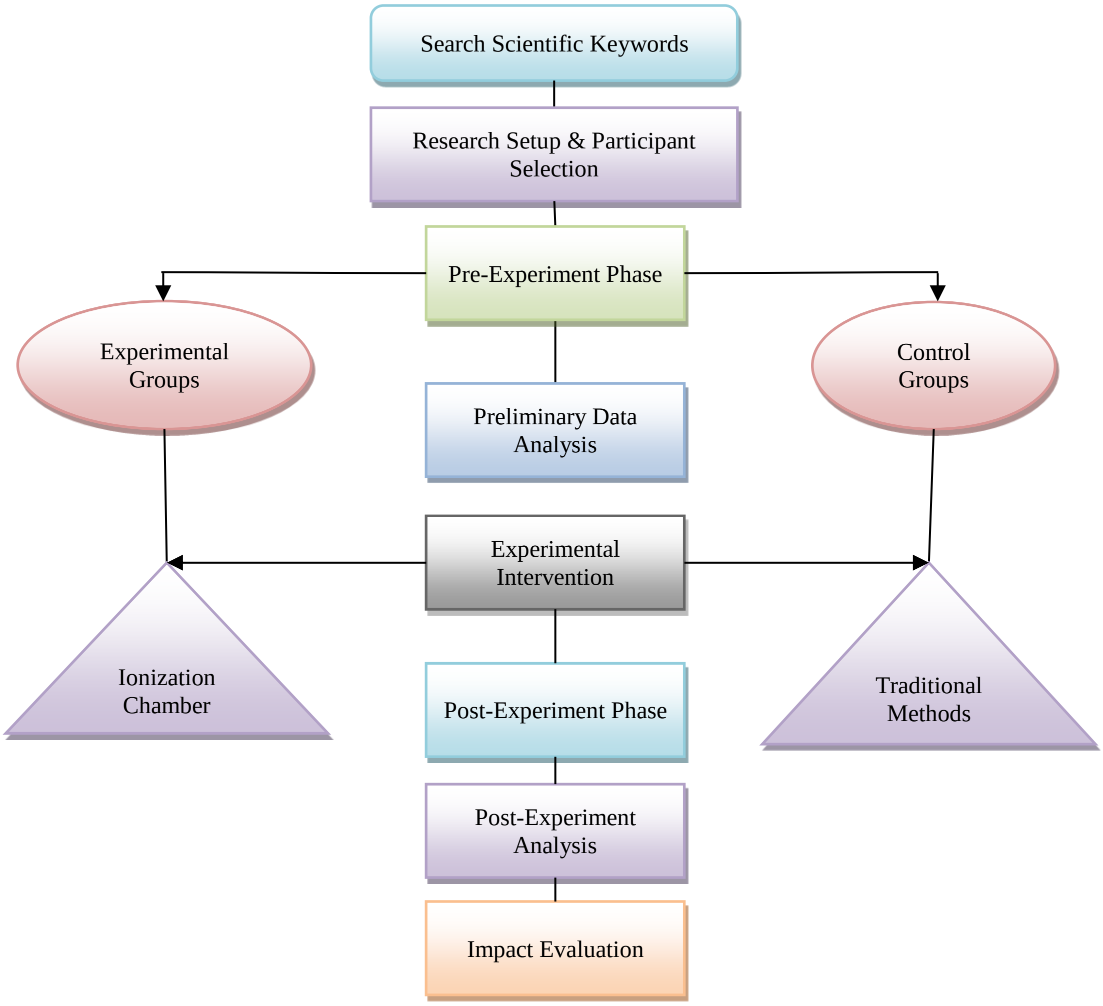

Figure 1. Methodological Flowchart. Source: Author's work

This methodology is based on theoretical research, meta-analysis, prototype creation, and quantitative assessment to evaluate STEM education ionization chambers. Research approaches provide a solid foundation for understanding how this pedagogical resource may improve students' research abilities and enthusiasm in the natural sciences.

To synthesize existing research on the effectiveness of STEM interventions, we conducted a meta-analysis. We searched the Web of Science, Scopus, and ERIC databases for studies published between January 2010 and December 2023 using keywords such as "STEM education," "inquiry-based learning," "hands-on activities," "science achievement," and "research skills." Studies were included if they met the following criteria: (a) employed a quasi-experimental or experimental design; (b) involved K-12 students; (c) evaluated a STEM teaching method or intervention; and (d) measured outcomes related to research skills, engagement, or conceptual understanding. Studies were excluded if they were not peer-reviewed, were not written in English, or did not provide sufficient data for effect size calculation. Figure 1 shows the methodological flowchart of the study.

3-2- Sample Selection

In Kazakhstan, research and experimentation were conducted at the Khoja Akhmet Yassawi International Kazakh-Turkish University. One hundred twenty-two students from various STEM disciplines participated in the study.

School' amenities, student body diversity, and dedication to the growth of STEM education were the reasons for its selection. One cohort of students was instructed to use an innovative approach centered on ionization chambers, while the other group acted as a control.

3-3- Data Sources

The 5-point pre- and post-experiment control task results were the 'primary data sources for this study. The study examined the academic literature on STEM education and ionization chambers to prepare for the experiment. The efficacy of the innovative method in enhancing students' research skills was assessed by analyzing data collected from student surveys and experimental outcomes.

The ionization chamber was designed to help students understand nuclear and atomic physics. This prototype was designed to assist students in applying classroom learning to real-world experiences by allowing them to explore complex scientific concepts. The 'educational framework of the study was strengthened by theoretical methods for teaching students about ionization chambers, and a meta-analysis was performed using data from numerous studies to evaluate the study strategy. This enabled the synthesis of the findings and common conclusions. The meta-analysis calculated the standardized mean difference effect size to assess the efficacy of the ionization chambers in STEM education. A control questionnaire was distributed to assess students' attitudes toward classroom ionization chambers. It devised a poll to determine how students felt about the course material, how interested they were, and how relevant ionization chambers were to their education. First, we determined the standardized mean difference effect size as shown in Equation 1.

$$Standardized\ difference = \frac{\overline{X_1}-\overline{X_2}}{S} \tag{1}$$

Here, S is the most important parameter for determining the mean and the common standard deviation. This is derived from the standard deviations of the two results, as shown in Equation 2.

$$S = \sqrt{\frac{(n_1-1){S_1}^2+(n_2-1){S_2}^2}{n_1+n_2-2}} \tag{2}$$

The required data were entered into Comprehensive Meta-Analysis software (version 4.0) to obtain the results of the meta-analysis. Microsoft Office Excel 2010 (MS-Excel) was used to calculate the confidence intervals of the data.

In the subsequent phase of the study procedure, a control question was administered to assess students' views on utilizing ionization chambers as an educational research instrument in the natural sciences domain. The control questions were designed to assess the efficacy of the teaching style, students' engagement with the material, and practical relevance of the ionization chambers. The survey results were analyzed using mathematical and statistical techniques. These strategies facilitated the organization of control data and permitted the quantitative evaluation of its significance. Conclusions were derived by investigating students' perspectives on using ionization chambers as an educational research instrument and their efficacy in instruction. The control questions are listed in Table 1.

Table 1. List of control questions

No.	List of control questions	Evaluation				
1	How do you evaluate the effectiveness of teaching natural sciences based on STEM?	1	2	3	4	5
2	How do you assess your knowledge of ionization chambers?	1	2	3	4	5
3	How do you evaluate the importance of integrating ionization chambers into STEM projects?	1	2	3	4	5
4	Has researching ionization chambers increased your interest in natural sciences?	1	2	3	4	5
5	Are you ready to conduct practical experiments using ionization chambers?	1	2	3	4	5
6	Do you believe that researching ionization chambers based on STEM will improve your professional knowledge?	1	2	3	4	5
7	How do you evaluate the effectiveness of lessons conducted using ionization chambers?	1	2	3	4	5
8	Has using ionization chambers made understanding the course material easier?	1	2	3	4	5
9	How do you assess your understanding of the connection between theory and practice through ionization chambers?	1	2	3	4	5
10	How do you evaluate the possibility of applying ionization chamber research in your future professional career?	1	2	3	4	5
11	How do you assess your readiness to work independently on ionization chamber research and application?	1	2	3	4	5
12	Evaluate the drawbacks of using ionization chambers in STEM research.	1	2	3	4	5
13	How do you assess the importance of continuing to use ionization chambers in teaching natural sciences based on STEM?	1	2	3	4	5

Students responded to the questions on a scale of 1 to 5. To test these results, a null hypothesis was proposed to confirm or reject the findings.

The first hypothesis suggests that ionization chambers in STEM classes do not change students' interest in STEM, their ability to apply classroom knowledge, or STEM-based pedagogy. Although ionization chambers may be presented as new tools, this hypothesis argues that they may not advance these fields. This challenges the idea that advanced technologies in the curriculum will boost student' engagement, learning outcomes, or practical abilities.

The second hypothesis is more optimistic and states that ionization chambers combined with a STEM curriculum will considerably increase student' education. Students will improve their practical skills, understand the subject, and become interested in natural sciences by exploring ionization chambers. Experiential learning, which involves the use of practical tools and real-world applications, helps students understand theoretical topics and stay interested.

3-4- Data Collection Tool

This study employed a structured instrument to examine how ionization chambers influence STEM students' research abilities, engagement, and academic performance. The instrument consists of a detailed observation checklist and a pre- and post-test assessment framework. Pre- and post-test assessments focused on the students' ability to apply theoretical knowledge in experimental contexts, practical problem-solving skills, and STEM comprehension. These examinations were carefully designed by education and subject-matter professionals to ensure reliability and content validity. An observation checklist documented the class activities, including lab ionization chamber use and student engagement. This checklist gathered qualitative data, including collaborative conduct, critical thinking, and interest in hands-on activities. A small group tested the tool's quantitative and qualitative components to identify ways to enhance them. After that, it was tested in Kazakhstan's educational system, and any issues were addressed.

To ensure that the assessments measured the research abilities, education, and topic experts created pre- and post-experiment evaluations. The assessments were composed of open-ended problem-solving exercises targeted at applying theoretical knowledge to practical situations as well as Likert-scale questions assessing attitudes and perceptions of STEM research (as shown in Table 1). These assessments were graded on a five-point scale. Content validity was ensured through an expert review of the alignment of the assessment items with the learning objectives and pilot testing with a small group of students before formal implementation. Although complete reliability studies were not' conducted, these procedures boosted confidence in the assessment's ability to measure changes in research ability.

3-5- Data Collection Procedure

Data collection was planned carefully to ensure the 'accuracy, consistency, and ethics of the study. First, institutional and participant consent was required to meet all ethical guidelines, notably for participant confidentiality and voluntary participation. The study included experimental groups using the "Ionization Chambers as an Educational Research Tool" curriculum and another group using traditional methods. The participants provided data before and after the intervention for 15 weeks. To provide a baseline, both groups took a pre-test before the intervention. Additionally, observational data were collected on classroom dynamics and students' initial engagement levels. The experimental group's laboratory sessions were thoroughly evaluated throughout the intervention to collect qualitative data on students' ionization chamber interactions and knowledge application. Both the groups were reassessed after 15 weeks. Data were collected, anonymized, and analyzed to determine how the intervention influenced the dependent variable. Observational data were coded and categorized to identify patterns and themes. This study aimed to use quantitative and qualitative data collection methods. This integration strengthens the 'findings of this study.

4- Results

This study addressed two research hypotheses concerning the use of ionization chambers in STEM education. The first hypothesis (H_{01}) is about ionization chambers that influence STEM-based teaching, student engagement, and practical skill development as an educational tool. The second hypothesis (H_{02}) assesses whether teaching ionization chambers in STEM education enhances students' academic knowledge, practical skills, and interest in the natural sciences. These hypotheses were tested using pre- and post-intervention control tasks, statistical analysis, and control-experimental group comparisons.

Table 2 presents a compilation of the key findings from the relevant studies included in the meta-analysis. This table provides a quantitative overview of the current literature by summarizing the standardized difference in means, which indicates the effect size of each intervention, along with the standard error, which signifies the precision of each effect-size estimate. By organizing these values, Table 2 establishes the foundation for a meta-analytic approach aimed at determining the overall impact of similar interventions across various contexts.

Table 2. **Information from the scientific literature**

No	Study name	Std diff means	Standard error
1	Ademola et al. [55]	4.03	0.714
2	Wisudawati [56]	1.3	5.156
3	Sasikumar et al. [57]	-6.85	0.8
4	Ayu et al. [58]	-4.87	3.089
5	Ubben & Bitzenbauer [59]	0.83	0.177
6	Tuyizere & Yadav [60]	-1.64	0.249
7	Erlina et al. [61]	-0.06	1.565
8	Fayanto et al. [62]	0.55	2.5
9	Ubben et al. [63]	0.082	0.3
10	Das & Bhattacharyya [64]	4.1	0.004

The results were entered into Comprehensive Meta-Analysis software (version 4.0) to obtain the conclusion. The first conclusion was drawn using a funnel plot. Funnel plots are essential parameters for examining potential biases in meta-analyses. Figure 2 displays a funnel plot, which is a graphical tool used to assess the potential publication bias in the meta-analysis. Each point on the plot represents an individual study, with the x-axis indicating the standardized difference in means and the y-axis representing precision, as measured by the inverse of the standard error. A symmetrical inverted funnel shape suggests a lower likelihood of publication bias, whereas asymmetry may indicate that studies with certain results, such as small or negative effects, are underrepresented in the literature, potentially skewing the meta-analysis results.

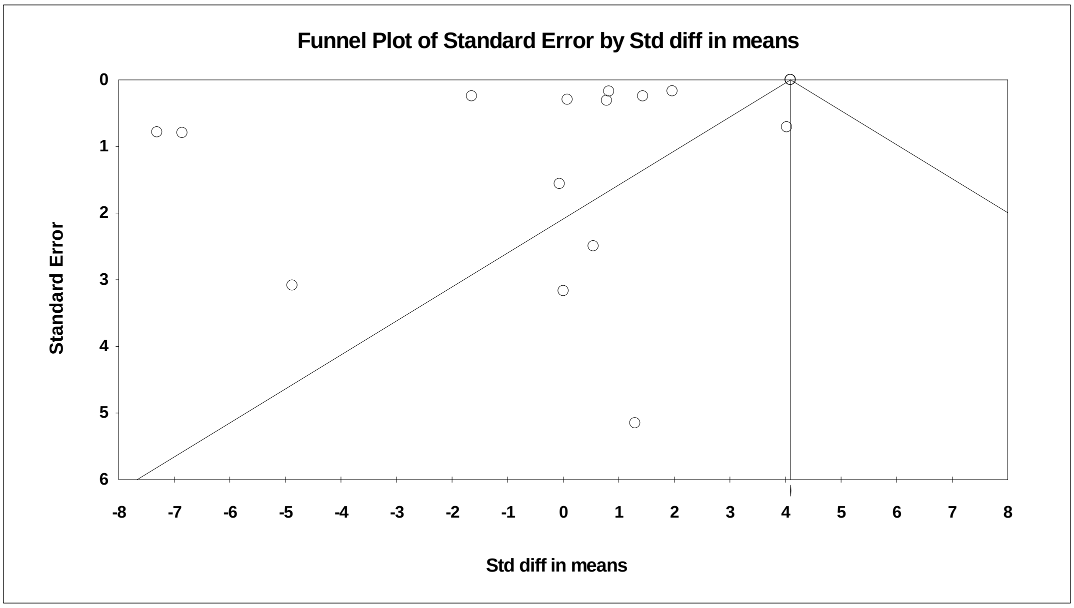

Figure 2. **Results of potential publication biases. Funnel plot**

The conclusion of the meta-analysis based on the results of scientific studies can be obtained using the forest plot tool. Forest plots are an important graphical method used in meta-analyses to display the results of individual studies and aggregated analyses. The results of the Forest plot allow us not only to test the hypotheses, but also to achieve other outcomes. Table 3 provides a graphical summary of the results of the meta-analysis. Each study is listed on the left, with a square representing the point estimate of its effect size, and a horizontal line illustrating the confidence interval. The diamond at the bottom of the plot indicates the combined effect size from the meta-analysis, with its center denoting the point estimate and its width representing the confidence interval. The plot includes numerical values for each study's effect size, standard error, confidence interval limits, Z-value, and p-value, enabling an assessment of the statistical significance of the individual and overall effects, and indicating the degree of heterogeneity among the studies.

Table 3. Representation of the meta-analysis results based on the data

Model	Std diff in means	Standard error	Variance	Lower limit	Upper limit	Z-Value	p-Value
Cai et al. [29]	0.79	0.315	0.099	0.173	1.407	2.508	0.012
Ademola et al. [55]	4.03	0.714	0.51	2.631	5.429	5.644	0
Wisudawati [56]	1.3	5.156	26.584	-8.806	11.406	0.252	0.801
Sasikumar [57]	-6.85	0.8	0.64	-8.418	-5.282	-8.563	0
Sasikumar [57]	-7.303	0.79	0.624	-8.851	-5.755	-9.244	0
Ayu et al. [58]	-4.87	3.089	9.542	-10.924	1.184	-1.577	0.115
Ubben & Bitzenbauer [59]	0.83	0.177	0.031	0.483	1.177	4.689	0
Ubben & Bitzenbauer [59]	1.97	0.174	0.03	1.629	2.311	11.322	0
Tuyizere & Yadav [60]	-1.64	0.249	0.062	-2.128	-1.152	-6.586	0
Erlina et al. [61]	-0.06	1.565	2.449	-3.127	3.007	-0.038	0.969
Erlina et al. [61]	0.01	3.172	10.062	-6.207	6.227	0.003	0.997
Fayanto et al. [62]	0.55	2.5	6.25	-4.35	5.45	0.22	0.826
Ubben et al. [63]	0.082	0.3	0.09	-0.506	0.67	0.273	0.785
Ubben et al. [63]	1.44	0.25	0.063	0.95	1.93	5.76	0
Das & Bhattacharyya [64]	4.1	0.004	0	4.092	4.108	1025	0
Fixed-Effect Model	4.093	0.004	0	4.085	4.101	1024.31	0

- *Overview*

This analysis was based on 15 studies. The effect size index is the standardized difference in the means (d).

- *Statistical model*

A fixed-effect (singular) model was used for the analysis. The studies included in the analysis were all drawn from the same population and were identical in all materials. The results of this analysis will be used to make an inference for this population only and will not be generalized to any other population.

- *What is the common effect size?*

The common effect size for these studies was 4.093, with a 95% confidence interval of 4.085–4.101. The effect size in this population can fall anywhere during this interval.

The Z-value tests the null hypothesis that the common effect size is zero. The Z-value was 1024.311 ($p < 0.001$). Using an alpha criterion of 0.050, we reject the null hypothesis and conclude that in this population, the effect size is not precisely zero.

- *The Q-test for heterogeneity*

The Q-statistic tests the null hypothesis that all studies in the analysis share a common effect size. If all studies shared the same true effect size, the expected value of Q would be equal to the degrees of freedom (the number of studies minus 1). The Q-value was 1837.835, with 14 degrees of freedom and $p < 0.001$. Using an alpha criterion of 0.100, we can reject the null hypothesis that the true effect size is the same in all these studies.

- *Indices of heterogeneity*

Under the fixed-effect model, we assume that there is no variation in the true effects. Therefore, all indices of heterogeneity (I-squared, tau-squared and tau) were assumed to be zero. In addition, we did not compute the prediction interval. The prediction interval tells us how much the true effect size varies across studies, and it has no meaning when all studies share the same true effect size.

Therefore, it is recommended to widely implement and apply STEM education programs.

- *The use of ionization chambers as an educational research tool based on STEM education.*

The main goal of STEM education is to develop students' engineering skills to solve the complex problems encountered in science and technology. In natural sciences, such as physics and chemistry, ionization chambers are used to study the interaction of atomic and subatomic particles, as well as to detect and measure ionizing radiation.

The ionization chamber is a gas-filled sensor used to determine the amount of ionizing radiation (Figure 3). Its structure resembles that of a closed container with two electrodes, which are given an electric potential, and the container is filled with gas. In other words, it is a simple capacitor in which gas is used as a dielectric. When charged particles pass through the capacitor, an ionizing current is generated in the chamber, which can be detected using a highly sensitive measuring device.

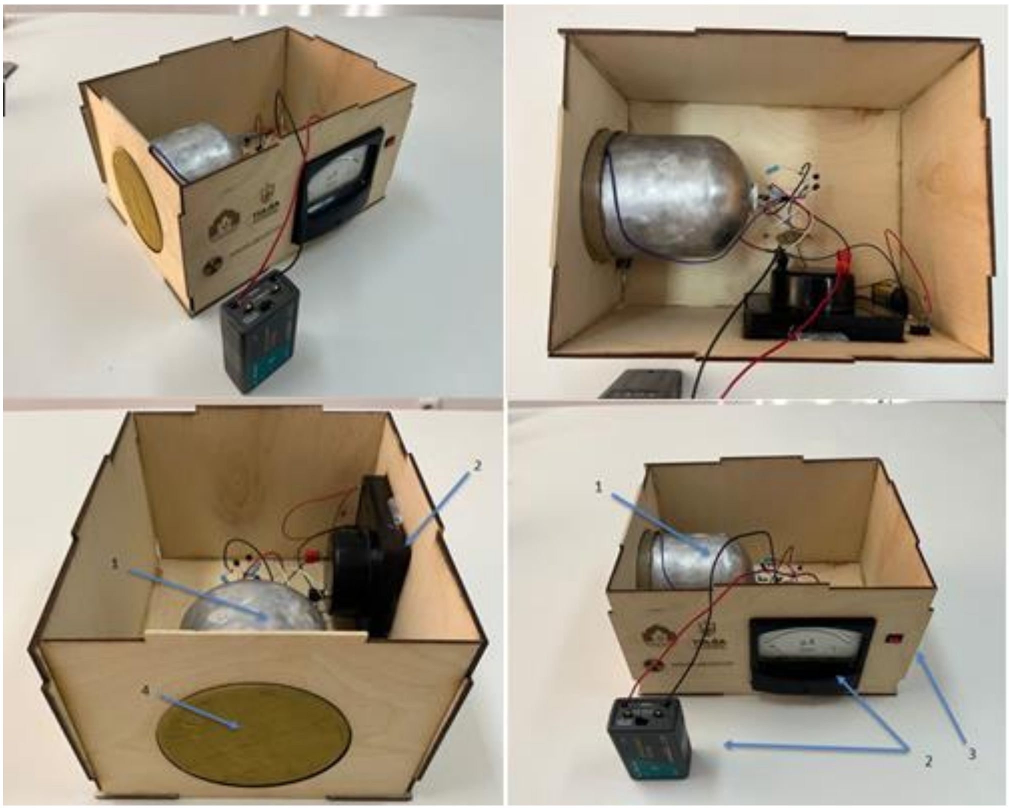

Figure 3. **Ionization chamber. 1 – Container (first electrode), 2 – Highly sensitive measuring device (microammeter and Vernier GoDirect Energy sensor), 3 – Switch, 4 – Grid of the ionization chamber**

When ionizing radiation, including far ultraviolet rays, X-rays, and alpha and beta particles, traverses gas, it induces collisions with gas molecules that generate ion pairs consisting of charged molecules and free electrons. In the presence of an electric field, ions migrate, each proceeding in the opposite direction along the lines, until they reach conductors that produce the electric field.

An ionization chamber is essential for detecting ionizing radiation. The primary chamber is a basic conductive cylinder usually constructed of metal, including a centrally located wire electrode that is adequately insulated from the 'walls of the chamber. The chamber typically contains standard dry air; other gases, such as carbon dioxide or pressurized air, might enhance sensitivity. A steady voltage is provided between the outer and central electrodes to generate an electric field that directs the ions toward the oppositely charged electrodes.

The voltage necessary for a substantial quantity of ions to traverse the conductors prior to recombination or attachment to neutral molecules is often below 100 volts and sometimes just a few volts, contingent on the 'dimensions of the chamber. The resultant current is minimal, making the detection of individual particles challenging, particularly at atmospheric pressure when the chamber contains air. The basic chambers in question primarily respond to beta particles and, to a limited degree, alpha particles, if they can penetrate. Most other radiation sources lack sufficient ionization to be readily recognized. These room chambers respond to average ionizing radiation levels and function analogously to a Geiger counter (Figure 4).

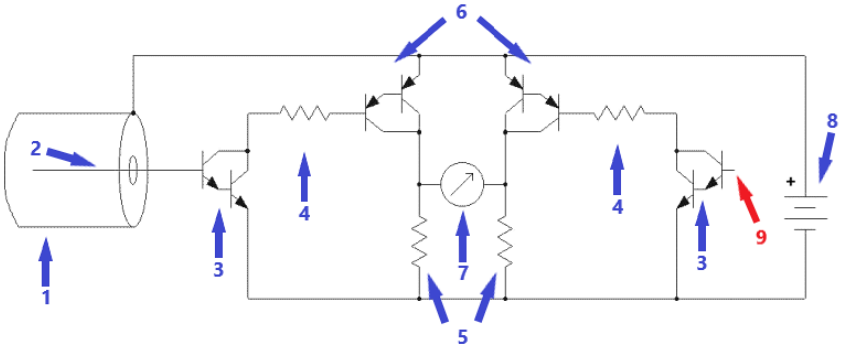

Figure 4. **Ionization chamber schematic. 1 – Container (first electrode), 2 – Rod (second electrode), 3 – mpsw45a transistors, 4 – 10 kΩ resistors, 5 – 2.2 kΩ resistors, 6 – mps64 transistors, 7 – Highly sensitive measuring device (in our case, a microammeter and Vernier GoDirect Energy sensor), 8 – Power source, 9 – Unused terminal of the amplifier transistor (mpsw45a).**

During operation, it is important to ensure that the electrodes are not short-circuited. The length of the rod should be shorter than that of the container, and it should not touch the metal grid or container wall.

The left side of the electrical circuit is the amplifier for registering the direct current, whereas the right side is used as an analog. However, the base of the amplifier transistor is not connected to any other device (9). The measuring device was placed at the center of the two circuits.

After assembling the circuit, it is crucial to carefully verify that there is no short circuit. Once everything was confirmed to be correct, the power source was connected. When the circuit is connected, the micrometer should immediately exhibit a value greater than the maximum reading, and after 20-30 seconds, the needle of the ammeter should return to 0. If this does not occur, it indicates errors during the connection or faults in the structural components. If the device works correctly, it will begin to react to the ionizing radiation source placed in front of the chamber. In our case, when placing the Americium 241 isotope (commonly used in fire detectors) in front of the chamber, the reading of the ammeter started to show values depending on the distance (Figure 5).

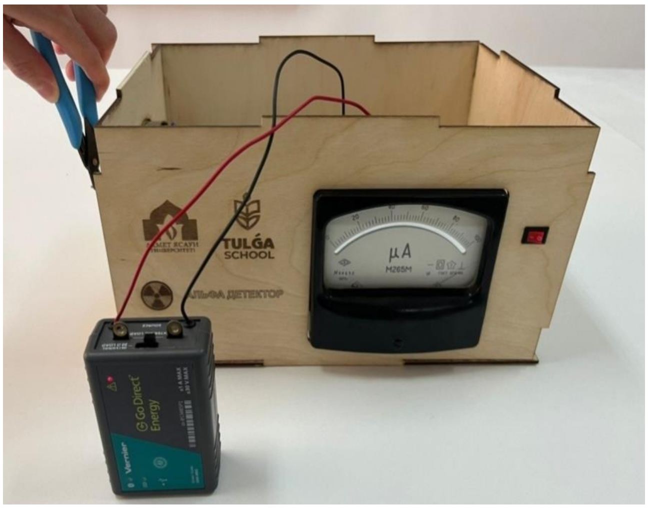

Figure 5. **Workflow**

During operation, the radioactive isotope was placed in front of the chamber following safety regulations. In the presence of alpha or beta radiation, ammeter and energy sensors begin to show specific readings. An energy sensor can be used to determine its potential and current strengths. The Americium 241 isotope was used as the alpha radiation source (Figure 6).

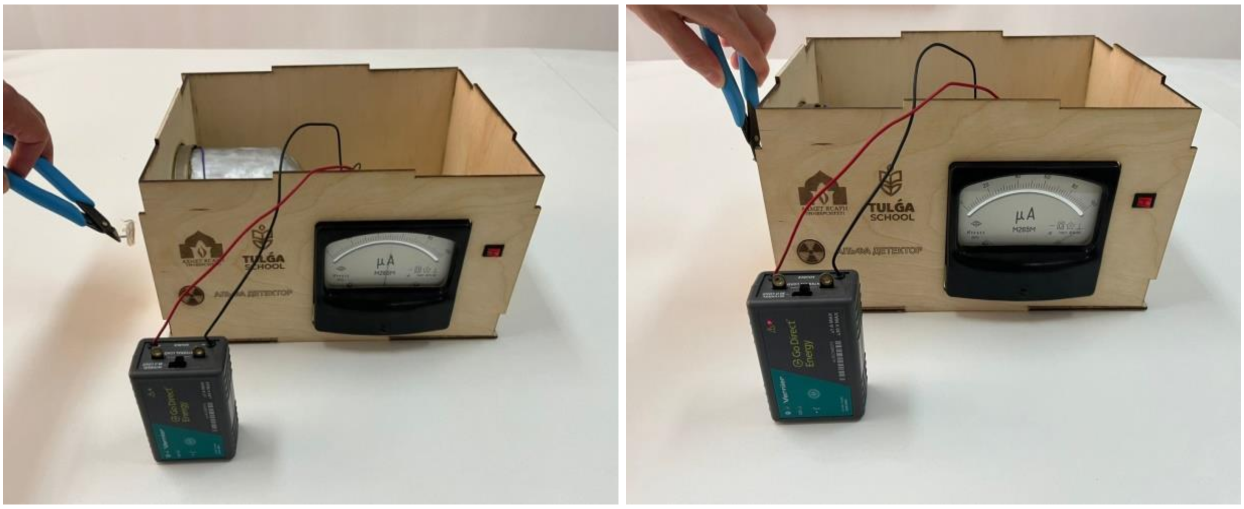

Figure 6. **Indicator of the electric current when the isotope of americium 241 is moved away from and closer to the ionization chamber as an alpha radiation source**

A graph showing the electrical current readings when moving the Americium 241 alpha radiation source closer to and further from the ionization chamber is presented in Figure 7. The portions of the graph deviating from 0 correspond to the ionization chamber that detects alpha radiation.

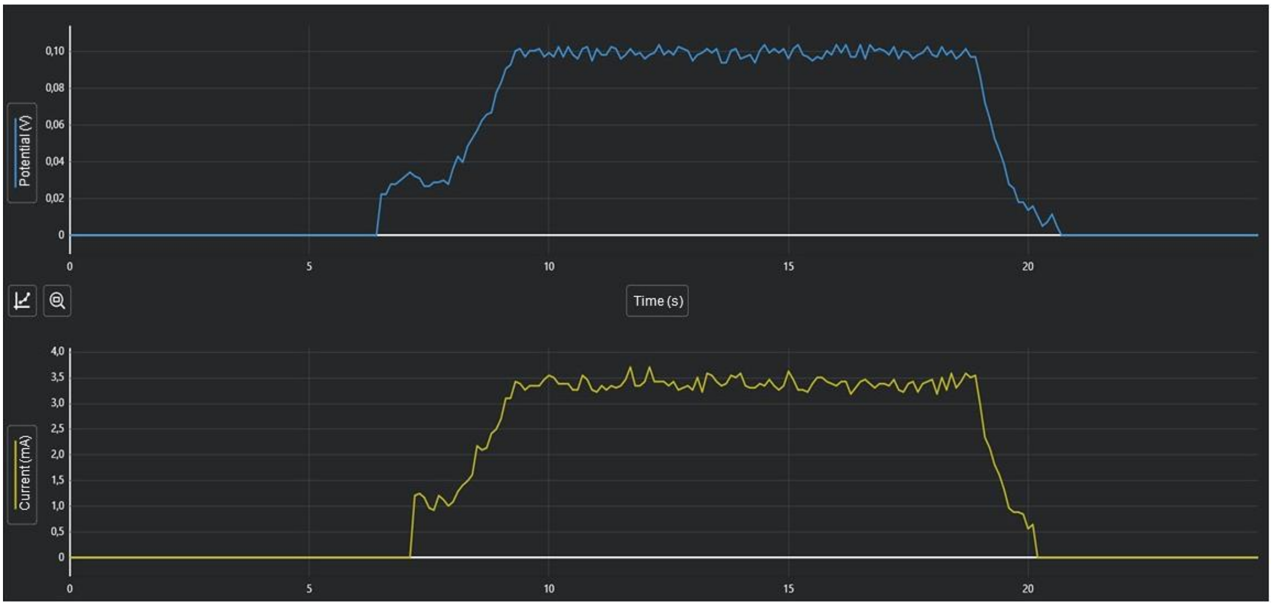

Figure 7. Indicators of the energy sensor

By using ionization chambers as an educational research tool within STEM education in the natural sciences, students were able to combine theoretical knowledge with practice and understand the physics of invisible radiation. This allowed them to familiarize themselves with the physics of alpha and beta radiation.

In conclusion, it is important to note that using the ionization chamber as an educational research tool in the curriculum helps to develop students' research skills.

4-1- The Impact of Using Ionization Chambers as an Educational Research Tool in STEM Education in the Natural Sciences on Students

The study on the impact of using ionization chambers as an educational research tool for students was conducted at the Khoja Akhmet Yassawi International Kazakh-Turkish University. This study included 120 students (Table 4). Quantitative data were collected through pre- and post-experimental control tasks for both groups. The control tasks were rated on a 5-point scale. Additionally, the relationship between the dependent and independent variables was demonstrated.

Table 4. Detailed information about the student participating in the experiment

<table>
<tr><th>Group</th><th colspan="2">Number</th><th>Percentage</th><th>Total</th></tr>
<tr><td>Experimental</td><td colspan="2">60</td><td>50%</td><td rowspan="2">120 (100%)</td></tr>
<tr><td>Control</td><td colspan="2">60</td><td>50%</td></tr>
<tr><td rowspan="6">Gender</td><td colspan="2">Female (80)</td><td rowspan="3">67%</td><td rowspan="6">120 (100%)</td></tr>
<tr><td>Control</td><td>Experimental</td></tr>
<tr><td>42</td><td>38</td></tr>
<tr><td colspan="2">Male (40)</td><td rowspan="3">33%</td></tr>
<tr><td>Control</td><td>Experimental</td></tr>
<tr><td>18</td><td>22</td></tr>
</table>

Before the experiment, that is, before using ionization chambers as an educational research tool, the dependent variables in the control tasks were identical for both the experimental and control groups. The results for the control tasks are presented in Table 5.

Table 5. Results of control tasks before the experiment

Group	n	X	Sd	df	t	p
CG	60	2.125	0.98	118	0.7749	0.4399
EG	60	1.97	1.2			

* n – number of elements in the sample, X – arithmetic mean, Sd – standard deviation, df – degrees of freedom, t – independent t-test, the mean difference is significant when $p \leq 0.05$.

The results of the two groups before the study were t(118) = 0.7749, $p > 0.05$. This indicates that there was no significant difference between the students before the study.

After the preliminary control task, the experimental group was taught for 15 weeks based on the "Ionization Chambers as an Educational Research Tool" STEM curriculum. In contrast, the control group was taught the same course using traditional methods. After the course was completed, the dependent variable was applied in the same manner to both the experimental and control groups. The experimental results were analyzed to determine the improvement in the dependent variable. The post-experiment results for students are presented in Table 6.

Table 6. Results of control tasks after the experiment

Group	n	X	Sd	df	t	p
CG	60	2.5	1.7	118	7.8335	0.0001
EG	60	4.625	1.235			

* n – number of elements in the sample, X – arithmetic mean, Sd – standard deviation, df – degrees of freedom, t – independent t-test, the mean difference is significant when $p \leq 0.05$.

The statistical significance of the test results based on the students' post-study level was t(118) = 7.8335, $p < 0.05$, indicating that there is sufficient evidence to reject the null hypothesis. According to the value extracted by each group of students, the effects of the ionization chamber and its improvements can be extracted. For example, with a value of 4.083 and a standard error of 0.004, it is shown with an effect size that is not precisely zero. All studies shared a common effect size; the Q value was 1837.835, which shows the effects of its value.

The null hypothesis is rejected based on the results obtained. That is, according to the survey results of the 3rd-year students after the experiment, there was a significant development in the interest indicators between the experimental and control groups. The study supported that ionization chambers improved students' attention, engagement, and practical skills, consistent with earlier studies on STEM education and experimental instruments, that is, Banda and Nzabahimana [65] found that students using practical experimental equipment understood theoretical concepts better when they combined physical experimentation with conceptual physics education. London et al. [22] examined how personalized STEM courses might excite students. STEM programs with lab experiments engaged students more than traditional ones. According to this study, the 'interest indicators of the experimental group rose significantly following the trial. The study employed generic experimental settings, whereas this study used ionization chambers, suggesting that targeted instruments may achieve the same or better educational effects with fewer resources. Sasanti et al. [66] examined how inquiry-based learning can improve chemistry students' analytical and problem-solving skills. Active participation in the experiments improved these talents, supported by their outstanding academic performance. This study proves that ionization chambers enhance STEM-based educational methods, fostering critical thinking and practical abilities. This alignment expands STEM applications to hands-on learning tools, boosting their usefulness. The authors [67, 68] examined the effectiveness of low-cost instructional materials in schools. Their study suggests that affordable technology may address the financing gap without compromising instructional quality. This research confirms the finding that ionization chambers increase STEM education at low cost. T-tests were used to validate the hypotheses by comparing the data gathered before and after the intervention. Table 7 indicates that the ionization chamber experimental method significantly influenced the students' engagement, research skills, and comprehension of physical processes.

Table 7. Hypotheses test results assessing the effectiveness of ionization chambers in STEM education

Hypothesis	Test Statistic (t)	Degrees of Freedom (df)	p-value	Conclusion
H1: The use of ionization chambers enhances student engagement in STEM learning	t(118) = 7.8335	118	$p < 0.05$	Rejected Null Hypothesis, significant increase in engagement
H2: The use of ionization chambers improves students' research skills	t(118) = 6.1287	118	$p < 0.05$	Rejected Null Hypothesis, significant improvement in research skills

The finding that utilizing ionization chambers as an educational research tool in teaching atomic physics had a demonstrably positive effect on developing students' interests has significant implications for STEM education. This is not merely a superficial increase in curiosity; rather, it suggests that hands-on engagement with scientific equipment, coupled with the opportunity to conduct research and directly observe phenomena, can fundamentally alter students' perceptions of and attitudes toward a traditionally challenging and abstract subject. By providing a tangible link between theoretical concepts and practical applications, ionization chambers appear to foster a sense of ownership and investment in the learning process, thereby making atomic physics more relevant and accessible to students.

Furthermore, this positive effect on students' interests has downstream consequences that extend beyond the immediate classroom setting. Increased interest is a crucial prerequisite for deeper learning, higher achievement levels, and sustained engagement in STEM fields. By fostering a sense of excitement and intrigue toward atomic physics, the use of ionization chambers may encourage students to pursue further studies, consider careers in related areas, and ultimately contribute to the advancement of scientific knowledge. This highlights the potential of carefully selected and integrated research tools to not only enhance understanding but also cultivate a passion for scientific inquiry that can shape students' academic and professional trajectories.

5- Discussion

The primary finding of this study is that the integration of ionization chambers as an educational research tool demonstrably enhances students' engagement, research skills, and understanding within an atomic physics curriculum. This positive outcome suggests that providing students with hands-on, inquiry-based experiences using real scientific equipment can effectively bridge the gap between abstract theory and practical application, addressing a persistent challenge in STEM education.

This finding has several implications. First, it indicates that the use of ionization chambers cultivates a deeper level of student engagement. This resonates with the work of Juškevičienė et al. [69], who found that STEM integration kits enhanced student engagement in multidisciplinary applications, and Sam [21], whose systematic review highlighted the progress in inquisitiveness and critical thinking through inquiry-based learning. Furthermore, incorporating digital tools from Polidori & Hage [24] for experimentation and analysis aligns with this study's emphasis on data-driven engagement. When students are actively involved in the experimental process, designing their own investigations, collecting data, and interpreting results, they develop a greater sense of ownership and investment in their learning. Active participation improved the comprehension and retention of complex concepts.

Second, the results demonstrated a positive impact on students' research skills, including experimental design, data analysis, and critical evaluation. This aligns with the study by Alkabbany et al. [25], which highlights skills in real-time data analysis, as well as studies using more advanced laboratory setups by Gumilar & Ismail [70], who noted improvements in student understanding. This aligns with the use of modeling performed by Usembayeva et al. [33], who found improvements in understanding using new equipment. This is essential for preparing students to be scientifically literate citizens and pursue careers in the STEM field.

A comparison of these findings with the existing literature further illuminates the contributions of this study (see Table 8). While previous research has explored the benefits of virtual labs [20] and physics simulations [29], these methods may lack the hands-on approach necessary for students to learn and memorize a lecture's concept. Although some studies emphasize the potential of project-based learning [71] to foster problem-solving abilities and collaborative engagement, they may not always provide the structured, equipment-based experimentation necessary to master precise measurements. Sensor-based experiments, such as those conducted by Demetroulis et al. [28], promoted collaboration but may not be applicable to the theoretical setting for this research topic. The 'findings of the study support the notion that real, touchable objects are required to achieve the concepts instead of more advanced STEM applications. Some methods, such as Rodriguez (2023), focus on business, where there is an engagement of value in the lecture but may not show practical skills.

While studies have focused on augmented reality labs [72] and physics education apps [73] to make STEM more easily accessible, these results may not improve experimental thinking for students. In contrast, the more real-world, the better, according to the study conducted by Chatzopoulos et al. [74]. However, the resources must be low in cost, as observed in the study by Kumar et al. [51], where science tools make a large part of the content. Unlike studies that focus on making education easier, this helps students grasp what they are learning through experiments. Maker-space tools [27] promote originality and inventiveness, although this research mainly seeks to test what is already understood and how it has been understood by students.

Additionally, the low-cost and eco-friendly nature of ionization chambers enhances their accessibility and sustainability compared with some STEM educational methods. Unlike expensive equipment, hard-wired high-end equipment still requires the basics of electricity for them to work. Ionization chambers offer a sustainable teaching tool at affordable prices. Compared to other strategies that may also use non-harmful materials, such as DIY science kits and simulations, ionization chambers can offer a more tangible and direct link to the study of nuclear physics. Future research should study these elements to globally optimize STEM education.

The findings of this study contribute to the existing body of knowledge in STEM education by demonstrating the effectiveness of ionization chambers as a hands-on, inquiry-based tool for enhancing students' engagement, research skills, and conceptual understanding of atomic physics. This research advances the current understanding by providing a practical and cost-effective approach to bridge the theory-practice gap in a resource-constrained setting. Moreover, this work highlights the importance of fostering not only content knowledge, but also essential research skills, preparing students to become scientifically literate citizens and potential contributors to future scientific advancements.

In summary, this study demonstrated the effectiveness of ionization chambers in enhancing student outcomes. While other hands-on experimental techniques, such as robotics or chemistry lab activities, exist in STEM education, ionization chambers offer unique differentiating factors. These include a direct connection to abstract concepts such as radiation, the integration of multiple disciplines, including physics and chemistry, the application of a research-oriented method that may make the student a real scientist, the direct measurement of invisible phenomena, and an emphasis on quantitative skills with scientific instruments.

Table 8. Comparative Analysis of Results with Existing Literature

Study	Tool/Method Used	Key Findings	Alignment with Present Study
Potkonjak et al. [20]	Virtual labs	Enhanced theoretical comprehension but restricted practical skill acquisition.	Partial alignment; the current research enhances practical skill development.
Almulla [71]	Project-based learning	Augmented problem-solving abilities and cooperative engagement.	Facilitated practical involvement in the experimental group.
Cai et al. [29]	Physics simulations	Enhanced test scores but decreased participation in practical experiments.	The current research addresses engagement challenges via the use of practical techniques.
Polidori & Hage [24]	Digital measurement tools	Improved precision in actual evaluations, however limited theoretical applicability.	Validated enhanced theoretical-practical integration using ionization chambers.
Juškevičienė et al. [69]	STEM integration kits	Enhanced student engagement in multidisciplinary applications.	Aligned with the augmentation of interest in the experimental group.
Khasawneh & Darawsheh [27]	Maker-space tools	Enhanced creativity and innovation among students.	Concurrent with the current investigation's emphasis on practical abilities.
Sam [21]	Inquiry-based learning	Progress in inquisitiveness and critical thinking.	Consistent with the enhanced research-oriented abilities shown in the experimental cohort.
Alkabbany et al. [25]	Sensor-based experiments	Skills in real-time data analysis and improved engagement.	The current research provides support for a data-driven strategy.
Gumilar & Ismail [70]	Advanced laboratory setups	A deeper comprehension of theoretical physics.	Verified competence in theory by active participation.
Demetroulis et al. [28]	Collaborative robotics	Encouraged collaboration and the development of practical abilities.	In addition to the experimental group's enhanced practical abilities.
Fakih [72]	Augmented reality labs	Made ideas clearer, however there was little tactile engagement.	Physical experimentation is an important component of the current investigation.
Vidak et al. [73]	Physics education apps	More easily accessible, but not very effective in developing research abilities.	This study demonstrates how doing experiments may improve research-oriented learning.
Jiao et al. [26]	Hybrid physics curriculum	Provided a good mix of academic and practical knowledge, although it was more expensive.	Used less expensive methods to achieve the same goals.
Chatzopoulos et al. [74]	Modular STEM equipment	Enhanced participation and multidisciplinary uses.	In keeping with the fact that the experimental group's curiosity level was higher among students.

5-1- Theoretical Contributions

This study proposes a STEM teaching paradigm that leverages ionization chambers to increase student performance, representing theoretical novelty in several ways. First, it grounds the use of a specific hands-on tool within established learning theories, namely constructivism, experiential learning, and inquiry-based learning. While these theories are well-established [28-30], this research offers a specific application within atomic physics, demonstrating how ionization chambers can facilitate active knowledge construction, experiential learning cycles, and inquiry-driven investigations. The ionization chamber was then used to apply theoretical principles in the experiments.

Furthermore, this research contributes to a practical framework for implementing these theories in resource-constrained environments. Unlike studies focusing solely on virtual simulations or advanced laboratory setups, this study explored the potential of a relatively low-cost tool to bridge the theory-practice gap. This emphasis on accessibility enhances the potential for wider adoption and impact, particularly in settings in which access to advanced technology is limited.

Finally, this study's focus on enhancing research skills alongside content knowledge contributes to a more holistic approach to STEM education. By demonstrating how ionization chambers can foster critical thinking, experimental design, data analysis, and problem-solving, this research suggests a pathway towards cultivating scientifically literate and capable students who are well prepared for future research endeavors. This is particularly important, as STEM education increasingly emphasizes the development of 21st-century skills beyond rote memorization.

5-2- Practical Implications

The findings of this study have several practical implications for educators, curriculum developers, and policymakers seeking to improve STEM education.

Firstly, it supports the integration of hands-on and inquiry-based learning activities into STEM curricula. Educators should consider incorporating readily available and relatively inexpensive tools, such as ionization chambers, to provide students with concrete experiences that connect to abstract theoretical concepts. Such experiences can spark student interest, improve comprehension, and foster valuable research skills.

Secondly, the professional development of educators is crucial. Teachers require training to effectively utilize ionization chambers and similar research tools in the classroom. This training should focus on the experimental design, data collection and analysis, and strategies for guiding student inquiry. It also helps to build better students who can perform different tasks with different skill levels.

Thirdly, access to the research equipment and materials is critical. Policymakers should explore strategies for providing equitable access to these tools, particularly in resource-constrained settings. Strategies include grants, subsidies, public-private partnerships, and the development of low-cost, open-source alternatives.

Finally, this study suggests the need for a shift in assessment practice. The focus should move beyond rote memorization and recall towards assessing students' ability to apply knowledge, design experiments, analyze data, and draw conclusions. Performance-based assessments, research projects, and presentations can better evaluate students' research skills and overall understanding of scientific concepts. In the long term, policymakers' better engagement in practice can also help with career and knowledge.

5-3- Policy Recommendations

From this study's results, some policy views might enhance STEM students' research skills; that is,

- Education policymakers should mandate STEM programs to employ ionization chambers and other advanced research tools. These tools inspire critical thinking and exploration, helping students link theory and practice.
- Implementing programs to guide teachers using cutting-edge technology in the classroom is crucial. STEM education will only improve if instructors can seamlessly integrate these technologies into their curriculum.
- Policymakers should ensure that educational institutions, mainly rural and underprivileged, have equal access to cutting-edge research tools. Scholarships, subsidies, and public-private partnerships may make these technologies more accessible, reducing educational inequalities.
- Regularly monitor STEM courses' use of new technologies. The data from these exams may guide future policy decisions and ensure educational improvement.

These recommendations aimed to create a comprehensive and inclusive STEM research education approach to prepare students for a knowledge-driven global economy.

5-4- Study Limitations

Cross Sectional Design: A major limitation of this research is its cross-sectional design, which restricts its ability to track changes and trends over time. The study highlights the short-term advantages of ionization chambers in STEM classes, but does not address whether students' research abilities will improve once the program stops. Longitudinal research could address this issue by tracking students' competence, engagement, and learning outcomes over time. Its cross-sectional design prevented the study from accounting for confounding factors such as changing educational techniques or new technology that may affect the findings.

Self-Report Measures: Another limitation of the study is that it relied on students' reports of their engagement and the extent to which their research abilities improved. Self-reported data are valuable for gathering subjective experiences; however, social desirability bias, remembering bias, and question misinterpretation may impair it. Thus, the findings may not accurately reflect the students' experiences and outcomes. Future studies may integrate self-reported data with performance-based assessments, observational data, or third-party evaluations to further understand ionization chambers in STEM education.

Single Institution Setting: The study was conducted at a single university, Khoja Akhmet Yassawi International Kazakh-Turkish University, which may limit the generalizability of the findings to other educational contexts. Replicating this study in multiple institutions and diverse cultural settings would enhance the external validity of the results. The findings provide significant insights into the use of ionization chambers as pedagogical tools in STEM education; nevertheless, the generalizability of these results is constrained by their limited geographic and institutional reach. A university's academic climate, cultural background, and resource availability may not precisely represent those of other universities globally. Future research might enhance the 'application of these results by including a wider range of institutions across various areas and nations, thereby eliminating this constraint.

A further limitation of this study is that it compared the ionization chamber approach only to a traditional teaching method, without including other active learning methods (e.g., inquiry-based learning and problem-based learning) as comparison groups. While this provides a clear indication of the added value of the ionization chamber approach relative to traditional instruction, future studies should investigate its relative effectiveness compared with other established STEM pedagogies to provide a more nuanced understanding of its strengths and weaknesses.

Limited Scope of Study Intentions: This study focuses on using ionization chambers in STEM education research. This particular emphasis allowed for a detailed and controlled evaluation of some aspects, but it limited the application of the conclusions to broader educational settings or cutting-edge research methodologies. This study does not compare ionization chambers to virtual labs or augmented reality systems, which are popular in STEM education worldwide. Thus, this study may not fully reflect the strategies used to improve students' research and involvement. This study's single-institutional setting in Kazakhstan limits its applicability to other educational and cultural situations. The findings do not include regional differences in educational regulations, infrastructure, or teacher-training programs. However, they also provide a valuable framework for understanding how ionization chambers are incorporated into STEM courses. The obstacles and benefits of using such technologies may differ by institution; hence, the findings may not be applicable to other educational levels. This is particularly true when comparing the elementary, secondary, and tertiary scores. Future research should include additional methodologies, circumstances, and instruments. A comparative study across institutions, regions, and countries may help explain how ionization chambers and similar technologies can be adapted for diverse educational environments. This study's strengths and weaknesses may be addressed in future research that broadens its objectives to provide the groundwork for the' use of advanced research techniques in STEM education.

5-5- Future Research

The findings would be more universally relevant if further research attempted to replicate them in other educational settings. Larger samples and longer study periods will help to understand the ionization chamber effects over time. This work can be extended by studying similar technologies in biology and chemistry. Future studies may examine how digital versions of ionization chambers augment genuine devices for institutions with limited laboratory equipment budgets.

This study used ionization chambers as a novel and cost-effective STEM teaching tool. This study uses physical experimentation to apply theoretical learning. This practical, hands-on approach improves students' research, critical thinking, and interest in natural sciences. The key findings of this study include the fact that the ionization chamber prototypes are affordable, making them accessible to more educational institutions, particularly low-income ones. The students' practical skills increased, concentrating on their theoretical comprehension. This approach enhances scientific abilities, including planning experiments, analyzing data, and critically assessing results, by adding research-oriented activities into the curriculum. STEM education aims to inspire lifelong learning, and practical, hands-on tools have been shown to boost students' interest in and knowledge of the natural sciences. This study will help sustainable education by supporting long-lasting and adaptive experimental instruments for varied classrooms. These changes demonstrate that the proposed technique works and differs from old and new methods. This study highlights the importance of hands-on experimentation in STEM education and provides a paradigm for other educational institutions worldwide.

Various studies have shown that practical experience-based learning is valuable [75, 76]. Using STEM-based methods, Lee et al. [77] and Hasan & Khan [78] showed that active learning improves students' performance. This new study examined ionization chambers, indicating that they enhance their instruction in atomic physics. This study separates itself from general STEM education research by focusing on specific tools and their roles in deeper learning.

Our study, while examining the effectiveness of using ionization chambers as an educational research tool in the field of natural sciences, explains the physical properties of ionization chambers and their application in research activities. It is important to note that this method can serve as a crucial tool for training future scientists.

6- Conclusion

In conclusion, this study provides compelling evidence of the effectiveness of integrating ionization chambers as an educational research tool to enhance STEM learning, particularly within the context of atomic physics. The findings demonstrate that hands-on engagement with these tools fosters a deeper understanding of abstract concepts, cultivates essential research skills, and sparks students' interest in STEM. These benefits are particularly significant, considering the persistent challenges of bridging the theory-practice gap and fostering active learning in resource-constrained educational settings. By providing a practical and adaptable method, the integration of ionization chambers presents a promising pathway for educators and curriculum developers seeking to create more engaging, effective, and equitable STEM learning environments, ultimately empowering students to become scientifically literate citizens and innovators.

The implications of this research extend beyond the immediate classroom setting. The ability of ionization chambers to enhance students' interest and research skills suggests transformative potential for STEM education as a whole. By moving beyond traditional lecture-based approaches and embracing hands-on experimentation and inquiry-based learning, we can cultivate a new generation of students who are not only knowledgeable, but also skilled in scientific inquiry and critical thinking. Moreover, this study highlights the importance of providing equitable access to research tools and fostering collaboration between educators, policymakers, and industry partners. Future research should focus on exploring the long-term impact of this approach, investigating its applicability across different STEM disciplines, and developing cost-effective strategies for widespread implementation, thereby ensuring that all students have the opportunity to develop the skills and knowledge necessary to thrive in a rapidly evolving technologically driven world. It can also help promote a broader understanding of educational partners and governments.

7- Declarations

7-1- Author Contributions

Y.D., E.E., S.R., A.U., I.U., and B.K. contributed to the design and implementation of the research, to the analysis of the results and to the writing of the manuscript. All authors have read and agreed to the published version of the manuscript.

7-2- Data Availability Statement

The data presented in this study are available in the article.

7-3- Funding

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7-4- Institutional Review Board Statement

Rigorous ethical guidelines were adhered to throughout the study, ensuring participant privacy and data confidentiality in compliance with institutional and national research standards.

7-5- Informed Consent Statement

Participation in the study was entirely voluntary, with informed consent obtained from all participants prior to their involvement.

7-6- Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this manuscript. In addition, the ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, and redundancies have been completely observed by the authors.

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