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# Research trends in modern physics education in Turkey

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**ABSTRACT**
This research involves a content analysis of studies on modern physics education conducted in Turkey between 2000 and 2023. In this context, 273 studies accessed in full text from different databases were examined. The studies were evaluated using the "Modern Physics Education Publication Classification Form" and analyzed using the content analysis method. According to the research findings, studies in the field of modern physics education in Turkey were mostly conducted between 2010 and 2020. The study objectives varied and quantitative research designs were preferred more. Purposive sampling was predominantly employed in the studies, with most samples consisting of high school and undergraduate students. The studies generally included sample sizes ranging between 31 and 100 individuals. The duration of the studies varied between 0 and 8 weeks. To enrich the data, various data collection tools were used. Frequency, percentage, and t-tests were commonly used for quantitative analyses, while content analysis was frequently preferred for qualitative analyses. Although different validity and reliability methods were used in the studies, not enough information was provided on this issue. The results of the studies examined have shown that there are positive developments as well as negative situations in modern physics education. However, these results were not sufficiently supported by the literature in the discussion section. Based on the findings of this research, it was recommended to use different analytical methods in modern physics education research, increase the sample size, enrich methods and intervention examples.

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## Introduction

Modern physics began with Max Planck's blackbody radiation, followed by Einstein's theory of relativity, Heisenberg's uncertainty principle, De Broglie's matter wave, Schrödinger's wave mechanics, the Pauli Exclusion Principle, and Dirac equation. Modern physics is a subfield of physics that examines microscopic particles in terms of probability, observability, operators, eigenvalues, expected values, and wave functions (Beiser, 2003). Modern physics, which studies the behaviour and interactions of atoms, nuclei and fundamental particles within the scope of quantum theory, has brought about an understanding of uncertainty, probability and non-locality in the foundations of physics (Mufit et al., 2024; Müller & Wiesner, 2002). This understanding initiated the process of reconsidering the "fact" that each physical quantity in classical physics is defined independently of the environment, the subject, the observer and the measuring device, contains clear information and has a fixed and definite value up to a certain speed limit (Ayene et al., 2011; Pospiech, 2000). This process has enabled the development of theories in modern physics but has also opened up new ways of thinking and new possibilities in chemistry, biology, engineering, medicine and many branches of science (Stadermann & Goedhart, 2020). This enabled the development of many novel technologies, such as lasers, LCD and plasma screens, MRI and X-ray computed tomography devices, thermal cameras, nuclear reactors, superconductors, transistors, cell phones, and electron microscopes (Bouchée et al., 2021; Serway & Beicher, 2007). Additionally, modern physics also promises many future technologies, such as quantum computing, quantum computers, and quantum internet technology (Vermaas, 2017). Understanding all these rapid developments is important not only for physicists but also for engineers, biologists, chemists, philosophers, and everyone else. Therefore, there is a need for meaningful learning and teaching of modern physics (Bonacci, 2018). However, modern physics is a difficult, abstract and complex subject for students to learn and also a challenging subject or field for teachers to teach, as it covers microscopic particles, uncertainty, and probability states (Alstein et al., 2023; Çalışkan, 2002). However, the inclusion of more advanced mathematical equations in modern physics compared to classical physics (Abhang, 2005), the incomplete understanding of its philosophy (Bouchée et al., 2021), and the similarity of its concepts to classical physics (Stadermann & Goedhart, 2020) make the teaching-learning process of modern physics more challenging. According to Levrini and Fantini (2013), the main reason for these challenges is the failure to abandon the classical physics mindset instead of the unique thinking style of modern physics. Stadermann et al. (2019), who believe that these difficulties may stem from the modern physics curriculum, examined the physics curriculum of 15 countries (Australia, Austria, Belgium, Canada, Denmark, Finland, France, Germany, Italy, the Netherlands, Norway, Portugal, Spain, Sweden and the United Kingdom). They concluded that these curricula do not adequately emphasise the philosophy of modern physics, ignore the historical development of science, lack interdisciplinary understanding, and inappropriately treat certain concepts contrary to the nature of modern physics provide a couple of examples. Additionally, the relevant literature has found that textbooks and traditional teaching methods (Giliberti & Organtini, 2021; Kalkanis et al., 2003), the examples and analogies in textbooks (Levrini & Fantini, 2013), the persistence of the classical physics perspectives, and the emphasis on mathematical problem-solving (Baily & Fingelstein, 2010), teachers' inadequate subject mastery (Bouchée et al., 2021), oversimplify modern physics and lead to conceptual misunderstanding in modern physics. All these challenges contribute to conceptual misconceptions when learning modern physics (Müller & Wiesner, 2002; Obbo et al., 2024; Vakarou et al., 2024). Some of the prominent conceptual misconceptions highlighted in the relevant literature include perceiving wave functions as mechanical waves, explaining De Broglie waves with basic wave knowledge, explaining the wave-particle duality of electrons according to the Bohr Atom Model, considering the Heisenberg Uncertainty Principle as a measurement error stemming from external influences, simplifying modern physics mathematics to a basic level, and misinterpreting modern physics mathematical systems and algorithmic steps (Ayene et al., 2011; Dubson et al., 2009; Mannila et al., 2002; Müller & Wiesner, 2002; Sadaghiani & Munteanu, 2015; Vokos et al., 2000). Taber (2005) identified conceptual misconceptions about believing that quantum spin in modern physics represents actual motion. Additionally, Didiş et al. (2014) identified conceptual misconceptions among students in providing intuitive responses in explaining light, energy and angular momentum concepts and establishing contexts. In their study conducted with high school students, Rodriguez et al. (2020) also found that 40% of the students were still attempting to explain the particle nature of light in the photoelectric effect with classical physics. The most crucial step to eliminating all these conceptual misconceptions is to update the modern physics curriculum (Çalışkan, 2002). Michelini et al. (2016) strongly emphasize that the modern physics curriculum should be prepared and implemented separately rather than as a subfield of physics. Alongside updating the modern physics curriculum, the teaching-learning process should also be organised and managed in a way that can handle modern physics knowledge effectively (Bezen et al., 2021; Michelini et al., 2014). Teachers should facilitate the learning process by creating an appropriate learning environment rather than directly delivering modern physics knowledge. The relevant literature suggests various practices, materials, teaching methods, and techniques for learning or teaching modern physics. These include strategies for active learning and virtual laboratories (Mufit et al., 2024; Müller & Weisner, 2002), discussion and experimentation teaching methods (Baily & Finkelstein, 2015; Kersting et al., 2023), using simulations and animations in cooperative learning (Bungum et al., 2015), conducting theory-oriented experiments and discussing their results (Alstein et al., 2023; Bitzenbauer & Meyn, 2020), technology-supported active learning simulations (Swandi et al., 2020), e-learning based-STEM (Yusuf et al., 2018) problem-solving teaching methods, fostering mathematical thinking through analogies, and using different visual elements for the same content (Erol & Oflaz, 2020), and analysing multiple visual elements and original texts related to the topic (Levrini & Fantini, 2013). Other recommended practices include inquiry-based learning, 5E learning cycles, cooperative learning, and using interactive videos (Obbo et al., 2024; Rodriguez et al., 2020).

Aspden et al. (2016) underline the importance of highlighting modern physics concepts more frequently and adopting explanatory approaches instead of classical physics thinking and speaking styles to understand the true nature of modern physics. Doyan et al. (2021) support this idea and emphasize the importance of adopting a historical approach in the learning and teaching process of modern physics to instil in students the notion that modern physics has its own unique characteristics. Dekarchuk (2023) and Gilberti and Organtini (2021) who share similar views, emphasise that in order to understand modern physics, mathematical formulas, operations, experiments and interdisciplinary understanding should be included without trying to stick to models based on daily experience. Bunge (2003) suggests that there is no single common approach to teaching modern physics and highlights the need to sometimes continue from a historical development process perspective and at other times from the lack of consensus in current debates. Thus, students become intrinsically motivated towards modern physics and develop an understanding of "Why should I learn modern physics?" in their lives (Bungum et al., 2015). In order for all these elements and understandings stated for modern physics to be sustainable and developable, the "International Modern Physics and Education Research Seminar Series Symposium (IMPRESS)" emphasizes that studies conducted on modern physics education should be examined and trends should be determined (Kersting et al., 2023). Thus, the problems experienced in the curriculum, learning outcomes, content, learning-teaching process, technologies and daily life practices of modern physics can be determined, and appropriate solutions and different understandings can be developed. In this direction, when the content analysis studies conducted for modern physics education are examined, it is striking that the research is limited. Krijtenburg-Lewerissa et al. (2017) reviewed 74 articles on quantum physics published between 1997 and 2016, available in Scopus, Web of Science, and ERIC indexes. They analysed the articles in detail under students' learning difficulties, data collection tools, teaching strategies used, research methods, multimedia activities, and applications. They determined that students continued to interpret quantum physics with a classical physics understanding, and the data collection tools did not reflect the entirety of quantum physics. Furthermore, they found that the research studies were predominantly designed based on qualitative research designs, a non-mathematical conceptual understanding was mostly adopted in quantum physics education, and multimedia visuals were primarily used for undergraduate students. However, no study examining modern physics education in Turkey has been undertaken. There is a need for a comprehensive and holistic review of studies conducted in the field of modern physics education in Turkey. The results obtained from the research would help curriculum developers, teachers and students access the necessary information from a single source. Thus, it would serve as a guide in creating learning environments for students to develop a modern physics identity during the teaching-learning process of modern physics. Additionally, enabling students to acquire the skills of understanding modern physics theories in detail, engaging in discussions on their implications, providing necessary information, and interpreting their numerous problems may contribute to the understanding that "modern physics is important for everyone." The research results may encourage more high-quality and comprehensive studies to address the shortcomings in the field. In this context, the purpose of this research is to combine the results obtained from independent studies on modern physics education in Turkey. Accordingly, the main research problem was formulated as "How is the current state of the studies conducted in modern physics education shaped in Turkey?" In this respect, responses were sought to the following research questions:

1. What is the distribution of studies conducted in modern physics education according to their descriptive information regarding the research identity (e.g., publication type, publication year, publication language, and database)?
2. What is the distribution of studies conducted in modern physics education by their subject areas?
3. What is the distribution of studies conducted in modern physics education by their objectives?
4. What is the distribution of studies conducted in modern physics education by research design?
5. What is the distribution of studies conducted in modern physics education by sample types, sample levels, and sample sizes?
6. What is the distribution of studies conducted in modern physics education by intervention duration?
7. What is the distribution of studies conducted in modern physics education by data collection techniques\tools and types of data analysis?
8. What is the distribution of studies conducted in modern physics education by types of validity and reliability?
9. How have the results, discussions, and recommendations of studies conducted in modern physics education been shaped?

In this context, the research provides significant contributions to the field of physics education in terms of examining the studies conducted within the scope of modern physics education and determining the trends. The methodological contribution of the research is the development of the publication classification form in the research and the holistic and in-depth examination of the studies according to this form. It is thought that the detailed description of the findings obtained in the research will contribute to teachers, researchers, programme development specialists and will guide the development of different applications, materials, activities, etc. in the learning-teaching process of modern physics. The results obtained from the research will contribute to the understanding of "Modern physics is important for everyone" in recognising/defining the scope of modern physics in detail, discussing its inferences, providing information, and interpreting its problems. It is also thought that the suggestions regarding the research results will guide more qualified and comprehensive studies in eliminating the deficiencies in modern physics education.

## Method

### Research Model

This research is a bibliometric study examining studies conducted within the scope of modern physics education in Turkey. Bibliometrics is the process of examining journal articles, conference proceedings, book chapters and various publication types on any subject, discipline or field with quantitative and descriptive statistical analyses (Irwanto & Rini, 2024). Bibliometrics is divided into descriptive, evaluative and citation analyses (Kırık, 2024). Descriptive bibliometrics involves revealing the distribution and trends of the relevant literature according to years, subjects, languages etc. with descriptive statistics; evaluative bibliometrics involves revealing the interactions between authors, publications and countries, the interaction of authors and citation status and providing the measurement of the results (Yelman & İnal, 2024); and citation analysis on the one hand is the statistical analysis of the citations cited to the published studies (Kırık, 2024). In this direction, the method of the research was determined as descriptive bibliometrics.

## Sample

A purposive sampling method (Yıldırım & Şimşek, 2006) was employed in selecting the sample of 273 studies for the research based on the following criteria:

- Studies conducted within the scope of education in Turkey
- Studies conducted with sample(s) selected in Turkey
- Studies conducted between 2000 and 2023
- Studies reported as theses, articles, or conference papers
- Studies including the following keywords either in English or Turkish: "modern physics, quantum physics, quantum mechanics, photoelectric event, Compton event, De Broglie matter wave, Heisenberg uncertainty principle, blackbody radiation, Einstein theory of relativity, Lorentz transformations, double slit experiment, ionization energy, Pauli exclusion principle, Michelson Morley experiment, tunnelling event, atom, atomic models, atom concept orbital, electromagnetic waves, x-ray radioactivity, nuclear energy, nuclear reactions"

## Data Collection Tools

The Modern Physics Education Publication Classification Form (MPEPCF), developed during the research process was used to collect data in the study. The forms of studies conducted within the scope of the publication classification form were examined when developing the MPEPCF, and a new publication classification form was developed based on the purpose of this research. MPEPCF includes descriptive information about the research identity, topic, purpose, type, method, study group or sample, data collection tools, intervention duration, data analysis methods, validity and reliability methods, discussion, conclusions, and recommendations. For its validation, MPEPCF was presented to an expert in physics education, two experts in curriculum development and instruction, and two experts in measurement and evaluation. A draft form was created based on the expert opinions. Subsequently, the researchers conducted a pilot application of the draft form in 12 randomly selected studies. After the pilot application, to enhance the reliability of the form, consistency among researchers was examined. Necessary revisions and additions were made based on the shared opinions of the experts, and the final version of the form was created.

## Data Collection

The data collection for the research began in April 2023 and continued until the completion of the study in December 2023. Priority was given to including newly published studies in the data. Studies included in the research were selected from the YOK National Thesis Centre, Tübitak Ulakbim, Sobiad, Doaj, Tei, Elsevier, Ebscohost-ERIC, Scopus, SpringerLink, Taylor & Francis, and Google Scholar databases. Studies on modern physics education were searched in databases using the keywords determined in Turkish and English. As a result, 303 studies were retrieved. However, sufficient information could not be obtained about the contents of 12 theses, 10 articles, and 7 conference papers due to their inaccessibility or unavailability in full text. In this context, attempts were made to contact the relevant authors, whereby the full texts of 283 studies were obtained. Upon examining the contents of the accessed studies, it was determined that 10 studies were not within the scope of modern physics education, and therefore, 273 studies were included in the research. However, some studies had the same title as conference papers, theses, or articles. To avoid repetition, only the article versions of the studies were included in the research.

## Data Analysis

In the research, content analysis, one of the qualitative data analysis techniques, was used in the analysis of the data of the studies included in the research. Content analysis enables the objective and systematic determination of the explicitly stated characteristics of studies that cannot be directly measured or observed, allowing for inferences to be made about them (Cavitt, 2006). According to Yıldırım and Şimşek (2006), the primary goal in content analysis is to bring together similar data within the framework of specific concepts and themes, interpreting them in a way that the reader can understand. Thus, it serves as a guide for researchers in determining trends and areas of interest in the field. In this context, all the research studies included in this study were initially saved in data storage in PDF format. Subsequently, on a Microsoft Excel worksheet, the author names and study titles were entered in rows, while in columns, the main and subheadings of MPEPCF (e.g., database, publication year, publication language, subject area, purpose, data collection tool, and database) were determined and classified and a template was created. Studies were examined one by one according to this template and recorded in a Microsoft Excel worksheet. However, at these stages, it was determined that some studies included insufficient information, especially regarding the research methods, types of data collection tools, and data analysis methods. After all these processes, the data for each study were coded in a Microsoft Excel sheet and analysed using the SPSS statistical software package.

## Validity and Reliability

To ensure the validity of the research, the process followed in each part of the study was explained in detail. To ensure coding reliability during the data analysis process, researchers independently reviewed the studies and created themes and codes. Meetings and discussions were held when there were differences between the two coders in the process of comparing the codes. When necessary, expert opinions (one in Curriculum and Instruction, one in Physical Education, and one in Measurement and Evaluation) were sought to reach a consensus. The coding reliability calculated using Huberman and Miles's (2002) formula (Reliability = Consensus / Consensus + Disagreement x 100) was 91%. Subsequently, the data obtained for each study were tabulated and presented in the findings section. Finally, the findings were presented again to the same experts and reported based on the feedback received.

## Ethical Measures

For the ethical measures of the research, initially, an application was submitted to the Social and Humanities Ethics Committee of a state university in Turkey, and the research was deemed ethically appropriate with decision No. E-74009925-604.01.02-750991. Further, to avoid data redundancy in studies conducted within the scope of modern physics education, each reviewed study was coded as S1, S2...S273.

# Findings

The findings obtained in the research are presented in order according to the research questions and tabulated in the form of frequency and percentage values.

## Distribution of Studies Conducted in Modern Physics Education According to Descriptive Information Regarding the Research Identity

In this section of the research, information regarding studies, such as database, publication type, publication language, publication year, and years, was examined, leading to the findings presented in Table 1.

**Table 1**

*Distribution of studies by publication years and databases*

| Database | f | % | Database | f | % |
|---|---|---|---|---|---|
| Tübitak Ulakbim | 114 | 41.8 | Springerlink | 6 | 2.2 |
| YOK | 75 | 27.5 | Taylor & Francis | 5 | 1.8 |
| ERIC | 30 | 11.0 | Doaj | 4 | 1.5 |
| Scopus | 22 | 8.1 | Sobiad | 2 | 0.7 |
| Science Direct | 7 | 2.6 | Tei | 1 | 0.4 |
| Google Scholar | 7 | 2.6 | | | |

As seen in Table 1, 273 studies were conducted within the scope of modern physics education in Turkey and published in various databases. Most studies ($f$ = 114) were published in Ulakbim, followed by YOK ($f$ = 75), ERIC ($f$ = 30), and Scopus ($f$ = 22) databases, respectively.

**Table 2**

*Distribution of studies by types of studies*

| Type | f | % |
|---|---|---|
| Article | 189 | 69.2 |
| Master's thesis | 54 | 19.8 |
| Doctoral dissertation | 21 | 7.7 |
| Conference paper | 9 | 3.3 |

As seen in Table 2, the majority of studies on modern physics education were articles ($f$ = 189), followed by Master's theses ($f$ = 54) and doctoral dissertations ($f$ = 21), respectively.

**Table 3**

*Distribution of studies by publication language*

| Publication Language | f | % |
|---|---|---|
| Turkish | 188 | 68.9 |
| English | 85 | 31.1 |

According to Table 3, the studies were conducted in Turkish ($f$ = 188) and English ($f$ = 85) languages.

**Table 4**

*Distribution of subject areas of studies by year*

| Year | Subject Areas | f | % |
|---|---|---|---|
| 2000 | Compton effect (f=1) | 1 | 0.4 |
| 2001 | Compton effect (f=1), Photoelectric effect (f=1), Theory of relativity (f=1), Heisenberg uncertainty principle (f=1) | 4 | 1.5 |
| 2002 | Photoelectric effect (f=1), Heisenberg uncertainty principle (f=1), Double slit experiment (f=1), Radiation (f=1), Quantum mechanics (f=1) | 5 | 1.8 |
| 2003 | Blackbody light (f=1), X-Ray (f=1) | 2 | 0.7 |

| | | | |
|---|---|---|---|
| 2004 | Photoelectric effect (f=2) | 2 | 0.7 |
| 2005 | Atom (e.g., Atom models, Atomic structure, and Atom concept) (f=2), Compton effect (f=1), Doppler effect (f=1), Theory of relativity (f=2), De Broglie matter waves (f=1) | 7 | 2.6 |
| 2006 | De Broglie matter waves (f=1), Blackbody Radiation (f=1) | 2 | 0.7 |
| 2007 | Atom (e.g., Atom models, Atomic structure, and Atom concept) (f=2), De Broglie matter waves (f=1), Laser (f=1) | 4 | 1.5 |
| 2008 | Atom (e.g., Atom models, Atomic structure, and Atom concept) (f=1), Theory of relativity (f=2), Heisenberg uncertainty principle (f=1) | 4 | 1.5 |
| 2009 | Atom (e.g., Atom models, Atomic structure, and Atom concept) (f=1), Compton effect (f=2), Photoelectric effect (f:1), Electromagnetic wave (f=1), Theory of relativity (f=2), Radiation (f=1), Tunneling effect (f=1) | 9 | 3.3 |
| 2010 | Atom (e.g., Atom models, Atomic structure, and Atom concept) (f=1), Photoelectric effect (f:5), Heisenberg uncertainty principle (f=1), Double slit experiment (f=1), De Broglie matter waves (f=2), Blackbody Radiation (f=1), Radioactivity (f=1), Radiation (f=1), X-Ray (f=2) | 15 | 5.5 |
| 2011 | Atom (e.g., Atom models, Atomic structure, and Atom concept) ( f =2), Compton effect (f=2), Photoelectric effect (f:1), Doppler effect (f=1), Electromagnetic wave (f=1), Theory of relativity ( f=3), Ionization energy (f=1), Double slit experiment (f=1), Blackbody Radiation (f=2), Radioactivity (f=3), Pauli exclusion principle (f=1), Energy levels (f=2) | 20 | 7.3 |
| 2012 | Atom (e.g., Atom models, Atomic structure, and Atom concept) (f=2), Photoelectric effect (f:2), Nuclear chemistry (f=1), Electromagnetic wave (f=1), Theory of relativity (f=2), De Broglie matter waves (f=2), Michelson Morley experiment (f=1), Pauli exclusion principle (f=1) | 12 | 4.4 |
| 2013 | Atom (e.g., Atom models, Atomic structure, and Atom concept) (f=1), Compton Effect (f=1), Photoelectric effect (f:1), Orbital (f=1), Theory of relativity (f=2), Heisenberg uncertainty principle (f= 3), Double Slit Experiment (f=1), Radioactivity (f=1), Radiation (f=1), X-Ray (f=1) | 13 | 4.8 |
| 2014 | Atom (e.g., Atom models, Atomic structure, and Atom concept) (f=4), Compton Effect (f=1), Photoelectric effect (f:3), Electromagnetic wave (f=1), Theory of relativity (f=2), Heisenberg uncertainty principle (f) =3), Double slit experiment (f=1), De Broglie matter waves (f=1), Blackgrass light (f=1), Spin (f=1), Nuclear energy (f=1), Tunneling event (f=1) ) | 20 | 7.3 |
| 2015 | Atom (e.g., Atom models, Atomic structure, and Atom concept) (f=2), Compton Event (f=2), Photoelectric event (f:5) Orbital (f=2), Electromagnetic wave (f=2), Theory of relativity (f=2), Heisenberg uncertainty principle (f=3), Double slit experiment (f=3), De Broglie matter waves (f=2), Blackbody Radiation (f=2), Radioactivity (f=3), Radiation (f=1), Quantum mechanics (f=2) | 31 | 11.4 |
| 2016 | Atom (e.g., Atom models, Atomic structure, and Atom concept) ( f =4), Compton effect (f=1), Photoelectric effect (f:2), Theory of relativity (f=2), Heisenberg uncertainty principle (f=3), Blackbody Radiation (f=1), Radioactivity (f=5), Pauli exclusion principle (f=1), Quantum number (f=1), Quantum mechanics (f=3), Redshift (f=1), X-Ray (f=2), Tunneling effect (f=1) | 27 | 9.9 |
| 2017 | Atom (e.g., Atom models, Atomic structure, and Atom concept) (f=4), Compton effect (f=1), Photoelectric effect (f:1), Theory of relativity (f=2), Ionization energy (f=1), Heisenberg uncertainty principle (f) =1), De Broglie matter waves (f=4), Blackbody Radiation (f=1), Radiation (f=1), Energy levels (f=1), Quantum mechanics (f=1), X-Ray (f= 1), Particle accelerator (f=1) | 20 | 7.3 |

| | | | |
|---|---|---|---|
| 2018 | Atom (e.g., Atom models, Atomic structure, and Atom concept) (f=1), Compton effect (f=5), Photoelectric effect (f:1), Orbital (f=1), Electromagnetic wave (f=2), Theory of relativity (f) =2), Ionization energy (f=1), Radioactivity (f=1), Pauli exclusion principle (f=1), Quantum number (f=2), Harmonic oscillator (f=1), Quantum paradigm (f=1) | 19 | 7.0 |
| 2019 | Atom (e.g., Atom models, Atomic structure, and Atom concept) (f=4), Compton effect (f=4), Photoelectric effect (f:3), Electromagnetic wave (f=3), Theory of relativity (f=4), Heisenberg uncertainty principle (f=3), De Broglie matter waves (f=3), Blackbody Radiation (f=1), Radioactivity (f=2), Radiation (f=2), Energy levels (f=1), Quantum mechanics (f=1), Quantum paradigm (f=1), X-Ray (f=1) | 33 | 12.1 |
| 2020 | Photoelectric effect (f:1), Doppler effect (f=1), Theory of relativity (f=1), Heisenberg uncertainty principle (f=2), Radioactivity (f=1), Pauli exclusion principle (f=1), Quantum number (f=1) | 8 | 2.9 |
| 2021 | Electromagnetic wave (f=1), Relativity (f=2), De Broglie matter waves (f=1) | 4 | 1.5 |
| 2022 | Atom (e.g., Atom models, Atomic structure, and Atom concept) (f =1), Photoelectric Effect (f:1), Electromagnetic wave (f=1), Heisenberg uncertainty principle (f=2), De Broglie matter waves (f=1), X-Ray (f=2) | 8 | 2.9 |
| 2023 | Compton effect (f=2), Photoelectric effect (f:1) | 3 | 1.1 |

When Table 4 is examined the most studies were conducted in 2019 (*f* = 33), followed by 2015 (*f* = 31) and 2016 (*f* = 27). The years in which the least studies were conducted were between 2000-2009. The number of studies has decreased in the last five years. The most preferred topic in the studies was the atom (atomic models, atomic structure, concept of the atom, etc.), followed by the photoelectric effect, Theory of Relativity, nuclear energy and the Compton Effect respectively. In recent years, different topics such as the Pauli Exclusion Principle, electromagnetic waves, quantum mechanics, Quantum number and the harmonic oscillator have also been included.

## Distribution of Studies Conducted in Modern Physics Education by Subject Areas

In this section of the research, findings related to the subject areas of studies conducted in modern physics education are discussed and presented in Table 5.

**Table 5**

*Distribution of studies according to their frequency of topic areas*

| Code | f | % |
|---|---|---|
| Atom (e.g., Atom models, Atomic structure, and Atom concept) | 99 | 24.4 |
| Photoelectric effect | 34 | 8.4 |
| Theory of relativity (Special and General Relativity) | 34 | 8.4 |
| Nuclear energy | 33 | 8.1 |
| Compton effect | 28 | 6.9 |
| Heisenberg uncertainty principle | 27 | 6.7 |
| Radioactivity | 22 | 5.4 |
| De Broglie matter waves | 20 | 4.9 |
| Electromagnetic waves | 15 | 3.7 |
| Blackbody Radiation | 12 | 3.0 |
| X-Ray | 11 | 2.7 |

| | | |
|---|---|---|
| Radiation | 10 | 2.5 |
| Quantum mechanics | 9 | 2.2 |
| Double slit experiment | 9 | 2.2 |
| Orbital | 6 | 1.5 |
| Energy level | 5 | 1.2 |
| Quantum number | 5 | 1.2 |
| Pauli exclusion principle | 5 | 1.2 |
| Tunneling effect | 4 | 1.0 |
| Ionization energy | 3 | 0.7 |
| Doppler effect | 3 | 0.7 |
| Spin | 2 | 0.5 |
| Nuclear chemistry | 2 | 0.5 |
| Quantum paradigm | 2 | 0.5 |
| Particle accelerator | 2 | 0.5 |
| Laser beam | 1 | 0.2 |
| Michelson Morley experiment | 1 | 0.2 |
| Redshift | 1 | 0.2 |
| Harmonic oscillator | 1 | 0.2 |

As observed in Table 5, most studies focused on atoms (e.g., atom models, atomic structure, and atom concept) (*f* = 99), followed by the Photoelectric effect (*f* = 34), Theory of relativity (*f* = 34), Nuclear energy (*f* = 33), Compton effect (*f* = 28), and Heisenberg uncertainty principle (*f* = 27). The least studied topics were laser beams, the Michelson-Morley experiment, the red shift, and harmonic oscillators.

## Distribution of Studies Conducted in Modern Physics Education by Their Objectives

In this section, the objectives of studies conducted in modern physics education are identified, and the findings are presented in Table 6.

**Table 6**

*Distribution of studies by their objectives*

| Theme | Code | f | % |
|---|---|---|---|
| Instructional Method and Technique Effectiveness | Computer-assisted instruction | 19 | 7.0 |
| | Constructivist approach | 11 | 4.0 |
| | Cooperative learning | 9 | 3.3 |
| | Argumentation | 7 | 2.6 |
| | Experimentation | 6 | 2.2 |
| | Writing for learning | 5 | 1.8 |
| | Blended (hybrid) learning | 4 | 1.5 |
| | Analogy | 4 | 1.5 |
| | Problem-based | 2 | 0.7 |
| | Drama | 2 | 0.7 |
| | Educational trip | 2 | 0.7 |
| | Peer teaching | 2 | 0.7 |
| | Conceptual map | 2 | 0.7 |
| | Roleplay | 1 | 0.4 |
| Material Effectiveness | Simulation/animation | 5 | 1.8 |
| | Conceptual change text worksheets | 4 | 1.5 |
| | 3D drawing | 4 | 1.5 |

| | | | |
|---|---|---|---|
| | Modelling | 3 | 1.1 |
| | Pictures (photographs, caricatures, and more) | 2 | 0.7 |
| | Marbling art | 1 | 0.4 |
| Test-Scale-Questionnaire Development/ Adaptation | Multiple-choice achievement test | 7 | 2.6 |
| | Two-stage achievement test | 2 | 0.7 |
| | Three-stage achievement test | 2 | 0.7 |
| | Four-stage achievement test | 1 | 0.4 |
| | Scale and questionnaire development/ adaptation | 3 | 1.1 |
| Curriculum | Curriculum development | 5 | 1.8 |
| | Curriculum review or evaluation | 3 | 1.1 |
| Textbooks | Physics, chemistry, and science textbook review or evaluation | 11 | 4.0 |
| Cognitive Characteristics | Mental model | 20 | 7.3 |
| | Knowledge level | 20 | 7.3 |
| | Conceptual understanding | 15 | 5.5 |
| | Conceptual misconception | 10 | 3.7 |
| | Problem-solving skills | 9 | 3.3 |
| Affective Characteristics | Perception | 10 | 3.7 |
| | Awareness | 5 | 1.8 |
| | Attitude-anxiety relationship | 3 | 1.1 |
| | Interest-motivation | 2 | 0.7 |
| Situation Determination | General views on the subject | 38 | 13.9 |
| | Metaphor | 8 | 2.9 |
| Literature Review | Review | 2 | 0.7 |
| Structural Equation Modeling | - | 2 | 0.7 |

As shown in Table 6, the main foci of the studies were the themes of instructional method and technique effectiveness, material effectiveness, test-scale-questionnaire development/adaptation, curriculum, textbook, cognitive and affective characteristics, situation determination, literature review, and structural equation modelling. In the theme of instructional method and technique effectiveness, the primary focus was on the effectiveness of computer-assisted instruction ($f$ = 19) and the constructivist approach ($f$ = 11), followed by cooperative learning ($f$ = 9), argumentation ($f$ = 7), and experimentation ($f$ = 6) methods, respectively. Within the scope of material effectiveness, the effectiveness of simulation/animation ($f$ = 5), conceptual change text worksheets ($f$ = 4), and 3D drawings ($f$ = 4) in learning was explored. Under the theme of test-scale-questionnaire development/adaptation, the focus was on developing achievement tests. These tests included multiple-choice, two-stage, three-stage, and four-stage achievement tests. Within the scope of the curriculum, the objectives of the studies focused on curriculum development ($f$ = 5) and curriculum review/evaluation ($f$ = 3). In the theme of textbooks, researchers have examined and evaluated physics, chemistry, and natural sciences textbooks ($f$ = 11) within the scope of the research objectives.

As seen in Table 6, some studies also aimed to examine the cognitive and affective characteristics of students regarding modern physics topics. Among the cognitive characteristics aimed to be investigated, prominent ones included determining students' mental models ($f$ = 20) and knowledge level ($f$ = 20), followed by determining their level of conceptual understanding ($f$ = 15) and conceptual misconceptions ($f$ = 10), respectively. Regarding affective characteristics, the focus has been on examining perception, awareness, the attitude-anxiety relationship, and interest/motivation related to the subject. Other elements included determining the existing situation regarding modern physics education, literature review, and structural equation modelling.

## Distribution of Studies Conducted in Modern Physics Education by Research Design

Studies in modern physics education included in this research were conducted using different research designs. In this context, the findings obtained are presented in Table 7.

**Table 7**

*Distribution of studies by research design*

| Theme | | Code | f | % |
|---|---|---|---|---|
| Quantitative | Experimental | True experimental | 10 | 3.7 |
| | | Quasi-experimental | 54 | 19.8 |
| | | Weak experimental | 9 | 3.3 |
| | Non-experimental | Descriptive survey | 25 | 9.2 |
| | | Scale-questionnaire-test development/ adaptation | 15 | 5.5 |
| | | Correlational survey | 8 | 2.9 |
| | | General survey | 4 | 1.5 |
| | | Comparative correlational survey | 3 | 1.1 |
| | | Structural equation modelling | 2 | 0.7 |
| Qualitative | Interactive | Case study | 82 | 30.0 |
| | | Phenomenology | 8 | 2.9 |
| | | Unreported | 2 | 0.7 |
| | Non-interactive | Document analysis | 14 | 5.1 |
| | | Literature review | 2 | 0.7 |
| Mixed | | Explanatory design | 3 | 1.1 |
| | | Exploratory design | 4 | 1.5 |
| | | Convergent design | 1 | 0.4 |
| | | Intervention design | 2 | 0.7 |
| | | Unreported | 14 | 5.1 |
| Unreported | ----- | Unreported | 11 | 4.0 |

As observed in Table 7, among the studies using quantitative methods, 73 preferred experimental models and 57 preferred non-experimental models. Of experimental approaches, the quasi-experimental method ($f$ = 54) was preferred more than other experimental methods. In non-experimental methods, descriptive survey ($f$ = 25) and scale-questionnaire-test development/adaptation ($f$ =15) were the most commonly used designs. Furthermore, 108 studies conducted in modern physics education preferred qualitative research methods. Among interactive qualitative methods, case study ($f$ = 82) was preferred the most, followed by phenomenology ($f$ = 8). In non-interactive qualitative methods, document analysis ($f$ = 14) and literature review ($f$ = 2) were preferred. Considering the mixed-method studies, exploratory design ($f$ = 4) was preferred the most, followed by explanatory ($f$ = 3), intervention ($f$ = 2), and convergent ($f$ = 1) designs, respectively. Another noteworthy finding here is that 14 studies opting for mixed methods did not specify which mixed-method design they used in the research process. Additionally, 11 studies did not report the research design they preferred during the research process.

## Distribution of Studies in Modern Physics Education by Sample Types, Sample Levels, and Sample Sizes

Sample types, sample levels, and sample sizes of studies conducted in modern physics education were coded in the research. Descriptive statistics showing the distribution obtained after this coding are presented in Table 8.

**Table 8**

*Distribution of studies by types of samples*

| Sampling Method | | f | % |
|---|---|---|---|
| Random sampling | Simple random | 39 | 13.6 |
| | Unreported | 4 | 1.4 |
| Non-random sampling | Purposive | | |
| | *Criterion* | 31 | 10.8 |
| | *Maximum* | 23 | 7.7 |
| | *Stratified* | 8 | 2.8 |
| | *Typical case* | 5 | 1.7 |
| | *Homogenous* | 4 | 1.4 |
| | Convenient | 59 | 20.6 |
| | Systematic | 4 | 1.4 |
| | Unreported | 17 | 5.9 |
| Unreported | --- | 93 | 32.5 |

According to the findings in Table 8, studies conducted in modern physics education mostly preferred simple random sampling ($f$ = 39) in random sampling and purposive sampling ($f$ = 71) in non-random sampling. In purposive sampling, criterion sampling ($f$ = 31) was preferred the most, followed by maximum ($f$ = 23) and stratified sampling ($f$ = 8). However, 17 studies did not specify the type of purposive sampling. Additionally, 93 studies did not report any information about the type of sampling.

**Table 9**

*Distribution of studies by sample levels*

| Sample Group | f | % |
|---|---|---|
| Primary school | 1 | 0.3 |
| Middle school | 35 | 11.7 |
| High school | 65 | 21.7 |
| Associate degree | 4 | 1.3 |
| Undergraduate (Education faculty) | 148 | 49.3 |
| Undergraduate (Not from education faculty) | 9 | 3.0 |
| Graduate | 2 | 0.7 |
| Teacher | 17 | 5.7 |
| Expert | 4 | 1.3 |
| Parents | 3 | 1.0 |
| Other | 12 | 4.0 |

As seen in Table 9, in studies conducted in modern physics education, the sample group of education faculty undergraduate level ($f$ = 148) was most commonly preferred, followed by high school ($f$ = 65), middle school ($f$ = 35), and teachers ($f$ = 17). Graduate, parent, and primary school levels were the least preferred sample groups.

**Table 10**

*Distribution of studies by sample size*

| Sample Size | f | % |
|---|---|---|
| 1-10 | 28 | 9.3 |
| 11-30 | 55 | 18.3 |
| 31-100 | 103 | 34.3 |
| 101-300 | 67 | 22.3 |
| 301-1000 | 31 | 10.3 |
| 1001+ | 4 | 1.3 |
| Other | 12 | 4.0 |

As observed in Table 10, the studies were mostly conducted with sample sizes ranging between 31 and 100 (*f* = 103). Following this range, sample sizes ranging between 101 and 300 (*f* = 67) and between 11 and 30 (*f* = 55) were used. According to the research results, it was determined that studies with sample sizes exceeding 1000 were less common (*f* = 4) compared to others.

## Distribution of Studies Conducted in Modern Physics Education by Intervention Duration

The intervention durations of studies conducted in modern physics education were analyzed, and descriptive statistics related to the coding after the analysis are presented in Table 11.

**Table 11**

*Distribution of studies by intervention duration*

| Intervention Duration | f | % | Intervention Duration | f | % |
|---|---|---|---|---|---|
| Unreported | 112 | 41.0 | 21-24 weeks | 4 | 1.5 |
| 0-1 week | 44 | 16.1 | 25-28 weeks | 3 | 1.1 |
| 1-4 weeks | 45 | 16.5 | 49-52 weeks | 8 | 2.9 |
| 5-8 weeks | 14 | 5.1 | 2 years | 2 | 0.7 |
| 9-12 weeks | 10 | 3.7 | 3 years | 3 | 1.1 |
| 13-16 weeks | 23 | 8.4 | 4 years | 1 | 0.4 |
| 17-20 weeks | 4 | 1.5 | | | |

As seen in Table 11, the majority of the studies examined within the scope of this research did not report the intervention durations. Among the studies that reported the intervention duration, the majority preferred the 0–1-week (*f* = 44) and 1–4-week (*f* = 45) ranges, followed by the 13–16-week (*f* = 23) and 5-8 week (*f* = 14) ranges. It was also determined that there were few long-term studies in the field of modern physics education.

## Distribution of Studies Conducted in Modern Physics Education by Data Collection Techniques/Tools and Data Analysis Types

Studies conducted in modern physics education employed various data collection techniques/tools and data analysis types. The findings obtained are given in Tables 12 and 13.

**Table 12**

*Distribution of studies by data collection tools*

| Theme | Code | f | % |
|---|---|---|---|
| Interview | Semi-structured interview | 73 | 18.5 |
| | Unstructured interview | 6 | 1.5 |
| | Structured interview | 4 | 1.0 |
| | Other | 10 | 2.5 |
| Observation | Unstructured observation | 8 | 2.0 |
| | Semi-structured observation | 4 | 1.0 |
| | Structured observation | 4 | 1.0 |
| | Other | 4 | 1.0 |
| Scale | Likert type | 43 | 10.9 |
| | Multiple-choice | 14 | 3.5 |
| | Other | 9 | 2.3 |
| Test | Multiple-choice | 39 | 9.9 |
| | Open-ended | 31 | 7.8 |
| | Other | 19 | 4.8 |
| Questionnaire | Likert type | 35 | 8.9 |
| | Open-ended | 23 | 5.8 |
| | Other | 9 | 2.3 |
| Alternative tools | Performance, portfolio, etc. | 36 | 9.1 |
| | Other | 2 | 0.5 |
| Documents | Books, developed activities, texts, etc. | 22 | 5.6 |

As seen in Table 12, the data collection tools preferred in the research process of studies were interviews, observations, scales, tests, questionnaires, alternative tools and documents. The most preferred measurement tool was interviews ($f = 93$), followed by tests ($f = 89$), questionnaires ($f = 67$), and scales ($f = 66$). The least used data collection tool was observation.

**Table 13**

*Distribution of studies by data analysis methods*

| Theme | Code | f | % |
|---|---|---|---|
| Quantitative | *Descriptive* | | |
| | Frequency/percentage | 105 | 23.0 |
| | Mean/standard deviation | 9 | 2.0 |
| | Visualization with graphics | 8 | 1.8 |
| | Other | 4 | 0.9 |
| | *Inferential* | | |
| | t-test | 51 | 11.2 |
| | Item analysis | 48 | 10.5 |
| | ANOVA/ANCOVA | 37 | 8.1 |
| | Non-parametric tests | 18 | 3.9 |
| | Factor analysis | 13 | 2.9 |
| | MANOVA/MANCOVA | 12 | 2.6 |
| | Correlation analysis | 3 | 0.7 |
| | Structural equation modeling | 2 | 0.4 |

| | | | |
|---|---|---|---|
| | Path analysis | 2 | 0.4 |
| | Regression analysis | 1 | 0.2 |
| Qualitative | Content analysis | 97 | 21.3 |
| | Descriptive analysis | 27 | 5.9 |
| | Document analysis | 9 | 2.0 |
| | Other | 7 | 1.5 |
| Unreported | ----- | 3 | 0.7 |

As seen in Table 13, studies conducted in modern physics education mostly employed frequency/percentage (*f* = 105) for quantitative descriptive values and the t-test for quantitative inferential values in data analysis. In qualitative analyses, content analysis (*f* = 97) and descriptive analysis (*f* = 27) were the most commonly used types of analysis. Another noteworthy finding is that three studies provided no explanation regarding the analysis methods.

## Distribution of Studies Conducted in Modern Physics Education by Validity and Reliability Types

In this section, the validity and reliability methods used in studies conducted in modern physics education are presented, and the findings are given in Tables 14 and 15.

**Table 14**

*Distribution of studies by validity types*

| Theme | Code | f | % |
|---|---|---|---|
| Design | Ensuring data diversity/collecting data from multiple sources | 33 | 3.0 |
| | Determining a purposeful sample | 30 | 2.7 |
| Study Group | Reporting the sampling method | 85 | 4.1 |
| | Describing the sample characteristics | 75 | 10.4 |
| | Using codes instead of participant names | 72 | 6.5 |
| | Participants' freedom to withdraw | 23 | 2.1 |
| | Describing the research population | 14 | 1.3 |
| | Longtime interaction | 13 | 1.2 |
| Research Process | Expert review | 170 | 15.4 |
| | Providing a detailed description regarding the intervention process | 128 | 11.6 |
| | Explaining the rationale for the method and relating it to the literature | 73 | 6.6 |
| | Describing assumptions and limitations | 53 | 4.8 |
| | Pilot application | 51 | 4.6 |
| | Describing the validity and reliability measures | 43 | 3.9 |
| Data Analysis | Providing a detailed explanation of the data collection process | 132 | 12.0 |
| | Describing the data analysis procedure | 88 | 8.0 |
| Unreported | --- | 18 | 1.6 |

According to Table 14, studies conducted within the scope of modern physics education utilized various validity types in research design, study group, research process, and data analysis themes. In the research design, ensuring data diversity (*f* = 33) and determining a purposeful sample (*f* = 30) were more prominently expressed in the study group. Reporting the sampling method (*f* = 85) and describing the sample characteristics (*f* = 75) were also mentioned. In the research process, expert review (*f* = 170) and detailed description of the intervention process (*f* = 128) were emphasized. In terms of data analysis, the preferred validity methods were mostly focused on providing a detailed explanation of the data collection process.

**Table 15**

*Distribution of studies by reliability types*

| Theme | Code | f | % |
|---|---|---|---|
| Researcher | Calculating inter-coder consistency | 78 | 15.4 |
| | Separate analyses by two researchers | 55 | 10.9 |
| | Explaining the researcher's role | 18 | 3.6 |
| | Seeking expert opinion in comparing findings and results | 16 | 3.2 |
| | Internal audit among researchers with independent controls | 10 | 2.0 |
| Study Group | Direct quotations from participants' statements | 62 | 12.3 |
| | Participant control | 27 | 5.3 |
| Data Analysis | Employing variation in data analysis | 32 | 6.3 |
| | Data quality | 18 | 3.6 |
| | Considering code and category consistency | 15 | 3.0 |
| | Data analysis at different times | 13 | 2.6 |
| | Cronbach Alpha | 51 | 10.1 |
| | KR20-21 | 35 | 6.9 |
| | Item total score correlation | 4 | 0.8 |
| | Test-retest | 3 | 0.6 |
| | Spearman Brown | 4 | 0.8 |
| | Parallel Test | 4 | 0.8 |
| | Kendall | 3 | 0.6 |
| Unreported | ---- | 58 | 11.5 |

As seen in Table 15, the reliability methods of the studies reviewed within the scope of modern physics education were categorized under researcher, study group, and data analysis themes. In the researcher theme, calculating inter-coder consistency ($f$ = 78) and separate analysis by two researchers ($f$ = 55) were more prevalent, while in the study group theme, direct quotations from participants' statements ($f$ = 62) were utilized more. In the data analysis theme, employing variation in data analysis, Cronbach's Alpha, and KR20-21 were the most preferred reliability methods. Additionally, 61 studies did not report any information on reliability methods.

## Distribution of Studies Conducted in Modern Physics Education Based on Their Results, Discussions, and Recommendations

This section presents findings regarding the results, discussions regarding the results, and recommendations for future research based on studies conducted in modern physics education.

**Table 16**

*Distribution of studies based on their results*

| Theme | Code | f | % |
|---|---|---|---|
| Instructional methods and techniques | *Positive* | | |
| | Increase in academic achievement | 59 | 9.6 |
| | Concretisation of knowledge | 43 | 6.9 |
| | Development of positive emotions and thoughts | 40 | 6.5 |
| | Acquiring problem-solving skills | 19 | 3.1 |
| | Developing higher-order thinking skills | 17 | 2.7 |

| | | | |
|---|---|---|---|
| | Improving mathematical operation skills | 10 | 1.6 |
| | Relating knowledge to daily life | 8 | 1.3 |
| | Establishing relationships between concepts | 7 | 1.1 |

| | | | |
|---|---|---|---|
| | Commenting on reading passages | 6 | 1.0 |
| | Relating information across disciplines | 5 | 0.8 |
| | Reasoning about the topic | 4 | 0.6 |
| | Developing an understanding of modern physics thinking | 2 | 0.3 |
| | Interpreting visual materials | 1 | 0.2 |
| | *Negative* | | |
| | Development of negative emotions and thoughts | 5 | 0.8 |
| | Inability to resolve conceptual misconceptions | 3 | 0.5 |
| | Inability to perform numerical operations in solving problems | 2 | 0.3 |
| | No change in emotions or thoughts | 2 | 0.3 |
| Materials | *Positive* | | |
| | Concretisation of knowledge | 10 | 1.6 |
| | Development of positive emotions and thoughts | 10 | 1.6 |
| | More active participation in lessons | 4 | 0.6 |
| | Relating knowledge to daily life | 4 | 0.6 |
| | Developing higher-order thinking skills | 3 | 0.5 |
| | Increasing awareness concerning the subject | 3 | 0.5 |
| | *Negative* | | |
| | Development of negative emotions and thoughts (disliking, difficulty, and more) | 4 | 0.6 |
| | Persistence of conceptual misconceptions | 4 | 0.6 |
| Curriculum | *Positive* | | |
| | Adding current topics to the modern physics curriculum | 2 | 0.3 |
| | Incorporating the quantum paradigm into the modern physics curriculum | 2 | 0.3 |
| | Placing more emphasis on higher-order thinking skills in the modern physics curriculum | 1 | 0.2 |
| | *Negative* | | |
| | Continuing with the classical physics understanding in the modern physics curriculum | 2 | 0.3 |
| | Including lower-order learning outcomes in the modern physics curriculum | 2 | 0.3 |
| | Updating frequently | 2 | 0.3 |
| | Inconsistencies between theory and practice | 2 | 0.3 |
| | Preparing the curriculum without considering the needs in terms of activities, content, and more | 2 | 0.3 |
| Textbooks | Lack of clarity and understandability of expressions | 11 | 1.8 |
| | Being unsuitable for the age and developmental characteristics | 9 | 1.5 |
| | Content not being supported with subject-related tables, figures, diagrams, and examples | 7 | 1.1 |
| | Not reflecting the understanding of modern physics in the content | 5 | 0.8 |
| | Insufficiency in the number of learning outcomes | 4 | 0.6 |
| | Being written in a non-scientific language | 3 | 0.5 |
| | Not reflecting the latest developments in the subject area | 2 | 0.3 |
| | Topics not supporting each other | 2 | 0.3 |
| Tests/Scales/ Questionnaires | Developing valid and reliable tests or scales | 15 | 2.4 |
| Cognitive | *Determining a Mental Model* | | |
| | Maintaining a classical physics understanding | 12 | 1.9 |
| | Non-scientific explanations | 10 | 1.6 |
| | Non-scientific drawings | 8 | 1.3 |
| | Generating alternative concepts or thoughts | 7 | 1.1 |
| | Drawing appropriate models for the subject. | 6 | 1.0 |
| | *Conceptual understanding and knowledge levels* | | |
| | Failing to relate to daily life | 22 | 3.5 |
| | Continuing with the classical physics understanding | 17 | 2.7 |
| | Operational inadequacy in quantum mechanics | 16 | 2.6 |
| | Failing to concretise concepts | 15 | 2.4 |
| | Failing to define concepts or formulas | 8 | 1.3 |
| | Knowing basic concepts | 7 | 1.1 |
| | Providing different examples related to the topic | 2 | 0.3 |
| | *Conceptual Misconception* | | |

| | | | |
|---|---|---|---|
| | Failing to establish relationships between topics | 10 | 1.6 |
| | Explaining concepts with non-scientific expressions | 7 | 1.1 |
| | Incorrectly associating current examples with modern physics | 6 | 1.0 |
| | Failing to establish a connection from classical physics to modern physics. | 5 | 0.8 |
| | Misunderstanding in the philosophy of modern physics | 3 | 0.5 |
| | *Problem-Solving Skills* | | |
| | Failing to understand the question content | 8 | 1.3 |
| | Failing to interpret the question content | 7 | 1.1 |
| | Failing to reach a conclusion | 7 | 1.1 |
| | Failing to explain the formulas | 6 | 1.0 |
| | Failing to perform operations adequately | 5 | 0.8 |
| | Solving context-based problems more easily | 2 | 0.3 |
| | *Metaphor* | | |
| | Causing conceptual misconceptions | 5 | 0.8 |
| | Limiting the understanding of modern physics | 3 | 0.5 |
| | Facilitating the integration of information into daily life | 3 | 0.5 |
| | Developing creative thinking in modern physics | 2 | 0.3 |
| Affective | *Positive* | | |
| | Feeling the importance of the subject | 5 | 0.8 |
| | Realising that the subject is intertwined with daily life | 4 | 0.6 |
| | Feeling that the subject is easy/learnable | 3 | 0.5 |
| | Having sufficient awareness about the subject | 2 | 0.3 |
| | *Negative* | | |
| | Having negative prejudices regarding the subject | 14 | 2.3 |
| | Difficulty in developing an interest in the subject | 10 | 1.6 |
| | Thinking that the subject has a negative impact on health | 9 | 1.5 |
| | Not knowing the impact of the subject on daily life | 5 | 0.8 |
| | Developing positive feelings and thoughts towards the subject | 4 | 0.6 |
| | Having no awareness about the subject | 3 | 0.5 |
| Review | Providing insufficient information about the scope of their studies | 2 | 0.3 |
| | Providing little information regarding the data collection process of the studies. | 2 | 0.3 |

As seen in Table 16, it was observed that positive or negative changes have occurred in participants as a result of the instructional methods and techniques employed in the studies. In positive developments, an increase in academic achievement ($f$ = 59), concretisation of knowledge ($f$ = 43), and the development of positive feelings and thoughts towards the subject ($f$ = 40) were most frequently expressed. This was followed by acquiring problem-solving skills ($f$ = 19), developing higher-order thinking skills ($f$ = 17), improving mathematical operation skills ($f$ = 10), and relating knowledge to daily life ($f$ = 8). The negative side included the development of negative feelings and thoughts towards the subject, the inability to resolve conceptual misconceptions, and the inability to perform numerical operations in problem-solving. Similarly, the materials utilized in research studies brought about positive or negative changes in participants. Prominent positive developments include concretisation of knowledge ($f$ = 10), development of positive feelings and thoughts ($f$ = 10), and more active participation in lessons ($f$ = 4). On the negative side, there were the development of negative feelings and thoughts towards the subject (e.g., disliking, difficulty, and more; $f$ = 4) and persistence in conceptual misconceptions ($f$ = 4).

In the table, positive changes in the curriculum theme included adding current topics to the modern physics curriculum, incorporating the quantum paradigm into the modern physics curriculum, and placing more emphasis on higher-order thinking skills in the modern physics curriculum. The negative side involved maintaining a classical physics understanding, including lower-order learning outcomes, updating frequently, and inconsistencies between theory and practice. The results obtained for modern physics topics in physics/chemistry/science textbooks were generally negative. Accordingly, the most frequently mentioned issues included the lack of clarity and understandability of the expressions in textbooks, being unsuitable for the age and developmental characteristics of students, content not being supported with subject-related tables, figures, diagrams, and examples, and not reflecting the understanding of modern physics in the content. According to the research results, many valid and reliable tests/scales/questionnaires have been developed in the studies. Additionally, many studies have found that participants have positive or negative perspectives in both cognitive and affective aspects.

**Table 17**

*Distribution of studies based on their discussions*

| Code | f | % |
|---|---|---|
| The discussion is supported by the literature, but explanations of the literature are insufficient. | 106 | 35.9 |
| The discussion is supported by the literature, and explanations of the literature are sufficient. | 97 | 32.9 |
| The discussion is supported by the literature, but there are no explanations of the literature. | 40 | 13.6 |
| The discussion is supported by the intervention process of the research. | 24 | 8.1 |
| There is no discussion; only the conclusion is presented. | 12 | 4.1 |
| There is no literature in the discussion, only the researcher's interpretation. | 11 | 3.7 |
| The discussion is supported by the sample group characteristics. | 5 | 1.7 |

Considering the discussion section of the studies on modern physics education examined in Table 17, most studies were supported by literature, but there were differences in the explanations of the literature. From these explanations, it was concluded that 106 of them were insufficient, 97 were sufficient and 40 did not provide any explanations. Another noteworthy finding was that 12 studies did not include any discussion.

**Table 18**

*Distribution of studies based on their recommendations*

| Theme | Code | f | % |
|---|---|---|---|
| Investigating different variables | Interdisciplinary associations | 18 | 2.8 |
| | Examining affective characteristics | 18 | 2.8 |
| | Inquiry-based thinking | 3 | 0.5 |
| | Scientific literacy | 3 | 0.5 |
| | Retention of modern physics knowledge | 3 | 0.5 |
| | Relating the problems to daily life | 2 | 0.3 |
| | Development of scientific process skills | 2 | 0.3 |
| | Critical thinking | 1 | 0.2 |
| | Traditional problem-solving | 1 | 0.2 |
| | Academic achievement | 1 | 0.2 |
| Methods | More quantitative studies (e.g., true experimental) | 11 | 1.7 |
| | More qualitative studies (e.g., action, case, etc.) | 10 | 1.6 |
| | More mixed-method studies | 4 | 0.6 |
| Sample Groups | Secondary education | 48 | 7.6 |
| | Middle school | 37 | 5.9 |
| | Primary school | 21 | 3.3 |
| | Those studying in different departments of education faculties | 8 | 1.3 |
| | Those studying outside the education faculty | 5 | 0.8 |
| | Different countries | 3 | 0.5 |
| Sample Sizes | Larger sample sizes | 19 | 3.0 |
| | Smaller sample sizes | 5 | 0.8 |
| Instructional Methods and Techniques | Applying the same instructional method and technique to other modern physics subjects | 36 | 5.7 |
| | Using individualized instruction techniques more | 33 | 5.2 |
| | Placing more emphasis on problem-solving teaching methods | 18 | 2.8 |
| | Incorporating out-of-class instruction techniques | 10 | 1.6 |
| | Increasing teacher-student communication in the learning process | 5 | 0.8 |

| | | | |
|---|---|---|---|
| Materials | Animations/simulations | 42 | 6.6 |
| | Interactive experiments | 36 | 5.7 |
| | Visual elements (e.g., photographs and caricatures) | 34 | 5.1 |
| | Augmented reality experiments | 15 | 2.4 |
| | Using stories, brochures, and worksheets for different learning purposes | 8 | 1.3 |
| | Using experimental designs developed within the scope of the literature | 6 | 0.9 |
| | Using worksheets with graphical and visual content | 5 | 0.8 |
| | Incorporating writing activities for learning purposes | 3 | 0.5 |
| | Technological tools and equipment | 2 | 0.3 |
| Duration | Increasing the intervention duration | 13 | 2.1 |
| | Decreasing the intervention duration | 3 | 0.5 |
| Subject Content | Incorporating the philosophy of modern physics | 19 | 3.0 |
| | Relating topics to each other | 11 | 2.1 |
| | Placing more emphasis on problem-solving | 8 | 1.3 |
| | Relating more to daily life | 7 | 1.1 |
| | Including the history of science in the content | 5 | 0.8 |
| | Including current examples | 3 | 0.5 |
| | Reducing the content | 2 | 0.3 |
| | Simplifying numerical operation skills | 2 | 0.3 |
| | Interdisciplinary association | 2 | 0.3 |
| Curriculum | Developing a new curriculum related to modern physics | 18 | 2.8 |
| | Evaluating other curricula related to modern physics | 11 | 1.7 |
| | Including the modern physics philosophy in curricula | 8 | 1.3 |
| Textbooks | Increasing visuals | 6 | 0.9 |
| | Increasing content details | 6 | 0.9 |
| | Using a scientific language | 6 | 0.9 |
| | Organizing the content according to the history of science | 4 | 0.6 |
| | Including other modern physics topics in the content | 3 | 0.5 |
| | Including more examples related to daily life. | 2 | 0.3 |
| No recommendation | ---- | 17 | 2.7 |

As seen in Table 18, when examining the suggestions related to the results of the studies, themes such as investigating different variables, research methods, sample groups, sample sizes, instructional methods and techniques, materials, duration, subject content, textbooks, curriculum, and recommendations emerged. In the theme of investigating different variables, interdisciplinary associations ($f = 18$) and examining affective characteristics ($f = 18$) come to the forefront. In the theme of method, it was suggested that more quantitative studies ($f = 11$) should be conducted. In the theme of the sample groups, it was recommended to conduct more research with secondary school ($f = 48$) and middle school students ($f = 37$), and it is noteworthy that conducting research with different countries was also recommended. In addition, it was suggested that a larger number of samples should be included in the sample groups. The instructional methods and techniques recommended for research included applying the instructional methods and techniques used in the intervention processes of the reviewed studies to other modern physics subjects ($f = 36$) and using individualized instruction techniques more frequently ($f = 33$). Regarding the materials to be used, there was a stronger recommendation for the use of computer-aided animations/simulations ($f = 42$) and interactive experiments ($f = 36$), followed by visual elements ($f = 34$) and augmented reality experiments ($f = 15$). Additionally, it was also indicated that the intervention duration should be increased. In the theme of subject content, it was suggested to incorporate the philosophy of modern physics. In the textbook theme, it was suggested to increase visual elements, increase content details, and use scientific language. In the theme of curriculum, developing a new curriculum related to modern physics was recommended. Another notable finding in the research was that 17 studies did not provide recommendations for modern physics education.

## Discussion, Conclusion and Implications

In the research, 273 studies conducted between 2000 and 2023 and published in different databases were examined. Most studies were published in the Tübitak Ulakbim database (41.8%), in article format (69.2%), and in Turkish (68.9%). It was determined that the studies highly intensified between 2010 and 2019, but in recent years, there has been a decreasing trend in research activities. The main reasons for this decrease may include the abstract nature of modern physics concepts, the lack of direct observation in daily life, the persistent adherence to classical physics understanding, and the difficulty in acquiring technological devices for the teaching-learning process. Muştu and Şen (2019) note that simplifying the content in modern physics subjects not only hinders students' connected learning but also leads to a decreasing interest in the subject. Baily and Finkelstein (2010) note that the persistence of teachers and students in maintaining a classical physics understanding of modern physics topics and their failure to establish a wave-particle understanding of modern physics has also reduced the inclination towards engaging in modern physics studies. In this regard, Ensari and Bayrak (2023) indicate that there is less research on modern physics topics due to excessive conceptual misconceptions in students' basic physics knowledge. It was determined that the studies have concentrated on the atom, photoelectric effect, theory of relativity, and nuclear energy. The concentration on these topics could be explained by their status as fundamental subjects in modern physics, their significance for the understanding of modern physics, their greater relevance in daily life, and the increased support through computer-aided applications in the teaching-learning process. Baily and Finkelstein (2010) state that a clear understanding of the fundamental topics in modern physics is essential for students to make realistic interpretations in quantum mechanics. Atoms are a topic of focus for many researchers because they are taught in all educational levels, from primary school to university (Nakiboğlu, 2008). The fact that the theory of relativity acts as an important bridge in the transition from classical physics to modern physics (Dimitriadi & Halkia'a, 2012) and that the photoelectric effect is an interdisciplinary subject at the centre of explaining the nature of light and technological advances (Balabanoff et al., 2020; Jho et al., 2023) explains why more studies should be conducted on these topics. The reasons for the scarcity of studies on other modern physics topics in the research may include the more abstract nature of these topics, their prevalence in higher education levels, their involvement of more complex mathematical skills, their relatively lesser emphasis in the physics curriculum, and the lack of direct encounters with examples related to daily life. The reasons are also consistent with the relevant literature (Baily & Finkelstein, 2015; Hughes & Kersting, 2021; Huseby & Bungum, 2019; Kersting et al., 2023; Saglam & Eroglu, 2022).

Another dimension examined in the research was the objectives of the studies. The majority of the examined studies aimed at the effectiveness of instructional methods and techniques, followed by determining the current state and examining cognitive and affective characteristics. The relevant literature also supports the results of this research (Bonacci, 2018; Mannila et al., 2002; Stadermann & Goedhart, 2020). Levrini and Fantini (2013) suggest that, for the development of a modern physics understanding, it is essential to first determine students' views on modern physics, followed by the use of appropriate teaching methods and techniques. Baily and Finkelstein (2015) argues that students, through enriched learning environments, can develop reasoning skills in modern physics, allowing them to move away from classical physics understanding and intuitive physics thoughts. Therefore, it is essential to first characterise students' perspectives, followed by determining cognitive and affective characteristics, and then utilizing appropriate teaching methods and techniques (Bakri et al., 2023). Otherwise, students may develop ideas and beliefs that are not specific to modern physics (Şen, 2002). Another result obtained in the research is that the studies aim to examine and develop modern physics textbooks and curriculum. In their study examining the physics curriculum of 15 different countries, Stadermann et al. (2019) concluded that, for better teaching of modern physics, the physics curriculum should allocate more space to modern physics and delve into it more deeply. Similarly, Aktaş (2023) concluded in his study that modern physics is not given enough space in physics curricula and emphasised that physics curricula and textbooks should be revised and prepared according to the needs of the age in order to eliminate this problem.

An examination of the studies included in this research according to research designs indicated that quasi-experimental and descriptive survey designs were more commonly preferred in quantitative research. The research results were similar to the findings of existing content analysis studies in physics education (Arslan & Paliç, 2012; Bingöl & Baran 2023; Şenkal & Dinçer, 2016; Ünsal et al., 2018). The reasons behind opting for the quasi-experimental method more in quantitative research could be explained by easier and quicker access to samples, collecting data in a shorter time, and interpreting them quickly (Selçuk et al., 2014). Bitzenbauer and Meyn (2020) emphasize the need for more experimental studies with various learning activities for in-depth learning of modern physics independent from classical physics, supporting the results of the present research. Another extensively preferred quantitative research design was the descriptive survey method. Pereira and Solbes (2022) argue that the lack of a common method in experimental approaches of quantitative research in modern physics education prevents the formation of a distinctive understanding of modern physics. Therefore, they recommend reaching more samples and collecting more data through the survey method. Thus, by determining a general perspective and the current state regarding topics in modern physics, suitable instructional methods and techniques can be developed. This circumstance supports the research result. It was also determined that the studies examined in this research preferred the case study design more in qualitative research. Akaydın and Çeçen (2015) and Aktaş (2023) maintain that qualitative studies play a crucial role in presenting problems related to the subject more accurately, obtaining more in-depth information, and finding clearer responses to difficult questions. Qualitative studies should be given more place in modern physics education because qualitative approaches contribute more to the development of reading and analytical skills in students (Purwaningsih et al., 2024). According to Yılmaz (2015) and Doğan et al. (2023), only quantitative or qualitative studies are not sufficient to meet the needs of students concerning the subject in the teaching-learning process. Therefore, there is a need to increase mixed-method studies that utilise both qualitative and quantitative research methods together. This study also indicated that many researchers have preferred the mixed-method approach to conducting their studies. Utilizing mixed-methods research in modern physics can establish different contexts, promote the development of teachers' and students' perspectives and ensure consistency (Baily & Finkelstein, 2010). Mixed-methods research plays a crucial role in enriching research by replacing rigid boundaries and labels in quantitative and qualitative methods with permeable and inclusive categories (Johnson & Onwuegbuzie, 2004). Another notable result of the research was that 11 studies did not report the research design.

In the reviewed studies, researchers mostly preferred non-probability purposive sampling methods in sample selection. Due to the abstract nature of modern physics content, participants need to possess abstract thinking skills and master classical physics topics for a thorough understanding. According to Bitzenbauer and Meyn (2020), to make sense of modern physics, students need to have sufficient knowledge and inquiry skills in basic physics, especially regarding photons and atoms. Arbabifar and Nazerdeylamin (2024) Mastering the mechanics and electromagnetism subjects is a necessity for meaningful and permanent learning of modern physics. Therefore, working with sample groups possessing these skills enhances the validity of the research. As mentioned by Büyüköztürk et al. (2012), purposive sampling requires working with cases that meet specific criteria or possess certain characteristics. Some of the studies reviewed in this research have also preferred random sampling due to a lack of sufficient time and difficulties in reaching the intended sample. This result is consistent with the literature (Akaydın & Çeçen, 2015; Selçuk et al., 2014). Additionally, some of the examined studies on modern physics education did not mention the selected sample type.

Considering the sample sizes in the research, most studies carried out the research processes with sample groups ranging from 31 to 100 participants. However, the number of studies conducted has decreased, with an increase in sample sizes in study groups. Fraenkel et al. (2012) state that the sample size should be at least 30 in quantitative studies, as a sample size of 30 or more tends to show a normal distribution. In this research, the emphasis on quantitative studies could explain the preference for sample sizes ranging from 31 to 100. The selection of sample sizes of 101 and above in studies reviewed in the present research could be attributed to the studies' preference for the survey method and the need for a larger sample size for developing or adapting measurement tools. Selçuk et al. (2014) emphasize the importance of reaching a larger sample size in survey model research, as it involves investigating how the subject is distributed in terms of the sample. The small sample sizes observed in studies examined in this research may be associated with the prevalence of qualitative studies, especially those involving parents, administrators, and experts, where smaller sample sizes are common. Yıldırım (2023) In order for modern physics education to be meaningful and productive, research should be conducted with qualitative designs and small sample groups. Thus, more detailed and in-depth information about the learning-teaching process of modern physics can be obtained and necessary arrangements can be made in a short time. However, in qualitative studies, having a small number of samples is important for effective use of time in order to write down, clean, organize and analyze large amounts of data (Guisasola et al., 2023). Another finding obtained in the research was the variability in intervention durations of the studies reviewed, ranging from 0 to 4 and 5 to 16 weeks. The primary reason for this variability might be adjustments in intervention durations based on the objectives of the studies and challenges in creating suitable conditions for research. According to Baily and Finkelstein (2010), due to the abstract nature and complex philosophy of modern physics content, it is necessary to conduct longer-term studies. Bitzenbauer (2021) suggests that in modern physics, studies should be conducted over a longer period to facilitate the understanding of the paradigm, the qualitative acquisition of concepts, and achieving targeted development. This way, technological advancements in modern physics can also be understood more clearly.

In the studies reviewed within the scope of this research, the most preferred measurement tools in data collection were interviews, scales, tests, and questionnaires, followed by alternative measurement and evaluation tools. The preference for scales, tests, and questionnaires in data collection may be explained by their ease of use, cost-effectiveness, validity, and reliability in gathering data. Using scales and questionnaires in physics subjects allows for collecting the appropriate data in a shorter time, aiding in determining the general situation and outlining a roadmap (Arslan & Paliç, 2012; Resbiantoro et al., 2022; Ünsal et al., 2018). The reason for the more frequent use of interview types could be collecting more detailed data and adding new questions to the interview process when needed during the research (Guisasola et al., 2023). To obtain more detailed information about students' mastery of modern physics topics, interviews and alternative measurement and evaluation tools should be employed (Muştu & Şen, 2019). The least used data collection tools were observation types and documents. The main reason for this could be that both measurement tools involve a detailed and time-consuming analysis process. As a result of the research, the studies examined mostly preferred frequency/percentage, t-test, item analysis, and content analysis in data analysis methods. They also employed different quantitative and qualitative analyses. The efforts of researchers in the examined studies to determine the general state of modern physics education and obtain more detailed information about the content may explain the preference for quantitative descriptive analyses and content analysis (Guisasola et al., 2023). It could also be stated that the researchers conducted their analyses in line with their research objectives. The research results are parallel to the relevant literature. (Akaydın & Çeçen, 2016; Şenkal & Dinçer, 2016).

In the studies on modern physics education examined in the research, the most commonly utilised validity methods were expert review, detailed description of the research process, and detailed explanation of the data collection process. The reliability methods included inter-coder consistency calculation, direct quotation from participant statements, and separate analysis by two researchers. In this regard, it is possible to say that the validity and reliability methods in the studies may not have been conducted at an adequate level. Additionally, in some of the studies examined, it was found that the researchers used the validity and reliability evidence reported in previous studies without changing them in their own research (Guisasola et al., 2023). The research results consistent with the relevant literature (Arbağ & Ertekin, 2020; Öztürk, 2020).

The content analysis indicated that studies have reached different results in themes concerning instructional methods and techniques, materials, curriculum development, textbooks, tests/scales/questionnaires, cognitive characteristics, affective characteristics, and reviews. Although the results of the studies were generally positive, negative results were also obtained. In the themes of materials and instructional methods and techniques, the most positive results achieved included an increase in academic achievement, concretizing or understanding information, acquiring problem-solving skills, enhancing higher-order thinking skills, and developing positive emotions and thoughts. The negative aspects included developing negative emotions and thoughts and failing to eliminate conceptual misconceptions. Baily and Finkelstein (2010) suggest that despite the differences in instructional methods and techniques employed in modern physics education, students began to better understand the philosophy of modern physics, concretize knowledge, and improve their problem-solving skills through each intervention. Huseby and Bungum (2019) suggest that the teaching methods and techniques applied in modern physics education and the materials used should be structured in a manner that aligns with the understanding, nature, and philosophy of modern physics. Otherwise, continuing conceptual misconceptions in modern physics may lead to the development of negative emotions and thoughts. In the cognitive theme, other results reached include maintaining a classical physics understanding, failing to relate knowledge to daily life, continuing non-scientific explanations, and failing to develop thinking skills. In the affective theme, the result indicated that there were more negative emotions and thoughts towards modern physics. Zhu and Singh (2012) suggest that not understanding the nature of modern physics leads to conceptual, mathematical, and practical confusion, paving the way for the development of negative emotions and thoughts. Díaz et al. (2023) Inadequate teacher-student communication and interaction, materials that do not fully reflect the content, and little space given to scientific conversations can cause many negativities in the learning-teaching process of modern physics. Additionally, curriculum and textbooks that are not compatible with the nature of modern physics may lead to both cognitive and affective negative outcomes in students. In this regard, many studies reviewed in this research have examined modern physics curricula and textbooks, concluding that their contents were inadequate and not suitable for students' levels. Stadermann et al. (2019) and Aktaş (2023) emphasize the importance of considering student needs when preparing a curriculum and textbook for modern physics education, as neglecting student needs may lead to undesirable cognitive and affective outcomes.

In the studies reviewed, the majority of the discussions of the studies were supported by literature, but the literature explanations were insufficient or absent. Some studies only presented the results in the discussion section, while others did not include any literature support. Other studies structured the discussion process around the research's implementation and sample characteristics. The inadequacy or absence of the discussion section in the reviewed studies could be attributed to factors such as the unavailability of suitable resources within the study scope, the inadequacy of educators in the field of modern physics, discussions specific to the researcher being contradictory to the probabilistic world of modern physics, and a decrease in the number of studies conducted in the field in recent years. In their study, Fuchs and Peres (2000) argue that the interpretation of modern physics studies by the researcher would limit the unique world of modern physics, and therefore, there should be an 'interpretation without interpretation' in modern physics. Similarly, Laloë (2001) suggests that having various interpretations based on the researcher's attitude may lead to misunderstandings. Baily and Finkelstein (2010) note that teachers and students do not have consistent concepts and understandings within and across fields due to the nature of modern physics. Therefore, instead of referring to concepts and interpretations, interpretations should be made from a more general perspective or context. Giliberti and Organtini (2021) discussions on the learning-teaching process of modern physics should be within the framework of classical physics, quantum physics, quantum mechanics and quantum field theory. In this process, attention should be paid to the discussion of concepts, facts and measurement processes.

The recommendations regarding the results of the studies conducted in modern physics education were also examined in this research. Prominent recommendations in the studies included data collection tools, sample groups, instructional methods and techniques, materials, examining different variables, subject content, and curriculum themes. The research results are consistent with the literature (Baily & Finkelstein, 2010; Bitzenbauer, 2021; Pereira & Solbes, 202; Swandi et al., 2020). Swandi et al. (2020) suggest that since modern physics is the technology of the future, the targeted outcomes can be reached by providing students with an enriched learning environment and using technological materials. Mufit et al. (2024) and Kersting et al. (2023) concept teaching approach, group work, computer technologies, interdisciplinary applications and science trips facilitate the understanding of modern physics. Baily and Finkelstein (2015) emphasize that for effective and efficient modern physics education, determining students' cognitive and affective discourses is necessary at the outset. Afterward, the philosophy of modern physics, the history of science, and operational skills should be included more in the subject content. Additionally, students should be provided with opportunities to learn from each other. In the study, Aksakallı et al. (2016) concluded that the underlying problems related to modern physics stem from teachers not being up-to-date on modern physics topics, textbooks being scientifically inadequate, and the lack of learning environments that enable students to learn on their own. In this regard, the recommendation for providing seminars to teachers, organizing the curriculum or textbooks, and conducting long-term studies in enriched learning environments is similar to the findings of the present research. In a study on blackbody radiation, Balta (2018) concluded that teachers' knowledge of modern physics was not up-to-date and that students did not learn the subject in an acceptable way. In this context, the researcher suggests updating modern physics education, modern physics curriculum, and textbooks, and also recommends that teachers participate in various courses. Krijtenburg-Lewerissa et al. (2017) suggest developing an understanding of "How can I better learn/teach the nature and philosophy of modern physics?" for modern physics education to be more comprehensible.

Based on the results of the content analysis in the research, it could be recommended to conduct more qualitative and scientifically valuable studies on different topics of modern physics education. In future studies, to acquire the unique thought structure and understanding of modern physics, researchers could enrich their goals, prefer mixed research methods designed with quality approaches, enhance their intervention samples, increase sample sizes, and use different data analysis methods, significantly contributing to the field. Additionally, future research should place more emphasis on, diversify, and provide detailed information on validity and reliability measures. Considering the significance of the study results, reassessing the outcomes and making international publications would be important for shedding light on modern physics education. Finally, in this study, content analysis was conducted based on studies retrieved through selected databases and keywords. To make the research more comprehensive, the research process could include different databases, different keywords, and studies conducted in various countries. Furthermore, for a more detailed analysis of studies on modern physics education, content analysis could be conducted specifically for qualitative, quantitative, and mixed-method research alone.

## Conflict of Interest

The authors have no conflicts of interest.

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