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DEVELOPING AND APPLYING FRAMEWORK OF MATHEMATIZATION IN PHYSICS EDUCATION IN DIGITALIZATION ERA

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Minchul Kim

Abstract. *Mathematics, as the language of science, enables the quantitative and structural description of physical phenomena. In physics education, mathematical representation underpins theoretical modeling and strengthens explanatory and predictive reasoning. As digital technology becomes integral to science learning, practices such as simulation, data visualization, and AI-based analysis increasingly depend on mathematical expression to construct scientific meaning. This Study analyzes how mathematical elements are differentially emphasized in Korean, U.S., and England's physics curricula and demonstrates that these differences systematically shape the forms of inquiry-based learning supported in digitally enriched educational contexts. The analysis focuses on three national curricula that explicitly connect physics and mathematics: Korea's 2022 Revised Curriculum, the United States' Next Generation Science Standards, and England's National Curriculum. A framework of mathematization elements was developed from prior literature and applied to achievement standards through frequency and qualitative analyses. A total of 134 mathematization elements were identified, revealing statistically significant cross-national differences. Korea places strong emphasis on mathematics as a means of perception through experimentation and data analysis, England highlights the expression of quantitative relationships, and the United States foregrounds modeling via approximation and visualization. These findings indicate that effective physics education in the digital era requires integrating established mathematization practices with data analysis, simulation, and coding-based approaches.*

Keywords: *digitalization in science education, nature of science, mathematization in science education*

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Introduction

In science education, digital orientation refers to the tendency to actively integrate digital technologies in order to transform teaching and learning processes and to expand learners' inquiry capabilities. This orientation manifests in diverse forms, including data science, simulations, artificial intelligence, virtual experimentation, and visualization tools. The use of such digital technologies enables students to engage in inquiry experiences that increasingly resemble authentic scientific research practices, rather than merely reproducing predefined procedures (Chang & Joung, 2017). Consequently, digital learning environments have begun to reshape not only how science is taught, but also what constitutes meaningful scientific knowledge and inquiry (Nielsen et al., 2014).

Within this transforming landscape, the role of mathematics in science education has become increasingly central. Mathematics, long regarded as the language of science, provides the logical and structural means by which scientific phenomena are quantitatively described, and scientific laws are expressed with precision (Gingras, 2001; Redish, 2005). In physics education in particular, mathematics functions as a core epistemic tool that reveals the underlying structure of phenomena and supports explanation and prediction through theoretical modeling (Uhden et al., 2012).

A substantial body of research has examined how mathematics supports learning in physics, often focusing on the relationship between physical concepts and their mathematical representations. Gingras (2001) and Redish (2005) have emphasized mathematics as a linguistic and epistemological tool that enhances precision in scientific reasoning and argumentation. Building on this perspective, Uhden et al. (2012) have conceptualized mathematization as a procedural transformation through which physical phenomena are translated into mathematical forms, enabling systematic explanation and prediction. Other studies have explored related dimensions, such as students' ontological and epistemological understanding of equations (Kim et al., 2023) and the cognitive impact of mathematical representations (graphs, equations, and visualization) on concept formation (Treagust et al., 2017).

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Despite these contributions, existing research on mathematization has largely been conducted with isolated instructional contexts, such as physical reasoning, problem solving, modeling, or experimentation, which are often treated as analytically distinct domains (Palmgren et al., 2025). While each context entails specific forms of mathematical thinking, authentic scientific inquiry requires these forms to operate in an integrated and dynamic manner. This limitation becomes particularly salient in digitally mediated learning environments, where mathematical activity is no longer confined to static representations but increasingly involves simulation based modeling, big data analysis, algorithmic reasoning, and iterative visualization.

Recent studies addressing digital tools in physics education have begun to highlight the close relationship between digitalization and mathematization (Euler et al., 2023). However, in much of this work, digital technologies are treated primarily as tools for implementing existing forms of mathematization, rather than as forces that fundamentally reshape what counts as mathematical activity in scientific inquiry. As a result, the meaning of mathematization in digitally oriented science education remains under-theorized, particularly at the level of curriculum design.

From an international perspective, this gap is especially significant. National curricula play a pivotal role in shaping instructional priorities and implicitly defining the forms of mathematical reasoning and scientific inquiry that are valued within educational systems. Examining how mathematization is embedded in curricula therefore offers insight into how different countries conceptualize the relationship between mathematics, physics, and digital inquiry. Yet, few studies have conducted systematic, cross-national analyses of mathematization that account for the challenges posed by digital transformation.

To address this gap, the present study develops a curriculum-level analytical framework of mathematization elements grounded in prior international literature and applies it to a comparative analysis of physics curricula from Korea, the United States, and England. By examining how mathematization is articulated across these national contexts, this study provides a systematic account of how different curricula prioritize distinct forms of mathematical reasoning in relation to digital inquiry practices. In doing so, the study moves beyond describing curricular differences to reconceptualize mathematization as an integrated process supporting inquiry, modeling, and meaning-making in digital-oriented physics education. Through this analysis, the study contributes to curriculum research by offering a theoretically grounded tool for analyzing mathematization at the curriculum level and to broader international discussions on how mathematics can meaningfully support scientific inquiry under conditions of rapid digital change.

Research Aim and Research Questions

The purpose of this study was to develop and apply a curriculum-level analytical framework for examining mathematical representations in physics curricula through international comparison. Specifically, the study aimed to clarify how different roles of mathematization were articulated in national curricula, to identify cross-national patterns in the presentation of mathematization elements, and to examine their educational significance within digital-oriented science education environments. Accordingly, the following research questions were formulated:

1. How were the roles of mathematization in physics education categorized at the curriculum level?
2. How were mathematization elements presented in the physics curricula of each country, and what cross-national characteristics did they exhibit?
3. What implications did these findings provide for understanding the meaning and role of mathematization in increasingly digitalized science education environments?

Research Methodology

General Background

This study adopted a qualitative document analysis design to examine how mathematization is positioned within national physics curricula. Document analysis was considered appropriate because national curricula function as authoritative policy texts that articulate intended forms of scientific knowledge, inquiry, and reasoning, thereby providing a meaningful basis for analyzing the roles assigned to mathematics at the curriculum level. The study was conducted in three main phases: developing an analytical framework, analyzing the curricula, and refining the framework through iterative validation.

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To develop a theoretically grounded analytical framework, a systematic literature review was conducted using the Web of Science database. Web of Science was selected because this study aimed to identify peer-reviewed international studies indexed in the Science Citation Index Expanded (SCIE) and the Social Sciences Citation Index (SSCI), which are commonly regarded as benchmarks of scholarly rigor and international impact in science education research. Previous methodological studies have shown that major bibliographic databases, such as Web of Science and Scopus, exhibit substantial overlap in their coverage of core international journals, particularly for conceptually influential research (Bennett et al., 2025).

Literature searches were conducted using the keywords "mathematization" and "mathematics." These terms were intentionally selected to capture studies that explicitly theorize or analyze the role of mathematics in science and physics education, rather than studies focusing on general mathematical achievement or instructional techniques. Studies retrieved through these keywords were then screened to identify those situated within physics education or closely related science education contexts.

To address potential concerns regarding database exclusivity, this study also considered major science education journals indexed in Scopus but not in Web of Science. Although several international science education journals indexed in Scopus but not in Web of Science were also considered, exploratory searches using the same keywords ("mathematization" and "mathematics") did not yield additional relevant studies addressing mathematization in physics education. Therefore, Web of Science was considered sufficient for identifying a coherent and theoretically relevant corpus for the purpose of analytical framework development. Because the purpose of this study was not to exhaustively map all publications, but to derive a coherent analytical framework of mathematization, the use of a single, well-established database was considered sufficient. Prior research has emphasized that, in theory-building and framework-development studies, conceptual relevance and analytical rigor are more critical than comprehensive database coverage (Luft et al., 2022). From an initial pool of 93 publications retrieved through keyword-based searches, 17 studies were selected based on predefined inclusion criteria, including relevance to mathematization, explicit engagement with mathematical representations in physics education, and conceptual or analytical rigor.

From the 17 selected studies, explicit descriptions of how mathematics functions in physics learning were systematically extracted. These descriptions included, for example, mathematics as symbolic representation, as a means of expressing relationships among physical quantities, as a basis for defining or justifying knowledge claims, and as a tool for modeling and simplifying physical situations. The extracted descriptions were first treated as preliminary codes and then compared across studies to identify recurring patterns in the roles attributed to mathematics. Conceptually similar codes were clustered into candidate mathematization elements, while analytically distinct roles were retained as separate elements. These elements were subsequently organized into higher-level categories based on their primary epistemic function in physics inquiry. Decisions regarding the inclusion, merging, or separation of elements were discussed among researchers and refined iteratively through cross-review to ensure conceptual coherence and analytical consistency across categories.

Using the resulting framework, the national physics curricula of Korea, the United States, and England were analyzed by extracting achievement statements containing mathematical representations and classifying them according to the framework. Although this classification involved interpretive judgment inherent in qualitative content analysis, analytical consistency was strengthened through repeated cross-checking among researchers and iterative refinement of the framework during analysis. The resulting patterns were then compared across countries to inform conclusions and implications for science education.

Analysis Procedure

The overall procedure for developing the analytical framework and analyzing the curricula is presented in Figure 1. The procedure was designed to ensure both theoretical grounding and analytical consistency and consisted of three main phases: framework construction based on literature, curriculum analysis using the framework, and iterative refinement and interpretation of results.

In the first phase, the analytical framework of mathematization elements was constructed based on the systematic literature review described above. Descriptions of the roles and functions of mathematics in physics learning were extracted from the selected studies and initially coded to generate a set of preliminary elements. These elements were compared across studies, clustered according to conceptual similarity, and organized into higher-level categories reflecting their primary epistemic functions in physics inquiry. The resulting framework was reviewed and refined through cross-examination among researchers to establish shared interpretations and conceptual coherence prior to curriculum analysis.

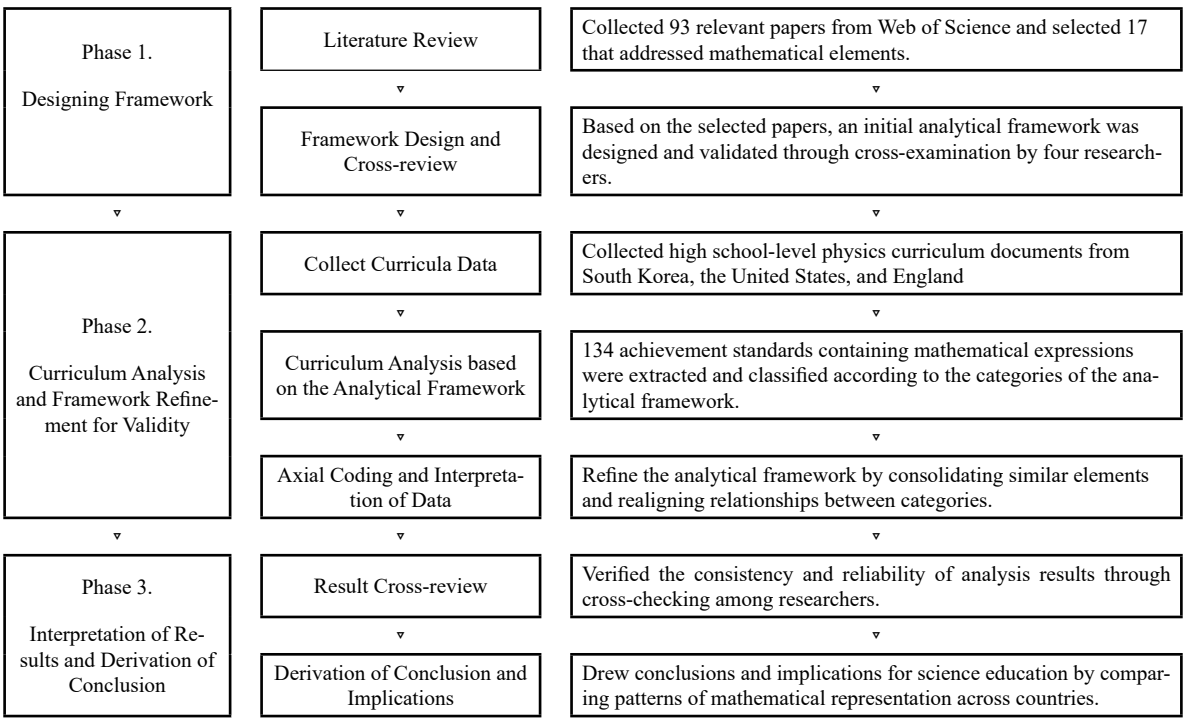
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In the second phase, official national physics curriculum documents from Korea, the United States, and England were analyzed. Achievement standards containing mathematical representations were extracted and classified according to the analytical framework. During this process, instances that challenged category boundaries or revealed ambiguity were discussed among researchers, leading to iterative refinement of element definitions and category relationships. This phase ensured that the framework remained analytically robust when applied to diverse curricular contexts.

In the final phase, the classified data were examined to identify frequency patterns and qualitative characteristics of mathematization elements within and across national curricula. Quantitative frequency analysis was conducted to compare the distribution of mathematization roles across countries, while qualitative comparison focused on interpreting how these roles were articulated within achievement standards. The consistency of interpretations was verified through cross-checking among researchers, and the resulting patterns formed the basis for the study's conclusions and implications for physics education.

Figure 1
Document Analysis Procedure



Curriculum Selection

The focus of this study is the national physics curricula of selected countries. To analyze mathematical representations, only curricula explicitly linking to mathematics were included. Accordingly, three national curricula were selected: the 2022 Revised National Curriculum of Korea, the Next Generation Science Standards (NGSS) of the United States, and the National Curriculum in England. To ensure consistent international comparison, the study analyzed upper secondary (Grades 11–12) physics content. In Korea, *Physics*, *Mechanics and Energy*, and *Electromagnetism and Quantum Physics* from the 2022 revision were included. For the United States, the study examined the *High School Physical Sciences* section of the NGSS. For England, it focused on the *Physics* component of *Key Stage 4* in the National Curriculum.

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Mathematization Elements Framework

To analyze how mathematization is positioned within physics curricula, this study employed an analytical framework developed through a systematic synthesis of prior research on the roles of mathematics in physics education. As described in the General Background, 17 studies were selected and analyzed to extract explicit accounts of how mathematics contributes to meaning-making, explanation, and inquiry in physics learning (Bing & Redish, 2009; Gingras, 2015; Kim et al., 2023; Redish, 2005; Uhden et al., 2012). Rather than adopting a single existing typology, the study consolidated recurring perspectives from the literature into a framework suitable for curriculum-level analysis.

From the selected literature, descriptions of mathematical functions were first identified and treated as preliminary codes, such as the use of symbols to structure concepts, the expression of relationships among physical quantities, the justification of knowledge claims, and the construction of models through idealization or visualization. These codes were compared across studies to identify recurring patterns and were clustered into analytically distinct elements. The elements were then organized into higher-level categories according to their primary epistemic function in physics inquiry, with particular attention to the nature of curriculum documents, which typically articulate intended learning outcomes rather than detailed instructional practices.

Based on this criterion, the role of mathematics in physics education was categorized into four overarching domains: mathematics as symbols, mathematics in expressing relationships, mathematics as epistemological roles, and mathematics in modeling physical situations. This categorization reflects well-established perspectives in the literature, while rearticulating them in a form appropriate for analyzing curriculum texts.

The first category, mathematics as symbols, corresponds to perspectives that emphasize mathematics as a formal language for representing physical quantities and operations (Kuo et al., 2013; Redish, 2005). It includes operational symbols, constants, variables, and units, which function as the foundational components of mathematical expression in physics. At the curriculum level, these elements signal how symbolic forms are introduced to structure physical concepts and relationships, rather than how calculations are performed.

The second category, mathematics in expressing relationships, draws on work that conceptualizes mathematization as the articulation of interactions, changes, and causal connections among physical quantities (Palmgren & Rasa, 2024; Uhden et al., 2012). This category includes interactive relationships, state relationships, and causal relationships. Although curriculum documents do not always present explicit equations, they frequently specify intended learning outcomes in terms of how variables relate to one another or how system states change. Such descriptions were classified under this category when they reflected relational structures typically conveyed through mathematical formulations in physics.

The third category, mathematics as epistemological roles, is grounded in research examining how mathematics functions in the construction and justification of physics knowledge (Bing & Redish, 2009; Kim et al., 2023). In this study, epistemological roles were interpreted in terms of how curricula position students' learning processes rather than the historical development of scientific knowledge. Accordingly, this category includes empirical laws, definitions, and principles. Empirical laws refer to instances in which regularities are identified or confirmed through observation, experimentation, or data analysis, including inquiry based on digital datasets. Definitions involve the formal introduction of concepts without explicit derivation, while principles denote foundational laws presented as theoretical premises within the curriculum.

The fourth category, mathematics in modeling physical situations, reflects perspectives that highlight mathematics as a means of abstraction, idealization, and representation of complex phenomena (Gingras, 2015; Pospiech & Karam, 2023). This category includes approximation and idealization, analogy, error and uncertainty, and visualization. These elements capture how mathematics supports the construction of models that mediate between empirical phenomena and theoretical descriptions, a role that is increasingly prominent in digitally oriented inquiry contexts involving simulations and graphical representations.

These four categories are intended to provide a structured yet flexible lens for examining the roles of mathematics in physics curricula. While analytically distinct, the categories are not assumed to operate in isolation; rather, they reflect complementary aspects of mathematical activity in physics inquiry. At this stage, the framework specifies conceptually distinct roles of mathematics derived from prior research. The empirical distribution and characteristics of these elements across national curricula are reported in the Results section.

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Document Analysis

Using the analytical framework developed in this study, the physics curricula of Korea, the United States, and England were analyzed. The unit of analysis was achievement statements that explicitly or implicitly involved mathematical representations relevant to physics learning, including equations, symbolic expressions, and relational descriptions of physical quantities. These statements were extracted from official curriculum documents using MAXQDA and constituted the dataset for analysis.

The extracted achievement statements were initially classified according to the mathematization framework. This framework-based coding focused on identifying the primary role of mathematics articulated in each statement. In cases where a statement reflected multiple roles, the dominant function of mathematics within the intended learning outcome was used as the basis for classification.

Following this initial classification, axial coding was applied to examine conceptual similarities and overlaps among elements within each category and to refine category boundaries. This process supported the consolidation of analytically coherent groups while preserving distinctions among conceptually different mathematization roles.

To enhance analytical consistency, the coding results and category definitions were reviewed by one doctoral researcher in science education, one doctoral student in science education, and two master's students specializing in physics education. Discrepancies in classification were discussed and resolved through consensus, and the framework definitions were refined accordingly.

Subsequently, quantitative analysis was conducted to examine the frequency distribution of mathematization categories across curricula. To complement this, qualitative comparative analysis was performed by comparing similarities and differences among achievement statements within each category, enabling interpretation of how mathematization roles were articulated across national contexts.

Research Results

The analysis identified four analytically distinct roles through which mathematics is articulated in physics curricula: mathematics as symbols, mathematics in expressing relationships, mathematics as epistemological roles, and mathematics in modeling physical situations. Each role captures a different function of mathematics as presented in physics achievement standards.

Table 1
Analytical Framework for Mathematical Element Analysis

Category	Element	Description
Mathematics as symbols	Operational symbol	Mathematical operations representing relationships among physical concepts
	Constant	Symbols representing physical quantities
	Variable	Independent and dependent variables in a given situation
	Unit	Symbols determining the dimension
Mathematics in expressing relationships	Interactive Relationship	Mathematical representations describing mutual interactions between system properties or entities
	State Relationship	Mathematical expressions describing changes in system states resulting from interactions among properties
	Causal Relationship	Mathematical representations explaining changes (effects) in a system's properties caused by external or internal interactions (causes)
Mathematics as Epistemological Roles	Empirical Law	Descriptions of regularities or relationships between observable quantities based on empirical evidence
	Definition	Specification of the meaning of a physical concept
	Principle	Fundamental law serving as a theoretical foundation that cannot be verified experimentally

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Category	Element	Description
Mathematics in Modeling Physical situations	Approximation and Idealization	Simplifying or ignoring certain conditions of complex real phenomena to express them mathematically
	Analogy	Use of structural similarity in mathematical expressions
	Error and Uncertainty	Representation of differences between real-world phenomena and their mathematical models, or of experimental accuracy, reliability, and reproducibility
	Visualization	Representing phenomena or objects in graphical, tabular, functional, or model-based forms

Table 1 summarizes the four categories of mathematization and their associated elements, which served as the coding scheme for analyzing the distribution and characteristics of mathematization across the national curricula examined.

Within the category of mathematics as symbols, mathematics appears as a formal representational system used to denote physical quantities and operations. This category includes operational symbols, constants, variables, and units, which together establish the symbolic structure through which physical concepts are expressed in curricular statements. Rather than emphasizing procedural calculation, these elements indicate how curricula introduce mathematical symbols as carriers of physical meaning. For instance, operational symbols reflect mathematical operations used to represent relationships among physical concepts, while variables specify independent and dependent quantities within a given physical situation. Constants denote fixed physical quantities commonly used in physics, and units determine the dimensions of physical quantities, thereby supporting dimensional reasoning even when explicit calculations are not required.

The category of mathematics in expressing relationships describes how mathematics is used to articulate interactions, changes, and causal connections among physical quantities at the curriculum level. This category comprises interactive relationships, state relationships, and causal relationships. Because curriculum documents often describe intended learning outcomes rather than presenting explicit equations, this category captures relational structures that are implicitly mathematical in nature. Interactive relationships refer to mutual interactions between system properties or entities, such as describing how force and acceleration are related or how electric field strength depends on charge and distance. State relationships describe changes in system states resulting from interactions among properties, for example, how velocity changes over time in uniformly accelerated motion or how gas pressure varies with temperature at constant volume. Causal relationships further explain changes in system properties by explicitly linking causes and effects, such as explaining that an increase in net force causes an increase in acceleration or that energy transfer leads to a change in temperature.

The category of mathematics as epistemological roles refers to the function of mathematics in constructing and justifying physics knowledge within the curriculum. This category includes empirical laws, definitions, and principles. Empirical laws involve identifying regularities or relationships between observable quantities based on empirical evidence, including inquiry activities that rely on experimental data or digitally mediated datasets. Definitions introduce physical concepts through formal specification without explicit derivation, such as defining velocity as the rate of change of displacement with respect to time. Principles refer to fundamental laws that serve as theoretical foundations, such as conservation laws or Newton's laws, which are presented as premises for explanation and prediction rather than as outcomes of empirical generalization.

The category of mathematics in modeling physical situations captures how mathematics supports abstraction and representation of complex phenomena. This category includes approximation and idealization, analogy, error and uncertainty, and visualization. These elements reflect the use of mathematics to construct simplified or representational models that mediate between empirical phenomena and theoretical descriptions. Approximation and idealization involve simplifying or ignoring certain conditions of real phenomena to make mathematical treatment possible. Analogy refers to the use of structural similarity between mathematical expressions or physical laws. Error and uncertainty address the representation of differences between real-world phenomena and their mathematical models, as well as experimental accuracy and reliability. Visualization includes graphical, tabular, functional, or model-based representations used to express physical phenomena or data.

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Table 2
Frequency of Mathematization Elements Presented in Each Curriculum

Category	Elements	Frequency			Total	
		KR	En	US		
Mathematics as symbols	Operational symbol	0	2	0	2	6
	Constant	0	0	0	0	
	Variable	1	3	0	4	
	Unit	0	0	0	0	
Mathematics in expressing relationships	Interactive Relationship	6	7	4	17	44
	State Relationship	4	7	2	13	
	Causal Relationship	6	5	0	11	
Mathematics as epistemological roles	Empirical Law	11	1	2	14	37
	Definition	8	4	0	12	
	Principle	10	1	0	11	
Mathematics in Modeling Physical Situations	Approximation and Idealization	12	1	10	23	50
	Analogy	0	0	1	1	
	Error and Uncertainty	1	0	2	3	
	Visualization	9	7	7	23	
Total		68	38	28	134	

Table 2 presents the results of the frequency analysis of mathematization elements identified in each region's curriculum. Analysis revealed that 68 mathematization elements were collected in Korea's 2022 Revised Curriculum, 38 in the England's National Curriculum in England, and 28 in the US's NGSS. The chi-square test examining the association between mathematization categories and countries was conducted using SPSS Statistics and yielded a Pearson χ^2 value of 39.190 with 6 degrees of freedom (df = 6), $p < .001$, confirming a statistically significant association. All expected cell frequencies met the assumptions required for the chi-square test. Notably, Korea frequently presented mathematics as epistemological roles, England emphasized mathematics in expressing relationships, and the US highlighted mathematics in modeling physical situations.

Figure 2
Curriculum-wise Proportions of the Role of Mathematics as a Symbol

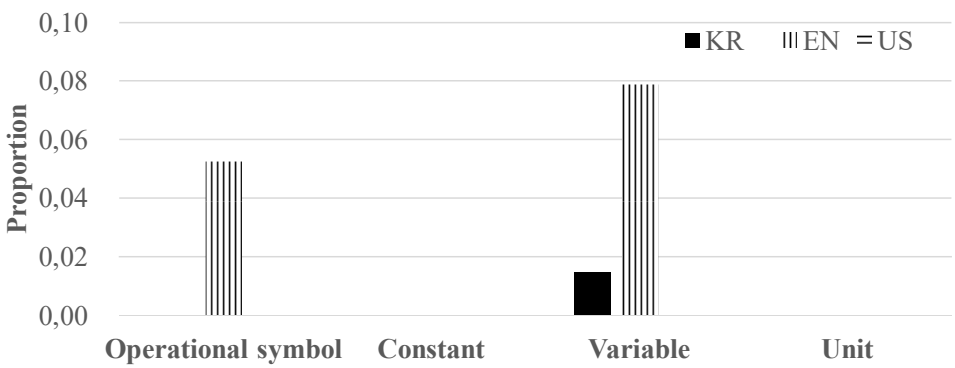


Figure 2 illustrates the frequency of mathematical roles represented by symbols by country, indicating the frequency of mathematization elements found in each country's curriculum. The ratio was calculated by dividing the frequency of a specific mathematization element collected in each country's curriculum by the total frequency

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collected across all countries' curricula. The ratio bar graphs for the three categories presented subsequently were also calculated using the same method. The role of mathematics as a symbol was primarily derived from the England's curriculum. For England, two operational symbols and three variables were collected. The England's curriculum explicitly states variables for specific physical quantities, presenting their relationships using operational symbols, such as: '*calculating work done as force × distance; elastic and inelastic stretching*' and '*quantity of charge flowing as the product of current and time*'. In contrast, the Korean curriculum collected one variable, and the US curriculum did not collect any corresponding content. The Korean curriculum explicitly states that wavelength, frequency, and propagation speed are variables, as seen in the example: '*[12 역학03-02] Describe the propagation of elastic waves using wavelength, frequency, and propagation speed*'. This explicitly presents these quantities as variables, similar to how the England's curriculum presents the role of mathematics through symbols. This category is characterized by the lowest overall frequency compared to other categories, a feature confirmed by curriculum organization. Notably, no achievement standards related to units and constants were collected from any of the three countries, as these topics are typically presented in earlier grades and are outside the scope of this study. In Korea, the Integrated Science course offered in the first year of high school presents content on units, as seen in '*[10통과1-01-02] Understand the meaning of fundamental quantities important in scientific inquiry and explain the significance and application of units in describing natural phenomena*'. In the United States, the NGSS Middle School Curriculum's MS-PS2-2 achievement standard description explicitly emphasizes units: '*Emphasis is on balanced (Newton's First Law) and unbalanced forces in a system, qualitative comparisons of forces, mass and changes in motion (Newton's Second Law), frame of reference, and specification of units*'.

Figure 3
Curriculum-wise Proportions of the Role of Mathematics in Expressing Relationships

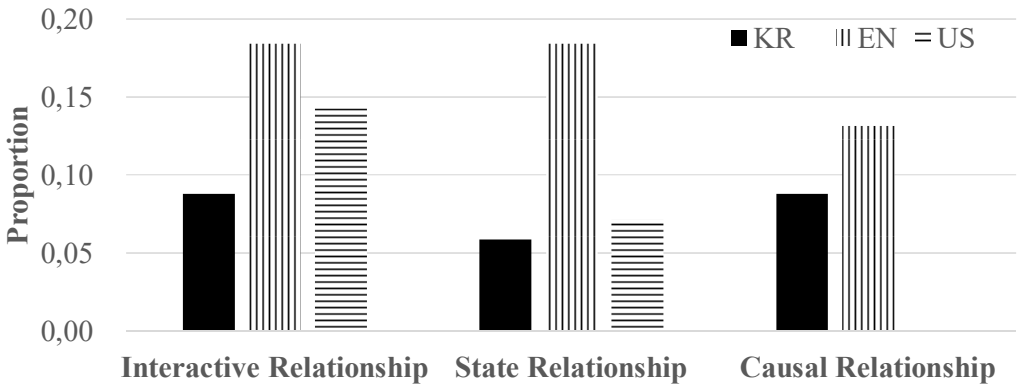


Figure 3 shows the frequency by country for the category of mathematics as a role in expressing relationships. The England had the highest frequency of presenting mathematics as an expression of relationships, with a frequency of 50% within the England's curriculum. Notably, interaction relationships and state relationships were most frequently collected within the England's curriculum. Within the England's curriculum, state relations are primarily explicitly presented as describing changes in properties within a system, as seen in '*links between pressure and temperature of a gas at constant volume, related to the motion of its particles*'. Interactive relations are explicitly presented as showing the causal relationship between physical quantities, as seen in '*that proportionality, for example, between weight and mass of an object or between force and extension in a spring, is an important aspect of many models in science*'. The United States was the next most frequent presenter, with the role of mathematics in expressing relationships appearing 21.4% of the time in its curriculum. Here, interaction relationships and state relationships were presented, but achievement standards for causal relationships were not specified. In the U.S. curriculum, interactive relationships are presented as '*Develop and use models to illustrate that energy at the macroscopic scale can be accounted for as a combination of energy associated with the motion of particles (objects) and energy associated with the relative position of particles (objects)*', explaining mechanical energy conservation as an interaction between kinetic energy and potential energy. State relationships are also presented as '*Use mathematical representations to support a claim regarding relationships among the frequency, wavelength, and speed of waves traveling in various media*', presenting it as an explanation of wave speed in different media using wave properties like frequency and wavelength. Notably, the U.S. curriculum emphasizes activities like expressing personal thoughts

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and creating models, so the role of mathematics in expressing relationships primarily functions as a prerequisite for student activities.

Figure 4
Curriculum-wise Proportions of the Role of Mathematics as Epistemological Roles

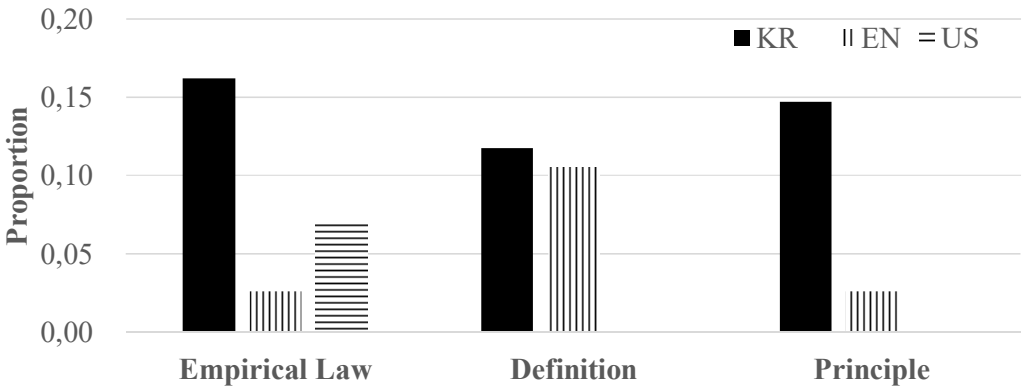
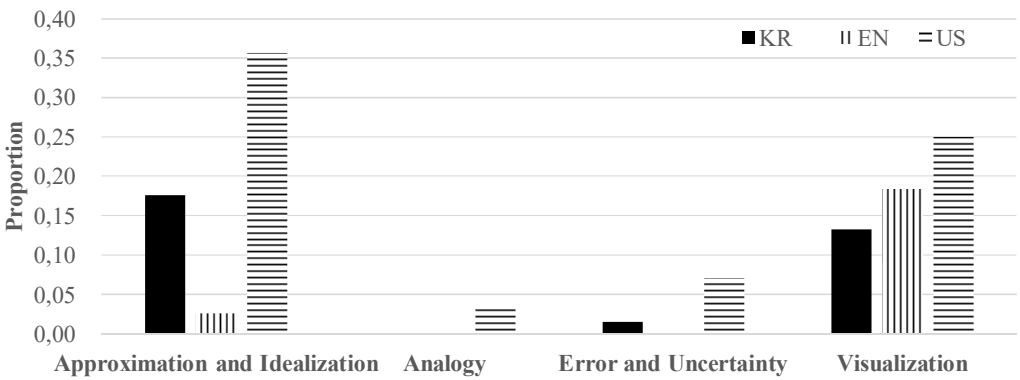


Figure 4 shows the frequency by country for the category of role of mathematics as epistemological roles. The role of mathematics as an epistemological role was most frequently presented in Korea, followed by the United States. In the case of Korea, since inquiry activities are presented in the curriculum documents, empirical laws were frequently cited. Specifically, activities such as '*analyzing the motion of various playground equipment using smartphones*' or '*analyzing the relationship between gas pressure, volume, and temperature using sensors*' were identified, where real-time data is collected and analyzed using smartphones or sensors. Furthermore, '*[12전자03-01] Through the double-slit experiment at the single-quantum level, particle-wave duality can be confirmed, and experimental results on the distribution of single quanta can be interpreted based on the interference of probability waves.*' as shown in [12전자03-01], simulations are used to obtain data on phenomena that are difficult to observe directly and to analyze trends. This category was the next most common in the England's curriculum, particularly within its curriculum, where '*power as the rate of transfer of energy*' was the most frequently presented definition as an achievement standard, representing the role of mathematics in understanding. The US curriculum only collected content related to empirical laws. This stands out more prominently because the NGSS emphasizes evidence-based explanations and discussions. Accordingly, the US curriculum collected items such as: '*Analyze data to support the claim that Newton's second law of motion describes the mathematical relationship among the net force on a macroscopic object, its mass, and its acceleration*', '*Plan and conduct an investigation to provide evidence that an electric current can produce a magnetic field and that a changing magnetic field can produce an electric current*'.

Figure 5
Curriculum-wise Proportions of the Role of Mathematics in Modeling Physical Situations



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Figure 5 shows the frequency by country for the category of mathematics in modeling physical situations. The role of mathematics in modeling physical situations was the most frequently collected category among the mathematization elements gathered from the three national curricula. Specifically, approximation and idealization, and visualization were each collected 23 times, making them the most frequently collected among all mathematization elements. Within the U.S. curriculum, approximation, idealization, and visualization were collected as the first and second most frequently occurring elements, respectively, compared to other mathematization elements. Notably, activities involving visualization or approximation and idealization as presented in the NGSS, such as '*Create a computational model to calculate the change in the energy of one component in a system when the change in energy of the other component(s) and energy flows in and out of the system are known*', frequently involve activities linked to digital tools, such as using simulations or coding to verify expected results. In the Korean curriculum, approximation and idealization were collected most frequently alongside empirical law. The role of mathematics in modeling physical situations presented in the Korean curriculum is primarily used to visualize abstract concepts, such as electric fields or ray tracing for light. Examples include: '*[12전자01-03] Can infer the strength and direction of the magnetic field around a current-carrying conductor using magnetic field lines*' and the consideration presented in the achievement standard application: '*Introduce ray tracing to explain the process of image formation*'. In the England's curriculum, visualization was the most frequently collected alongside interaction relationships and state relationships. A notable feature of the England's curriculum is that, apart from one instance each of approximation and idealization and seven cases of visualization, no instances of analogy, error, or probability expression were collected. Visualization in England's curriculum also primarily aims to visualize abstract concepts. Accordingly, the English curriculum mainly presented examples such as: '*forces as vectors*', '*relating models of arrangements and motions of the molecules in solid, liquid and gas phases to their densities*'. Notably, analogies and expressions of uncertainty and probability were collected with very low frequency across all countries. For analogies, the US presented an inference process utilizing the structural similarity of physical equations, such as: '*Use mathematical representations of Newton's Law of Gravitation and Coulomb's Law to describe and predict the gravitational and electrostatic forces between objects*'. Furthermore, expressions of error and probability were found to be presented in both the United States and Korea as grounds for ensuring the validity and reliability of experimental results. In the case of England, this content is presented not as an achievement standard but as a scientific competency within the 'Working Scientifically' list.

Discussion

This study set out to examine how mathematization is articulated within national physics curricula and to explore the implications of these patterns for inquiry-based science education in digitally oriented learning environments. By applying a theoretically grounded framework of mathematization elements to curricula from Korea, the United States, and England, the analysis revealed both shared tendencies and distinct national emphases in how mathematics is positioned within physics education.

Across all three curricula, mathematization extended beyond the use of mathematical symbols or formal equations to encompass relational, epistemological, and modeling functions. This finding is consistent with prior research that conceptualizes mathematization as a multifaceted process through which physical phenomena are structured, explained, and interpreted mathematically (Redish, 2005; Uhden et al., 2012). However, whereas much of the existing literature has examined mathematization primarily at the level of classroom instruction or student reasoning, this study provides evidence that these roles are already embedded at the curriculum level, shaping intended learning outcomes prior to instructional enactment. This finding highlights the curriculum as a key site where particular forms of mathematical reasoning and scientific inquiry are implicitly prioritized.

The Korean curriculum showed a pronounced emphasis on mathematics as an epistemological role, particularly through empirical laws, definitions, and principles. From the perspective of the nature of scientific knowledge (NOSK), this pattern reflects a curricular orientation in which mathematics functions as a means of formalizing and justifying physics knowledge. Empirical laws and principles are positioned as outcomes of mathematically mediated inquiry, conveying an image of science as a discipline grounded in systematic observation, experimentation, and data-based generalization. This orientation resonates with studies emphasizing the role of mathematics in supporting the construction and validation of scientific knowledge through empirical inquiry (Bing & Redish, 2009; Kim et al., 2023). At the curriculum level, such an emphasis suggests that students are expected to engage with physics knowledge as something to be derived, justified, and stabilized through mathematically structured inquiry processes.

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In contrast, the curriculum in England placed greater emphasis on mathematics in expressing relationships among physical quantities. Interpreted through the lens of the nature of scientific inquiry (NOSI), this relational focus frames inquiry as the identification and interpretation of interactions, dependencies, and system behavior. Rather than foregrounding the derivation of formal laws, the curriculum emphasizes understanding how variables are related and how changes in one quantity affect others. This orientation aligns with research that characterizes mathematization as a means of articulating the structural relationships that underlie physical phenomena (Uhden et al., 2012). From a nature of science (NOS) perspective, such an approach implicitly conveys a view of science as a process of making sense of patterns and relationships in the natural world, potentially supporting students' ability to reason qualitatively and quantitatively about physical systems without relying exclusively on symbolic manipulation.

The United States curriculum, while containing fewer overall instances of mathematization, demonstrated a distinctive emphasis on mathematics in modeling physical situations, particularly through approximation, idealization, and visualization. This emphasis is closely aligned with contemporary views of science as a model-based enterprise, a perspective strongly associated with both NOS and NOSI frameworks. Modeling elements foreground mathematics as a tool for constructing, testing, and refining representations of physical systems, rather than solely as a language for formal expression. This pattern is consistent with prior research highlighting modeling as a central practice in modern science education, especially in digitally enriched contexts involving simulations and representational tools (Gingras, 2015; Euler et al., 2023). At the curriculum level, this orientation suggests an expectation that students engage with scientific inquiry through the manipulation and evaluation of models, often supported by digital visualization and computational tools.

Taken together, these findings indicate that national curricula selectively emphasize different roles of mathematization, reflecting varied curricular conceptions of science, scientific inquiry, and scientific knowledge. Viewed through the integrated lenses of NOS, NOSI, and NOSK, these differences can be understood as reflecting distinct epistemic orientations toward what counts as scientific knowledge, how such knowledge is generated, and how inquiry should be conducted. Importantly, no single curriculum was found to comprehensively integrate all identified roles of mathematization. This observation supports arguments in the literature that authentic scientific inquiry requires the coordinated use of symbolic, relational, epistemological, and modeling forms of mathematical reasoning, rather than the privileging of a single mode (Palmgren et al., 2025).

From the perspective of digital orientation in science education, the results further underscore the evolving nature of mathematization in contemporary curricula. Digital tools such as simulations, data visualization, and computational modeling rely fundamentally on mathematical structures to mediate inquiry, thereby blurring traditional boundaries between representation, analysis, and modeling. The present findings suggest that curricula differ in the extent to which they anticipate and support these digitally mediated forms of mathematization. In this sense, the study extends existing discussions of digitalization and mathematization by demonstrating how curricular intentions may enable or constrain students' engagement with mathematically grounded digital inquiry practices.

Finally, this study highlights the value of curriculum-level analysis for advancing discussions of mathematization within broader frameworks of science education. By making explicit the forms of mathematization embedded in achievement standards, the proposed framework provides a lens for examining how curricula implicitly communicate particular views of the nature of science, scientific inquiry, and scientific knowledge. This contribution complements prior classroom- and learner-focused studies by situating mathematization within the structural context of curriculum design, thereby clarifying how epistemic expectations are established before instructional practice begins.

Conclusions and Implications

This study examined how elements of mathematization are presented in national physics curricula in order to clarify the roles mathematics plays in physics education within a digitally oriented learning context. To achieve this aim, a literature-based analytical framework of mathematization was developed and systematically applied to a comparative analysis of physics curricula from Korea, the United States, and England.

The analysis revealed that mathematization is articulated through multiple distinct roles across national curricula, rather than as a single, uniform process. Specifically, the Korean curriculum most frequently emphasized epistemological roles of mathematics, including empirical laws, definitions, and principles; the curriculum in England showed a stronger focus on expressing relationships among physical quantities; and the curriculum in the United States, while smaller in overall frequency, highlighted elements related to modeling physical situations, particu-

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larly approximation, idealization, and visualization. These findings demonstrate that national curricula selectively foreground different roles of mathematization, reflecting varied curricular priorities in supporting physics inquiry.

Beyond identifying cross-national differences, this study makes two key contributions to research on mathematization in physics education. First, it proposes a comprehensive analytical framework that conceptualizes mathematization as a set of analytically distinct yet complementary roles. Second, by comparing national curricula, this study shows that key roles of mathematization are not confined to classroom practices or students' reasoning, but are already structured at the level of curriculum design, shaping opportunities for mathematical engagement prior to instruction.

Several limitations of this study should be acknowledged. First, the research employed qualitative document analysis, which involves interpretive judgment in the identification and categorization of mathematization elements, despite the use of systematic procedures and cross-review processes to enhance analytical consistency. Second, the scope of analysis was limited to official national curriculum documents; consequently, the findings reflect intended curricular emphases rather than the enactment of mathematization in textbooks, instructional practices, or classroom interactions. Third, the analytical framework was developed based on a selected body of literature identified through a systematic review of the Web of Science database. While this ensured theoretical relevance and rigor, the framework does not represent an exhaustive synthesis of all research on mathematization in physics education, and additional perspectives may be found in studies indexed in other databases or scholarly contexts.

Future research should build on these findings by examining how curriculum-level mathematization elements are realized in textbooks and classroom practices, particularly in digitally mediated learning environments. Further studies focusing on students' mathematical reasoning, modeling activities, and use of digital tools would help to clarify how intended curricular roles of mathematization are translated into meaningful inquiry experiences in physics education.

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Declaration of Interest

The authors declare no competing interest.

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