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Mathematics and modern society: A Delphi study exploring mathematics education towards Education 4.0

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ABSTRACT

Mathematics plays a crucial role in fostering innovation and addressing societal challenges, making its enhancement essential in the context of Education 4.0. This study addresses a gap in the literature by providing expert-driven recommendations for transforming mathematics education in response to the demands of Education 4.0, which has been underexplored in existing research. Through an iterative consultation process, experts agreed on integrating key 21st-century skills such as critical thinking, creativity, collaboration, and digital literacy. The findings emphasize the importance of innovative teaching methods, ethical use of technology, and global competence in fostering adaptable, problem-solving learners. The study also highlights the need for inclusive and sustainable approaches within mathematics education. The proposed frameworks offer practical strategies for bridging theoretical content with real-world applications.

Keywords: Delphi study, Education 4.0, mathematical literacy, mathematics education, mathematics in the modern world

INTRODUCTION

Mathematics is a universal language underpinning modern society's function. As a foundational discipline, it provides essential tools for understanding and solving real-world problems, ranging from economic forecasting to environmental sustainability (Usmonov, 2024). The pervasiveness of mathematics in various domains highlights its role in driving innovation (Boaler, 2022), shaping decision-making processes (Harefa & Hulu, 2024), and fostering global advancements (Sitopu et al., 2024). Moreover, mathematical literacy is vital for active citizenship, equipping individuals to critically analyze information and contribute meaningfully to societal progress (Rizki & Priatna, 2019). In an era of rapid technological evolution, mathematics is a

cornerstone for workforce readiness and informed participation in the global economy (Novita & Herman, 2021).

The emergence of Education 4.0 marks a transformative shift in teaching and learning, aligning education systems with the demands of the Fourth Industrial Revolution (Shahroom & Hussin, 2018). Education 4.0 emphasizes personalized, technology-enhanced learning environments that promote adaptability and innovation (Mogoş et al., 2018). Central to its principles is the integration of digital tools, a focus on interdisciplinary approaches (González-Pérez & Ramírez-Montoya, 2022), and cultivating higher-order thinking skills (Yulıanto et al., 2019). In mathematics education, this paradigm shift necessitates the adoption of adaptive learning technologies and methodologies that foster creativity and analytical reasoning (Chaka, 2022). However, transitioning mathematics education to meet the standards of Education 4.0 presents significant challenges, including gaps in infrastructure (Costan et al., 2021), limited teacher preparation (Teo et al., 2021), misaligned curricula (Nhleko & Van der Westhuizen, 2021), and equity concerns related to accessibility and digital inclusion (Mhlanga, 2020).

In the 21st century, mathematics education must equip learners with critical thinking, problem-solving, and collaborative skills to thrive in a dynamic, interconnected world (Rizki & Priatna, 2019). These competencies enable students to apply mathematical concepts across various disciplines, address real-world challenges, and pursue careers in diverse fields (Maass et al., 2019). There is a growing shift from traditional rote memorization to innovative pedagogical approaches to achieve these outcomes (Boaler, 2022). Such practices empower students to explore mathematical concepts deeply and contextually, fostering a more engaging and meaningful educational experience (Skovsmose, 2020).

The Delphi method has become a powerful tool in educational research, particularly in addressing complex and future-oriented questions. The Delphi method in this study addresses the absence of structured expert consensus in shaping forward-looking strategies for mathematics education in the context of Education 4.0 (Kallia et al., 2021; Mengual-Andrés et al., 2016). While existing literature discusses the integration of 21st-century skills and technology in classrooms, there is limited research that systematically gathers and refines expert recommendations through an iterative and collaborative process. Gathering expert consensus through iterative feedback rounds ensures a comprehensive and informed perspective on critical issues (Majka, 2024). The Delphi method has been effectively applied in mathematics education to inform curriculum reforms, identify emerging trends, and shape policies that align with evolving societal needs (Kallia et al., 2021). Prior studies utilizing this method have demonstrated its utility in bridging gaps between theoretical frameworks and practical applications, offering actionable insights for educators and policymakers (Hallström et al., 2023).

Despite the increasing recognition of Education 4.0, there remains a notable gap in research exploring its intersection with mathematics education. Existing literature offers limited insights into how mathematics education can be modernized to meet the demands of this transformative era. Several studies have explored mathematics education in digital transformation and skill development (Adnan et al., 2019; Dziatkovskii et al., 2022; Kaput et al., 2020; Novita & Herman, 2021); however, most focus on curriculum implementation (Nhleko & Van der Westhuizen, 2021; Sitopu et al., 2024), case studies (Suharta & Suarjana, 2018), or quantitative performance outcomes (Gallardo, 2020). These studies often lack a comprehensive, forward-focused framework built on expert-driven dialogue. Moreover, they tend to emphasize individual tools or classroom practices without addressing the broader system-level shifts required to align with technological and societal changes (Chaka, 2022; Costan et al., 2021; Rehman et al., 2024). This study fills that gap by offering a collective vision informed by expert insights, addressing what should be taught and how education systems can strategically adapt for future readiness. This study seeks to address this gap by providing expert-driven perspectives on aligning mathematics education with the principles of Education 4.0.

LITERATURE REVIEW AND THEORETICAL FRAMEWORK

Mathematics Education in Modern Society

Mathematics plays a vital role in addressing the complex challenges of modern society (Abd Algani, 2022; Maass et al., 2019), offering tools and frameworks for problem-solving across various domains (Chew et al., 2019; Szabo et al., 2020). From climate modeling and financial forecasting to optimizing healthcare delivery and advancing technological innovations, mathematics is a cornerstone for informed decision-making (Dziatkovskii et al., 2022; Kaput et al., 2020; Taja-on et al., 2024). Mathematical application in these areas underscores the necessity of cultivating mathematical literacy among individuals (Rizki & Priatna, 2019; Sitopu et al., 2024), enabling them to analyze data (Hayati & Kamid, 2019), interpret patterns (Suharta & Suarjana, 2018), and devise practical solutions to real-world problems (Rusdi et al., 2020). This foundational competence is essential for tackling pressing global issues and fostering critical thinking and adaptability in an increasingly data-driven world (Juandi & Tamur, 2021; Usmonov, 2024).

Beyond its utility in problem-solving, mathematical literacy has become indispensable for active participation in society and the workforce (Boaler, 2022; Harefa & Hulu, 2024). As industries embrace automation, artificial intelligence, and data analytics, the demand for mathematical proficiency rises, particularly in sectors (Beswick & Fraser, 2019; Novita & Herman, 2021). Furthermore, mathematics is a key enabler of global citizenship, equipping individuals with the quantitative reasoning skills necessary to engage with societal issues such as sustainability, economic inequality, and public health (Pais & Costa, 2020; Palinussa et al., 2021). Understanding these trends in the application of mathematics highlights the need for educational approaches that bridge theoretical concepts with real-world applications, ensuring learners are prepared to contribute meaningfully in diverse contexts.

Education 4.0 Framework and Its Impact on Mathematics Education

Education 4.0 represents a transformative approach to learning, characterized by its alignment with the technological advancements and demands of the Fourth Industrial Revolution (Shahroom & Hussin, 2018). This educational framework emphasizes personalized, flexible, and technology-enhanced education designed to prepare learners for a rapidly evolving digital world (Bonfield et al., 2020; Mogoş et al., 2018; Sharma, 2019). Central principles of Education 4.0 include fostering higher-order thinking skills, nurturing creativity and innovation, and promoting lifelong learning through adaptive and interdisciplinary methods (González-Pérez & Ramírez-Montoya, 2022; Yulıanto et al., 2019). These characteristics underscore the need for educational systems to move beyond traditional models, integrating emerging technologies and learner-centered strategies to meet the dynamic needs of both individuals and industries (Adnan et al., 2019; Hımmetoglu et al., 2020; Qureshi et al., 2021).

In mathematics education, aligning with the principles of Education 4.0 requires reimagining curriculum and pedagogy to reflect the competencies demanded by the Fourth Industrial Revolution (Chaka, 2022; Costan et al., 2021). Mathematics enables advancements in artificial intelligence, data science, robotics, and other transformative fields. As such, an increasing emphasis is on embedding computational thinking, data analysis, and systems modeling into mathematics instruction to prepare students for future opportunities (Khoo et al., 2022; Mhlanga, 2020). This alignment also calls for integrating real-world applications and cross-disciplinary approaches, ensuring that mathematical knowledge is theoretical and directly relevant to solving complex societal and industrial challenges (Layco, 2022; Mizukami & Nanako, 2022; Vinitha et al., 2020).

Implementing Education 4.0 within mathematics education introduces significant implications for teaching and learning practices (Nhleko & Van der Westhuizen, 2021; Teo et al., 2021). Technology-enhanced approaches offer new possibilities for engaging learners and addressing diverse needs (Mogoş et al., 2018). At

the same time, there is a growing focus on developing critical and collaborative skills through inquiry-based and project-based learning models (Gómez-Chacón et al., 2024; Rehman et al., 2024). However, transitioning to these innovative practices also presents challenges, including the need for teacher upskilling, curriculum redesign, and equitable access to digital resources (González-Pérez & Ramírez-Montoya, 2022; Kayembe & Nel, 2019; Szabo et al., 2020). By addressing these challenges, education systems can harness the potential of Education 4.0 to make mathematics education more meaningful, adaptive, and future-focused.

Competencies for the 21st Century Learner

Developing critical thinking, problem-solving, and computational thinking has become essential for learners navigating the complexities of the 21st century (Hendriana et al., 2018; Rizki & Priatna, 2019; Szabo et al., 2020). As a discipline, mathematics provides a unique platform for cultivating these competencies, as it involves analyzing problems, identifying patterns, and formulating logical solutions (González-Pérez & Ramírez-Montoya, 2022; Hwang & Tu, 2021). Critical thinking in mathematics fosters the ability to evaluate assumptions, assess the validity of solutions, and explore alternative approaches (Hafni et al., 2020; Skovsmose, 2020). Meanwhile, computational thinking equips students to handle large-scale data and develop solutions for technology-based challenges (Geiger et al., 2023; Ye et al., 2023). These skills enable learners to address real-world problems with creativity, precision, and adaptability.

Collaboration and interdisciplinary learning have also emerged as crucial components of mathematics education in preparing students for modern challenges (Harefa & Hulu, 2024; Maass et al., 2019). As industries and societal problems increasingly require input from multiple fields, mathematics education must embrace interdisciplinary approaches that connect mathematical concepts to other domains, such as science, technology, and economics (Khreisat et al., 2024; Skovsmose, 2020). Collaborative learning environments encourage students to collaborate, share diverse perspectives, and co-create solutions to complex problems (Kang, 2019; Szabo et al., 2020). By integrating these approaches, mathematics education enhances academic outcomes and prepares learners for teamwork in professional settings, fostering their ability to engage effectively in diverse and dynamic work environments (Misra, 2018; Stephan, 2020; Zhang & Zhang, 2023).

In a technology-driven, data-rich workforce, mathematics education is critical in preparing students to thrive in the digital age. The growing reliance on data analytics, machine learning, and artificial intelligence in industries demands a workforce skilled in quantitative reasoning and data interpretation (Kaput et al., 2020; Hımmetoglu et al., 2020; Mogoş et al., 2018). Mathematics education must equip students to analyze, visualize, and communicate data effectively and adapt to emerging technologies (Maass et al., 2019; Sitopu et al., 2024). Beyond technical skills, there is a need to cultivate ethical reasoning and decision-making, ensuring learners can navigate the societal implications of data use and technology (Boaler, 2022; Ernest, 2018). By aligning mathematics education with these demands, students are better positioned to contribute meaningfully to the workforce and address the challenges of an increasingly interconnected world.

Policy and Curriculum Development for Education 4.0

Policy frameworks play a pivotal role in shaping mathematics education to align with the principles of Education 4.0 (Nhleko & Van der Westhuizen, 2021). These frameworks emphasize the need for educational systems to adopt strategies that prioritize digital literacy, problem-solving, and adaptability, reflecting the demands of the Fourth Industrial Revolution (Harefa & Hulu, 2024; Novita & Herman, 2021; Usmonov, 2024). Governments and education policymakers increasingly focus on embedding technology-enhanced learning, equitable access to resources, and teacher professional development within these frameworks (González-Pérez & Ramírez-Montoya, 2022; Nhleko & Van der Westhuizen, 2021; Szabo et al., 2020). Policies also encourage a shift from traditional assessment methods to competency-based evaluations (Gallardo, 2020), ensuring students develop practical and transferable skills (Skovsmose, 2020; Szabo et al., 2020). These policy

guidelines provide a clear vision and roadmap as the foundation for transforming mathematics education into a more innovative, inclusive, and future-ready discipline (Martin, 2019).

Curriculum reforms are essential for integrating 21st-century skills into mathematics education, ensuring that learners are equipped to navigate the complexities of modern society (Rizki & Priatna, 2019). These reforms advocate interdisciplinary learning (Yulianto et al., 2019), computational thinking (Khoo et al., 2022), and real-world problem-solving (Vinitha et al., 2020) in mathematics curricula (Kayembe & Nel, 2019). Additionally, they emphasize using project-based (Rehman et al., 2024) and inquiry-driven approaches (Gómez-Chacón et al., 2024) to foster critical and creative thinking. Technology integration is also a key focus, encouraging digital tools and platforms to enhance engagement and facilitate personalized learning experiences (Kaput et al., 2020). However, implementing such reforms requires collaboration among educators, policymakers, and stakeholders to address challenges such as curriculum alignment, teacher preparation, and resource accessibility (Costan et al., 2021; Teo et al., 2021; Ye et al., 2023). These changes aim to bridge the gap between traditional mathematics instruction and the evolving needs of learners in the context of Education 4.0.

Theoretical Model

The theoretical framework guiding this study incorporates Social Judgment Theory and Communication and Information Theory, both of which underpin the structured flow of the Delphi process. Social Judgment Theory (Aghbolagh et al., 2020) highlights the importance of individual perspectives and judgment in shaping collective understanding, aligning with selecting and orienting experts. During the first step, identifying and briefing qualified experts ensures that diverse yet relevant perspectives are incorporated into the study. By clearly explaining the study's objectives and scope, experts can better evaluate the research questions and contribute meaningful insights. This orientation aligns with Communication and Information Theory (Zubair, 2023), which emphasizes the clarity and precision of information transfer to reduce misinterpretation and enable constructive feedback.

The subsequent steps in the process—developing and distributing questionnaires, collecting expert opinions, and building consensus—are also anchored in these theoretical foundations. The design of structured questionnaires reflects the principles of Communication and Information Theory, ensuring that questions are precise and tailored to extract valuable insights. Social Judgment Theory becomes particularly relevant during the collection and analysis of responses, as it accounts for the diversity of expert judgments and perspectives, facilitating the identification of shared understanding. As responses are classified and areas of consensus and disagreement are identified, the Delphi process's iterative nature fosters collaboration and idea refinement (Majka, 2024). Compiling the Delphi study report, the final step synthesizes these expert-driven insights, ensuring the findings are communicated effectively to stakeholders (see **Figure 1**).

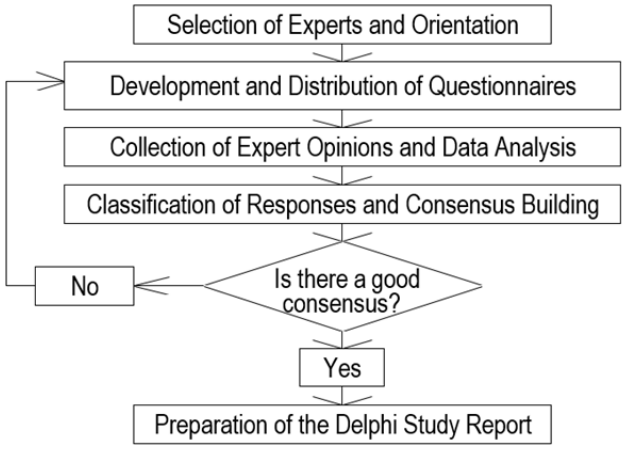

Figure 1. Flowchart of the theoretical framework of the Delphi technique in qualitative research

Objective of the Study

This study explores the intersection of mathematics education and Education 4.0 by identifying strategies, practices, and innovations that align mathematics instruction with the demands of the Fourth Industrial Revolution. Specifically, the study has the following objectives:

1. to determine the essential competencies that should be integrated into mathematics education to adapt to a highly digital and interconnected world in the context of Education 4.0;
2. to gather expert insights on the future direction of mathematics education through the Delphi method;
3. to achieve a consensus among experts on strategies, tools, and frameworks for embedding competencies into mathematics education; and
4. to propose recommendations for aligning mathematics education with the principles of Education 4.0.

METHODOLOGY

Research Design

The study utilized a three-round Delphi iterative consultation process, as outlined by Naisola-Ruiter (2022), to systematically gather and refine expert opinions on the evolving role of mathematics education within the framework of Education 4.0. The process began with developing and distributing an initial questionnaire to elicit broad insights from selected experts towards Education 4.0 and the associated 21st-century skills. After analyzing the responses, a second-round questionnaire was constructed to focus on areas of convergence and divergence, prompting participants to re-associate their views and refine their inputs for an intervention plan. The final round further narrowed down the areas of agreement, building a consensus on key themes and recommendations. This iterative process allowed for the gradual refinement of ideas, ensuring the reliability and validity of the findings.

Selection of Experts

The study employed criterion sampling, as outlined by McPherson et al. (2018), to identify experts with extensive knowledge and experience in mathematics education. The selection criteria required participants to be established professionals in mathematics education with substantial experience in teaching, research, and curriculum development. Experts were required to hold at least a master's degree and five years of teaching experience in mathematics. This thorough selection process ensured that the experts were well-qualified to provide informed and relevant insights, contributing to the credibility and depth of the study.

Participants

The study targeted mathematics education experts in secondary schools, colleges, and universities within Mindanao, Philippines. The study included seven participants to provide background knowledge and content-specific insights into mathematics education towards Education 4.0 (see **Table 1**).

The careful selection process enhanced the validity and applicability of the study's findings, contributing valuable insights to the mathematics education. The demographic profile of the panel members in **Table 1** illustrates the deliberate effort to ensure balanced representation across teaching levels, academic attainment, and years of experience. The study participants were seven mathematics education experts selected through criterion sampling. This diversity of backgrounds enriched the study by incorporating insights from both secondary and higher education settings and professionals at varying stages of their academic careers, which contributed to a more holistic and grounded expert consensus. All participants were contacted through formal email invitations and were provided with a detailed explanation of the study's purpose,

Table 1. Demographic profile of the panel members

Panel Member	Sex	Age	Years of Teaching	Educational Level	Educational Setting	Educational Attainment
MT-1	Male	32	12	Senior High	STEM	Master's Degree
MT-2	Female	47	26	Higher Education	Math. Ed.	Master's Degree
MT-3	Female	58	37	Higher Education	Grad. Study	Doctorate Degree
MT-4	Male	28	7	Junior High	Gen. Math	Master's Degree
MT-5	Male	36	16	Higher Education	Gen. Math	Master's Degree
MT-6	Male	41	20	Senior High	GAS	Master's Degree
MT-7	Female	43	11	Senior High	ABM	Doctorate Degree

STEM: Science, Technology, Engineering, and Mathematics
GAS: General Academic Strand
ABM: Accountancy, Business, and Management

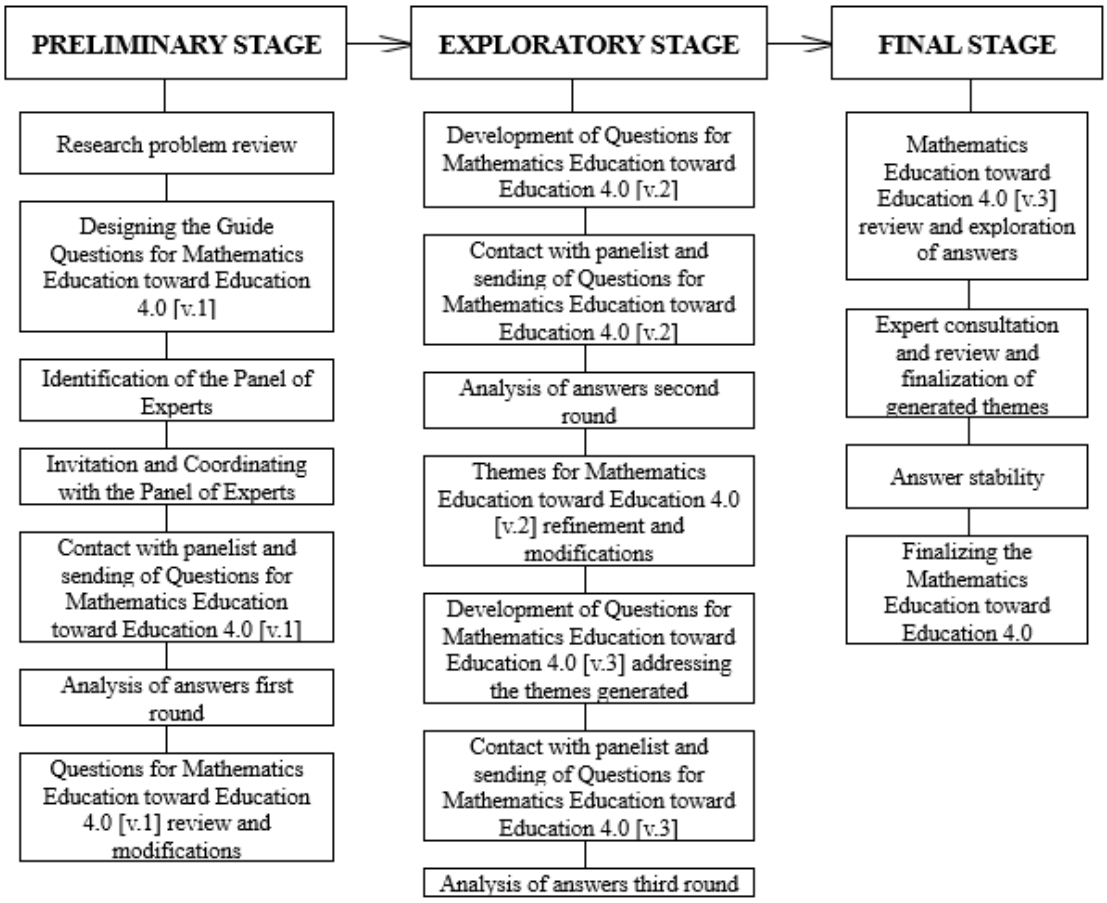

Figure 2. Procedural stages in the Delphi technique implemented

procedures, and expectations. Participation was voluntary, and informed consent was secured before data collection.

Procedure

The study adopted the procedural framework outlined by Mengual-Andrés et al. (2016). Each stage represents a structured phase within the iterative Delphi consultation process, designed to systematically collect, refine, and validate expert insights and recommendations for aligning mathematics education with the principles and demands of Education 4.0 (see **Figure 2**). The data collection followed a structured three-round Delphi process consisting of the preliminary, exploratory, and final stages. In the preliminary stage, the researchers reviewed

the research problem, drafted the initial guide questions, and identified qualified experts based on predefined criteria. Researchers were responsible for coordinating with the panelists, facilitating communication, and administering the questionnaires via email and online survey forms. During each round, the experts provided insights, evaluated proposed themes, and suggested refinements based on their professional experiences. In the exploratory and final stages, researchers synthesized the responses, conducted qualitative analysis through coding and thematic review, and developed revised questionnaires that reflected emerging consensus. After each round, feedback summaries were shared with the experts to inform their subsequent inputs. This iterative process ensured continuous refinement and validation of expert insights, with researchers as facilitators and analysts.

Preliminary stage

The preliminary stage established the foundation for the Delphi process by systematically reviewing the research problem and developing the first version of the guide questions for mathematics education aligned with Education 4.0. After finalizing the initial questions, the panel of experts was identified based on the established criterion to ensure their qualifications and relevance to the study's objectives. Invitations were sent to the selected experts, followed by coordination to explain the process and secure their commitment. Once the experts were onboarded, the initial guide questions were distributed, and their responses were collected and analyzed. This analysis highlighted key insights and gaps, which informed the review and modification of the initial questions to ensure their clarity and alignment with the emerging themes, setting the stage for deeper exploration in subsequent rounds.

Exploratory stage

Building on the groundwork laid during the preliminary stage, the exploratory stage focused on refining and deepening the inquiry through iterative feedback from the panel of experts. A second version of the guide questions was developed based on the insights generated from the first round, with careful consideration of the themes and patterns identified. These revised questions were sent to the experts, who analyzed responses to identify commonalities and areas requiring further exploration. The themes were refined using this analysis, and a third version of the guide questions was created to address the newly generated insights. This version was again sent to the experts for their input, and the responses from the third round were analyzed to provide a comprehensive and nuanced understanding of the key issues and recommendations for aligning mathematics education with Education 4.0.

Final stage

The final stage focused on consolidating the findings and ensuring the stability of the insights gathered throughout the iterative consultation process. The responses to the third version of the guide questions were carefully reviewed and explored, with the experts providing feedback to validate and finalize the generated themes. This consultation assessed the consistency and stability of the experts' answers, ensuring that the conclusions were rich and representative of collective consensus. The finalized themes and insights were then used to develop recommendations for mathematics education to align with Education 4.0.

Researchers' role

The researchers played a central role in facilitating each study stage throughout the Delphi process. The researchers' tasks included the development of the initial and revised versions of the guide questions, organizing and coordinating expert communication, consolidating inputs, and conducting the thematic synthesis of expert feedback. Meanwhile, the experts proposed, reviewed, and deliberated on intervention plans for mathematics education aligned with Education 4.0. The experts also evaluated the consolidated themes generated by the researchers, helping refine and validate the recommendations. This collaborative

structure ensured that the findings emerged from a balance of scholarly thoroughness and practical expertise, making the resulting recommendations informed and actionable.

Data Analysis

The study employed a systematic qualitative approach, as outlined by Bernard et al. (2016), to analyze the data gathered through the Delphi process, ensuring that expert insights were interpreted consistently and meaningfully across each round. The analysis began with open coding, where the researchers reviewed each response line-by-line to identify initial categories and concepts. This inductive process allowed themes to emerge naturally from the data without imposing pre-existing assumptions. Each code was assigned a label representing a recurring idea or issue raised by the experts. These initial codes formed the basis for deeper thematic exploration and provided a foundational understanding of expert perspectives on mathematics education in Education 4.0.

Following open coding, the researchers focused on coding, wherein the initial codes were compared, grouped, and refined to identify more significant and recurring patterns. At this stage, overlapping ideas were clustered, and less relevant codes were excluded to distill the most meaningful content. This process involved synthesizing the data into broader categories aligned with the study's purpose. Themes were identified by frequency, depth, and relevance of insights provided by the experts. This step allowed the researchers to translate raw expert input into organized themes that could guide the formulation of intervention plans and recommendations. The transition from open to focused coding ensured that the analysis remained systematic while progressively narrowing the scope to the most critical insights.

Once the themes were established, thematic analysis, as outlined by Clarke and Braun (2017), was employed to explore and interpret the underlying meanings and relationships within the data. These themes underwent an iterative review process (Neale, 2016), where they were re-evaluated and refined to ensure coherence and alignment with the study's goals. Data collection and analysis were conducted simultaneously over seven months, from April to November 2024, allowing ample time for the iterative rounds of consultation, feedback, and thematic validation required in the Delphi process and until data saturation was achieved—when no new themes or insights emerged.

To further validate the findings, member checking (Birt et al., 2016) was conducted, allowing the experts to review and confirm the accuracy of the interpreted data. This final step ensured that the analysis was credible, representative of the experts' perspectives, and robust enough to support the study's conclusions.

RESULTS AND DISCUSSION

The results collectively present a comprehensive progression of expert insights and consensus toward shaping mathematics education in alignment with Education 4.0.

Experts Input towards Education 4.0 and Alignment to the 21st-Century Skills in Mathematics Education

Table 2 presents the summarized input of the experts towards Education 4.0 and the alignment of the experts to the 21st-century skills in Mathematics Educations. Expert insights highlight the key competencies required to prepare learners for a highly interconnected and technology-driven world. These inputs emphasize the transformative role of mathematics education in fostering essential skills that support lifelong learning and adaptability in diverse contexts.

Table 2. Summary of the expert's input towards Education 4.0 and the consensus of the identified 21st-century skills in Mathematics Education by the experts

21st Century Skills	Experts Input
Critical Thinking and Problem-Solving	Integrating critical thinking in mathematics education. Enhancing problem-solving skills through mathematical concepts. Enhancing mathematical reasoning for effective decision-making. Developing adaptability and flexibility through mathematical thinking. Addressing real-world challenges through mathematical approaches.
Creativity and Innovation	Fostering creativity and innovation in mathematics learning. Integrating mathematical modeling for global problem-solving. Designing mathematics curriculum for global competence and engagement.
Communication	Developing communication skills through mathematical discussions. Enhancing mathematical communication through collaborative platforms.
Collaboration and Teamwork	Promoting collaboration and teamwork in mathematical problem solving. Strengthening leadership and initiative skills through collaborative projects.
Digital Literacy	Building digital literacy in mathematics education. Incorporating technology in mathematics instruction for 21st century skills.
Global Awareness and Cross-Cultural Competence	Cultivating global awareness through mathematics education. Teaching global citizenship through mathematical contexts. Developing cross-cultural competence in mathematical education.
Ethical Decision-Making	Encouraging ethical decision-making in mathematics applications.
Social Responsibility and Equity	Promoting inclusive education through diverse mathematical approaches. Integrating mathematical literacy for social change.
Environmental and Global Sustainability	Connecting mathematics to sustainable development goals (SDGS). Expanding mathematical approaches to support environmental sustainability.

Table 2 highlights the essential 21st-century skills identified by the panel, emphasizing their integration into mathematics education. The expert input underscores the importance of mathematics in fostering problem-solving abilities, ethical decision-making, and global competencies, particularly through innovative pedagogical approaches and curriculum designs that address real-world challenges.

Critical thinking and problem-solving

The experts recommended the integration of critical thinking and problem-solving into mathematics education which allows learners to develop essential skills for analyzing, reasoning, and making decisions in complex, real-world scenarios. By enhancing mathematical reasoning and encouraging adaptability, students are better prepared to approach unfamiliar problems with confidence and creativity. These skills extend beyond the classroom, as they empower individuals to address global challenges through structured, logical approaches (Hwang & Tu, 2021; Skovsmose, 2020). Incorporating these competencies into teaching practices ensures that mathematics education remains relevant in a rapidly evolving, interconnected world and fosters a culture of lifelong learning (Maass et al., 2019; Misra, 2018; Sitopu et al., 2024).

Creativity and innovation

The experts recommended to foster creativity and innovation in mathematics education that nurtures the learners' ability to think outside traditional boundaries and devise novel solutions to global problems. By emphasizing the use of mathematical modeling, students can tackle real-world issues through practical and imaginative applications of mathematical concepts. Designing curricula that encourage engagement with global challenges ensures that mathematics education not only builds technical proficiency but also inspires students to become proactive contributors to society (Boaler, 2022; Ernest, 2018; Szabo et al., 2020). This approach promotes a forward-thinking mindset essential for success in a technology-driven world (Kaput et al., 2020).

Communication

The experts recommended the integration of communication skills into mathematics education that promotes effective collaboration and the articulation of mathematical ideas. Encouraging discussions and the use of collaborative platforms helps students to engage in meaningful exchanges of perspectives, enhancing their understanding of complex topics. This focus on communication fosters a shared language for problem-solving and builds confidence in presenting and defending mathematical solutions, which are crucial skills in academic and professional settings (Chew et al., 2019; Hendriana et al., 2018; Skovsmose, 2020).

Collaboration and teamwork

The experts recommended the encouragement of collaboration and teamwork within mathematics education to foster the development of interpersonal skills and collective problem-solving. By engaging in collaborative projects, students not only enhance their understanding of mathematical concepts but also cultivate leadership and initiative. These experiences prepare learners for diverse, team-oriented professional environments where collaboration and the ability to work toward common goals are highly valued (Kang, 2019; Hwang & Tu, 2021).

Digital literacy

The experts recommended the development of digital literacy in mathematics education that equips learners with the tools and competencies to effectively use technology in problem-solving and data analysis. Incorporating technology into instruction enhances engagement and facilitates the development of skills critical for navigating a digital world. This integration ensures that students are prepared to meet the demands of modern industries that rely heavily on technological advancements and data-driven decision-making (Hwang & Tu, 2021; Novita & Herman, 2021; Sitopu et al., 2024).

Global awareness and cross-cultural competence

The experts recommended the development of global awareness and cross-cultural competence through mathematics education that fosters an appreciation for diversity and interconnectedness. By teaching mathematical concepts within global contexts, students gain the ability to approach problems with a broader perspective and engage responsibly in global citizenship. Cross-cultural competence is particularly important in preparing learners to work effectively in multicultural environments and address issues that transcend national boundaries (Kidman & Casinader, 2019; Maass et al., 2019; Pais & Costa, 2020; Zhang & Zhang, 2023).

Ethical decision-making

The experts recommended the incorporation of ethical decision-making into mathematics education which encourages students to consider the societal implications of mathematical applications. This competency ensures that learners can approach problems responsibly, balancing technical solutions with ethical considerations. Highlighting ethical practices in mathematical problem-solving prepares students to navigate the complexities of modern challenges with integrity and accountability (Ernest, 2018; Maass et al., 2019).

Social responsibility and equity

The experts recommended the promotion of inclusive education through diverse mathematical approaches that highlights the role of mathematics in fostering social equity. By integrating mathematical literacy as a tool for social change, education systems can empower students to address inequality and contribute to community well-being. These efforts ensure that mathematics education not only builds individual competencies but also serves to advance societal progress (Kang, 2019; Stephan, 2020).

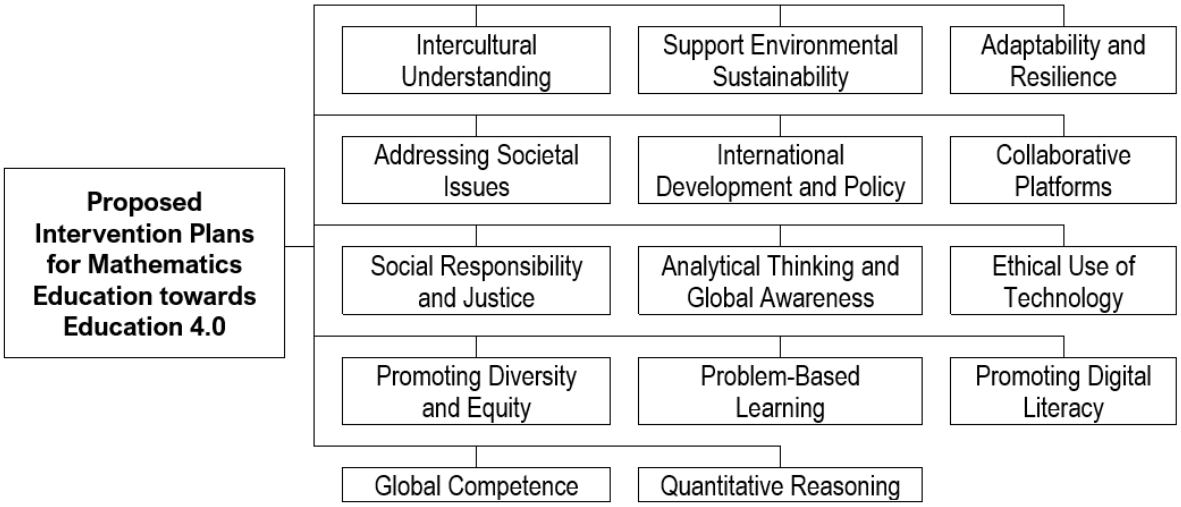

Figure 3. Thematic chart on the summary of the proposed intervention plans for mathematics education towards Education 4.0 as deliberate by the panel of experts

Environmental and global sustainability

The experts recommended to connect mathematics education to sustainability which emphasizes the relevance of mathematical approaches in addressing environmental challenges. By aligning mathematics with sustainable development goals, students learn to apply their knowledge to promote environmental stewardship and global well-being. These connections reinforce the importance of mathematics as a driver of solutions for pressing global issues, encouraging learners to engage in meaningful and impactful work (Geiger et al., 2023; Kidman & Casinader, 2019; Maass et al., 2019; Szabo et al., 2020; Usmonov, 2024).

Exploratory Stage of the Proposed Intervention Plans for Mathematics Education

Figure 3 illustrates the thematic chart connecting the proposed intervention plans for mathematics education towards Education 4.0. The analysis generated fourteen initial themes during the exploratory stage of the panel discussion. Through iterative consultation with experts, a range of themes emerged, reflecting innovative strategies and practices that aim to enhance the relevance and effectiveness of mathematics education. These themes represent a foundation for reimagining how mathematics can address the evolving needs of learners and society.

Figure 3 captures the exploratory stage of the study, mapping out fourteen initial themes proposed for intervention plans. The thematic chart reveals the panel's diverse considerations and recognition of mathematics as a tool for addressing societal issues, promoting sustainability, and advancing global competence. These themes illustrate a multidimensional approach to updating mathematics education by connecting it to broader societal and technological advancements.

Intercultural understanding

The experts recommended the facilitation of intercultural understanding through collaborative mathematical projects promotes teamwork and appreciation for diverse perspectives. By engaging students in projects that require cooperative problem-solving across cultural contexts, mathematics becomes a medium for fostering empathy and cross-cultural dialogue. This approach allows students to explore how mathematical principles apply universally while respecting different cultural viewpoints. Expert input highlights the importance of

collaborative platforms and frameworks that support these interactions, ensuring that students are prepared to work effectively in a globalized world (Hwang & Tu, 2021; Maass et al., 2019; Zhang & Zhang, 2023).

Support environmental sustainability

The experts recommended the integration of environmental sustainability into mathematics education which emphasizes the role of mathematical reasoning in addressing ecological challenges. By connecting concepts such as statistical modeling and optimization to sustainability goals, students are encouraged to develop solutions that support resource conservation and environmental protection. This approach highlights mathematics as a vital tool for analyzing data, predicting outcomes, and informing policy decisions related to sustainability. The consensus among experts underscores the need to prioritize these connections in curricula, making mathematics education more relevant and impactful in the context of global environmental concerns (Kidman & Casinader, 2019; Geiger et al., 2023; Harefa & Hulu, 2024; Hwang & Tu, 2021; Sitopu et al., 2024; Szabo et al., 2020).

Adaptability and resilience

The experts recommended to enhance the adaptability and resilience through math-related problem-solving that prepares students to navigate uncertainty and dynamic challenges. By encouraging flexible thinking and iterative approaches to problem-solving, mathematics education fosters the ability to adapt strategies in response to changing variables. This focus helps students build confidence in their capacity to address novel problems, a skill increasingly critical in a rapidly evolving world. Expert recommendations emphasize the importance of integrating real-world, open-ended problems into instruction to cultivate these essential attributes in learners (Hendriana et al., 2018; Kang, 2019; Rusdi et al., 2020; Szabo et al., 2020; Sitopu et al., 2024).

Addressing societal issues

The experts recommended the application of mathematical concepts to address societal issues which involves leveraging mathematical reasoning to understand and solve problems related to inequality, sustainability, and public health. Experts underline the importance of contextualizing mathematical instruction to reflect contemporary challenges, encouraging students to see mathematics as a tool for creating social impact. By emphasizing connections between abstract theories and practical applications, this approach fosters a sense of responsibility and empowers learners to contribute meaningfully to their communities (Bonfield et al., 2020; Layco, 2022; Taja-on et al., 2024).

International development and policy

The experts recommended to connect mathematical knowledge to international development and policy which demonstrates how mathematical principles can inform large-scale decision-making. By applying mathematical models to analyze trends and develop solutions for global challenges, such as economic disparities and infrastructure development, students see the broader impact of mathematics. This approach bridges the gap between abstract learning and practical applications, empowering learners to contribute meaningfully to international progress. Experts highlight the need to embed these connections into curricula to prepare students for roles that influence global development (Bonfield et al., 2020; Costan et al., 2021; Sharma, 2019; Vinitha et al., 2020).

Collaborative platforms

The experts recommended the enhancement of mathematical communication through collaborative platforms that fosters the exchange of ideas and collective problem-solving. Experts recognize the value of creating spaces where students can articulate their thought processes, critique peers' work, and refine their reasoning collaboratively. These platforms encourage teamwork and the development of shared solutions,

preparing learners to thrive in environments where communication and cooperation are critical. The emphasis on collaborative communication aligns with the evolving demands of technology-enabled education and global workforce dynamics (Kang, 2019; Sharma, 2019; Skovsmose, 2020).

Social responsibility and justice

The experts recommended the use of mathematics to foster social responsibility and justice that highlights the potential of mathematics education to address inequality and promote equitable solutions. Experts advocate for incorporating socially relevant themes into mathematical instruction, enabling learners to explore issues such as resource allocation, policy development, and environmental sustainability. This focus ensures that mathematics is not only seen as a technical discipline but also as a means to cultivate empathy, civic engagement, and social transformation. Through deliberate alignment with societal priorities, mathematics education becomes a platform for instilling values of justice and responsibility in students (Bonfield et al., 2020; Kidman & Casinader, 2019; Mogoş et al., 2018; Szabo et al., 2020; Usmonov, 2024).

Analytical thinking and global awareness

The experts recommended to foster analytical thinking and global awareness through mathematics that equips students with the ability to evaluate complex problems critically and understand their global implications. By embedding real-world challenges, such as economic trends and global sustainability, into mathematical instruction, students develop a broader perspective that extends beyond theoretical knowledge. This focus on analytical skills helps learners identify patterns and formulate solutions while enhancing their capacity to address interconnected global issues (Kang, 2019; Kaput et al., 2020; Maass et al., 2019; Skovsmose, 2020; Szabo et al., 2020). The iterative feedback process among experts ensures that the integration of these competencies reflects diverse perspectives and aligns with evolving societal needs.

Ethical use of technology

The experts recommended that educators encourage the ethical use of technology in mathematics by teaching students to navigate the digital landscape responsibly and responsibly. This includes integrating digital tools and platforms into lessons while explicitly addressing issues like data privacy, algorithmic bias, and responsible use. Educators can embed ethical discussions into everyday instruction by linking these practices to existing curriculum elements such as mathematical modeling, computational thinking, and data literacy. This ensures that students not only develop proficiency with technological tools but also gain the ability to evaluate their implications and limitations critically. Such integration empowers learners to make informed decisions in academic and real-life contexts, aligning technological fluency with ethical reasoning. Promoting these values alongside curriculum objectives helps ensure that the use of technology in mathematics remains both purposeful and socially responsible (González-Pérez & Ramírez-Montoya, 2022; Khreisat et al., 2024; Sharma, 2019).

Promoting diversity and equity

The experts recommended the promotion of diversity and equity in mathematics education which involves designing curricula and teaching strategies that are inclusive and reflective of diverse perspectives. By incorporating culturally relevant examples and addressing systemic barriers, mathematics education can create a more equitable learning environment. This approach encourages underrepresented groups to engage with mathematics while highlighting its role in addressing social inequalities. Expert feedback emphasizes the importance of fostering an inclusive culture within mathematics education to ensure that all students can access and benefit from learning opportunities (Ernest, 2018; Hwang & Tu, 2021; Martin, 2019; Zhang & Zhang, 2023).

Problem based learning

The experts recommended the integration of problem-based learning (PBL) into mathematics education that emphasizes real-world application and active engagement in solving complex problems. This approach allows learners to develop critical thinking and analytical skills by exploring mathematical concepts within meaningful contexts. By fostering collaboration and inquiry, PBL shifts the focus from rote memorization to deeper understanding, preparing students to tackle practical challenges. The iterative feedback process among experts highlights the importance of structuring PBL tasks to align with learners' needs and societal demands, ensuring that the integration of PBL supports innovative thinking and adaptability (Hafni et al., 2020; Skovsmose, 2020; Szabo et al., 2020; Zakaria et al., 2019).

Promoting digital literacy

The experts recommended the promotion of critical digital literacy that equips students with the ability to interpret, analyze, and apply data effectively in mathematical contexts. Experts emphasize the need for digital tools that enhance students' ability to process and evaluate quantitative information critically. This skill set is essential for making sound decisions in a technology-rich environment, enabling learners to navigate complexities in fields such as artificial intelligence and data science (Hwang & Tu, 2021; Sharma, 2019). Through iterative expert consultations, the focus on critical digital literacy ensures that students develop both technical and analytical proficiencies vital for modern problem-solving (Kang, 2019; Szabo et al., 2020).

Global competence

The experts recommended the development of global competencies through mathematical applications that involves the teaching of students to view mathematical problems from a global perspective. Experts stress the importance of embedding cross-cultural contexts and global challenges into mathematics education, helping learners connect abstract concepts to tangible issues. By fostering a critical awareness of global interconnections, mathematics education can cultivate skills that prepare students to address diverse challenges, ensuring their readiness for an increasingly interconnected world (Hafni et al., 2020; Szabo et al., 2020; Vinitha et al., 2020; Zhang & Zhang, 2023).

Quantitative reasoning

The experts endorsed that quantitative reasoning is essential for developing informed global citizens capable of interpreting data and making evidence-based decisions. By emphasizing skills within real-world contexts, mathematics education equips students to critically evaluate global issues such as public health and economic inequality. This focus ensures that learners not only understand mathematical concepts but also apply them to promote informed and responsible participation in society. Expert insights reinforce the value of quantitative reasoning as a cornerstone for preparing students to address the complexities of an interconnected world (Sitopu et al., 2024; Skovsmose, 2020; Szabo et al., 2020; Taja-on et al., 2024).

Finalization Stage of the Intervention Plans for Mathematics Education

Figure 4 illustrated the thematic analysis chart connecting the consolidated intervention plans for mathematics education towards Education 4.0. The analysis generated six overarching themes, namely *innovative teaching methods*, *ethics and technology in mathematics education*, *global competencies and citizenship*, *social responsibility and justice*, *sustainability and policy*, and *inclusive education*. Within each thematic category, subthemes have been associated by the panel members referring to the fourteen initial themes during the exploratory stage of the discussion. By synthesizing expert feedback into overarching themes, this stage provided a comprehensive roadmap for implementing innovative teaching methods. The finalized intervention plans ensure that mathematics education remains adaptive, inclusive, and forward-looking.

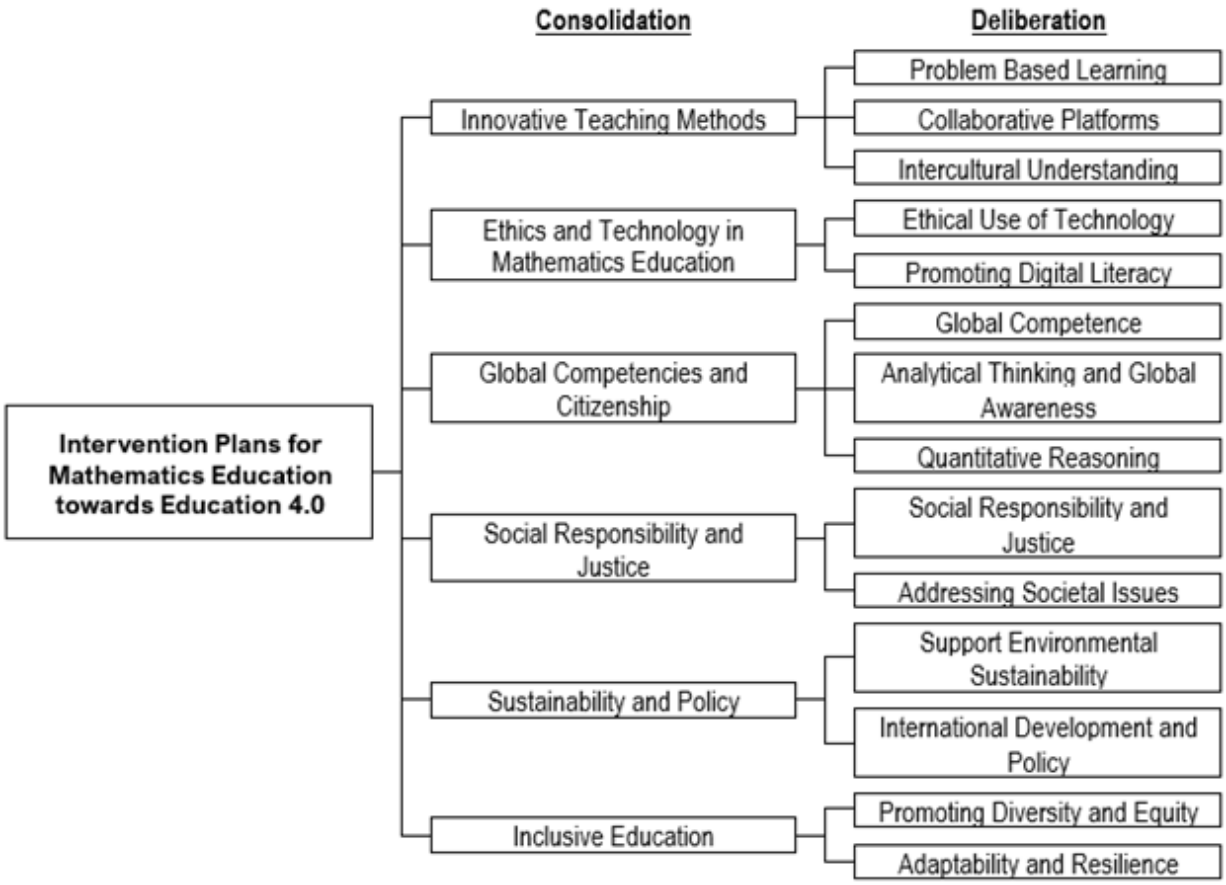

Figure 4. Thematic chart on the summary of the consolidated intervention plans for mathematics education towards Education 4.0 as streamlined by the panel of experts

Figure 4 consolidates the initial themes into six overarching categories. This refinement reflects a consensus among the panel on the strategic priorities for mathematics education, streamlining the intervention plans into actionable and cohesive directions. The analysis showcases mathematics education as a transformative force in developing globally aware, socially responsible, and technologically proficient learners.

Innovative teaching methods

The experts consolidated that emphasizing innovative teaching methods in mathematics creates dynamic learning environments where students engage in meaningful problem-solving and collaborative projects. Approaches that integrate real-world challenges into lessons foster critical thinking and creativity while helping learners deepen their understanding of core mathematical concepts. These methods enhance curriculum relevance while promoting student engagement by aligning with components of existing mathematics curricula. Using collaborative platforms and intercultural projects further supports communication and teamwork, essential competencies for students navigating diverse and interconnected global contexts. Expert input suggests that embedding these strategies into standard curricular frameworks can support a smoother transition to Education 4.0-aligned practices while ensuring continuity with national education standards. Through this alignment, innovative pedagogies can enrich individual growth and collective problem-solving within formal mathematics instruction (Kang, 2019; Bonfield et al., 2020; Hafni et al., 2020; Szabo et al., 2020).

Ethics and technology in mathematics education

The experts consolidated that embedding ethical considerations within the use of technology in mathematics encourages students to navigate digital tools responsibly while fostering critical analysis. By integrating

opportunities to reflect on the societal implications of technology, learners develop digital literacy alongside the ability to make informed, ethical decisions. Expert input underscores the importance of cultivating awareness of how technology shapes outcomes in mathematics, ensuring students are prepared to balance technical proficiency with moral accountability in a digital age (Ernest, 2018; González-Pérez & Ramírez-Montoya, 2022; Harefa & Hulu, 2024).

Global competencies and citizenship

The experts consolidated that incorporating global competencies into mathematics education enables students to address issues that transcend cultural and national boundaries. Through the integration of mathematical applications into global contexts, learners build analytical thinking, critical reasoning, and cross-cultural understanding. These practices not only enhance individual problem-solving skills but also prepare students to engage as informed citizens in a globalized world. Expert consensus reinforces the need for mathematics education to serve as a platform for fostering awareness and responsibility toward global challenges (Hendriana et al., 2018; Hwang & Tu, 2021; Zhang & Zhang, 2023).

Social responsibility and justice

The experts consolidated that focusing on social responsibility and justice in mathematics education ensures that students understand the broader impact of mathematical concepts on society. By connecting mathematical reasoning to societal issues, such as inequality and sustainability, learners develop ethical and critical thinking skills that prepare them to contribute meaningfully to their communities. Expert recommendations highlight the importance of emphasizing equity and social justice in curricula, making mathematics education a tool for promoting societal progress (Ernest, 2018; Geiger et al., 2023).

Sustainability and policy

The experts consolidated that linking mathematics to sustainability and policy equips students with the tools to analyze and address environmental and global challenges. By applying mathematical reasoning to sustainable development and international policymaking, learners gain a practical understanding of how mathematics supports real-world decision-making. Expert feedback stresses the importance of integrating these applications into mathematics education to foster environmental literacy and social responsibility, ensuring students are prepared to influence meaningful change (Kidman & Casinader, 2019; Maass et al., 2019; Szabo et al., 2020; Usmonov, 2024).

Inclusive education

The experts consolidated that fostering inclusive education in mathematics ensures equitable access to learning opportunities for all students, regardless of their background. Promoting diversity and equity through culturally responsive teaching methods and materials allows students to see themselves reflected in the curriculum, building engagement and confidence. Expert input emphasizes the role of mathematics education in creating inclusive environments that celebrate diverse perspectives while addressing systemic barriers (Martin, 2019; Zhang & Zhang, 2023).

Moreover, the experts consolidated that developing adaptability and problem-solving skills in mathematics education prepares students to navigate complex and changing challenges. Encouraging flexible thinking and resilience in tackling mathematical problems fosters creativity and critical reasoning, equipping learners with the ability to approach uncertainties. Experts highlight the need to integrate these competencies into curricula to prepare students for the evolving demands of modern society, ensuring their readiness to address real-world challenges confidently (Chew et al., 2019; Hendriana et al., 2018; Skovsmose, 2020).

CONCLUSION

The findings highlight the need to align mathematics education with the evolving demands of a technology-driven and interconnected society, emphasizing the integration of 21st-century skills such as critical thinking, creativity, collaboration, and digital literacy. The expert input generated actionable recommendations that bridge theoretical frameworks with practical applications, addressing what competencies are needed and how they can be embedded through innovative pedagogical approaches. Through expert input, the study identifies specific competencies—critical thinking, creativity, collaboration, digital literacy, ethical reasoning, and global awareness—essential for modern learners.

In addition to identifying key competencies, the study advances new knowledge by proposing a set of thematic intervention plans that reflect the evolving priorities of education systems. These include adopting innovative teaching methods, ethical and responsible use of technology, promoting global citizenship, sustainability, and inclusive practices. The Delphi process allowed for a more collaborative and future-oriented approach synthesizing expert judgment, making the findings highly relevant to curriculum planners, educators, and policymakers. This structured method of gathering and refining expert insights uniquely contributes by bridging conceptual frameworks with actionable strategies.

Moreover, the study fills a critical gap in the literature by moving beyond isolated innovations or classroom practices and instead offering a coherent framework that addresses the systemic transformation of mathematics education. The result emphasizes the role of mathematics not only in developing technical skills but also in preparing students to think critically, act ethically, and contribute meaningfully to society. These insights extend the current discourse in mathematics education, offering scholars a new lens through which to examine how education can be reshaped to meet future demands.

LIMITATIONS

The study is inherently limited by the scope and diversity of the expert panel, which, while carefully selected, may not fully represent all perspectives in mathematics education across different cultural, institutional, and technological contexts. The study's findings are based on the insights of only seven experts, which, while highly qualified, may limit the generalizability of the conclusions across broader educational contexts. The iterative Delphi process, while effective for building consensus, relies on subjective judgments that individual experiences and biases may influence, potentially narrowing the scope of insights. Additionally, the study focuses on conceptual recommendations and does not include the implementation or assessment of the proposed intervention plans in real-world educational settings, which limits the evaluation of their practical feasibility and impact. Time constraints and resource limitations also restricted the study's ability to explore in-depth the broader implications of integrating 21st-century skills across varying education systems.

RECOMMENDATIONS

Based on the findings, mathematics education could integrate innovative teaching methodologies such as problem-based learning, collaborative platforms, and interdisciplinary approaches to foster critical thinking, creativity, and global awareness. Digital literacy and ethical decision-making could be embedded into the curriculum to prepare students for a technology-driven world while promoting responsible use of digital tools. Additionally, mathematics instruction could emphasize addressing real-world challenges, including sustainability and societal issues, through applied learning experiences.

Educators and policymakers are encouraged to prioritize inclusive practices that promote diversity and equity, ensuring that all learners can access and benefit from quality mathematics education. Strengthening teacher training programs and providing ongoing professional development is crucial for equipping educators with the skills to implement these transformative strategies effectively. Stakeholders could collaborate to create policies and resources that align educational frameworks with these recommendations, ensuring their scalability and sustainability.

Teacher training programs could be redesigned to effectively bridge the gap between theory and practice to include focused modules on problem-based learning, digital integration, ethical technology use, and interdisciplinary instruction within mathematics education. These programs could provide hands-on experiences that allow educators to apply innovative strategies in realistic settings. In addition, national and local education policies could support this transformation by mandating continuous professional development, allocating funding for digital infrastructure, and embedding Education 4.0 competencies into teacher certification standards. Collaborative partnerships between educational institutions, government agencies, and industry stakeholders also facilitate the development of context-specific training resources and curriculum guidelines.

FURTHER STUDIES

Future studies could focus on testing and evaluating the proposed intervention plans in diverse educational settings to assess their effectiveness and feasibility. Further investigation is needed to explore how cultural and institutional differences influence the implementation of Education 4.0 principles, particularly in underrepresented and resource-constrained contexts. Studies that incorporate perspectives from a broader range of stakeholders, including students, parents, and industry leaders, would provide a more comprehensive understanding of the needs and expectations for mathematics education in a globalized society. Expanding research into the role of emerging technologies, such as artificial intelligence and data science, could also offer valuable insights into the future direction of mathematics education.

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