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Integration of artificial intelligence in national science curricula

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ABSTRACT

This study investigates the integration of artificial intelligence (AI) in national science curricula across 21 countries, including Australia, Cyprus, Estonia, France, Finland, Greece, Hong Kong, India, Iceland, Ireland, Nepal, New Zealand, Norway, Ontario (Canada), Poland, Singapore, South Africa, South Korea, Sweden, the United Kingdom, and the United States. By analyzing these curricula, the research identifies the presence of AI-related knowledge, skills, and attitudes, providing a comprehensive understanding of how AI is embedded in educational frameworks. The findings reveal a strong emphasis on practical AI skills, interdisciplinary knowledge, ethical considerations, and societal impacts, preparing students to thrive in an AI-driven future. This comprehensive approach highlights AI's transformative potential in education. The study emphasizes AI's role in fostering problem-solving skills and active learning, underscoring the need for practical AI applications and comprehensive teacher training in AI concepts. The analysis also identifies gaps in the explicit mention of "artificial intelligence" itself, suggesting a broader focus on related concepts. Notably, AI is not frequently mentioned explicitly in the curricula but is often approached under the umbrella of information and communication technology in relation to science. Recommendations for enhancing AI integration include comprehensive teacher training, continuous curriculum evaluation, and the inclusion of the ethical and societal implications of AI. This research provides valuable insights for educators and policymakers, highlighting the need for a well-rounded curriculum that prepares students for the future challenges and opportunities presented by AI technologies.

Keywords: artificial intelligence, science education, curriculum integration, knowledge and skills, ethical considerations, interdisciplinary learning

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INTRODUCTION

Artificial intelligence (AI) is a technological domain that has significantly developed over the last few decades. There has been extensive research and debate regarding the benefits and challenges this development can present for education. Researchers, engineers, and experts approach AI by investigating advancements in specific components of intelligence, such as learning, reasoning, problem-solving, perception, and language usage. AI is associated with several fields of advancement: machine learning, which involves programming computers to learn from data; deep learning, which involves creating various layers of knowledge based on visual representations, leading to a model of the data; data mining, which includes analyzing large volumes of data through processes such as statistics to find categories and relationships within data sets; and learning analytics, which investigates opportunities to improve teaching and learning. Learning analytics rely on using data to identify patterns between parameters of learning and teaching, such as learners' characteristics and responses. Through this perspective, research on AI focuses on four different dimensions: developing technological applications and means that can think humanly, think rationally, act humanly, and act rationally. These points have garnered the interest of educators and policymakers in an effort to examine how to leverage AI in schools and manage any potential risks (Pedro et al., 2019).

The potential benefits of using AI in education are numerous. It can lead to improved learning outcomes. The general idea behind using AI in education focuses on facilitating personalized learning in different contexts and promoting new opportunities for literacy and fruitful education for all citizens. This is achieved in several ways. First, it provides access to information and knowledge for learners from different groups, including the underprivileged. Second, it can promote pedagogical approaches that depend on group work, interaction, synchronous or asynchronous dialogue, analysis of information, discourse, and evaluation. Third, it supports personalized learning for students who need it, helping them better understand and apply new knowledge. Finally, it helps teachers manage paperwork or other time-consuming processes, allowing them to focus more on preparing teaching material and delivering instruction. These advantages rely on learning analytics, which involves developing digital technological applications that use knowledge from social sciences, pedagogy, sociology, and psychology in digital ways. These applications can detect insights, identify learning patterns, make decisions, and execute procedures that assist in achieving teaching goals and learning outcomes. Examples of such applications are already being used or tested. Indeed, the national governments of various countries, international enterprises, and non-profit organizations have been launching AI platforms where learners of various ages can access education. This is achieved through using texts, audio-visual material, personalized learning, simulation of classroom environments, gamification, promotion of team learning, and direct feedback.

Despite these benefits, the implementation of AI in education and social institutions should not be considered an opportunity for improvement by default. It presents challenges that must be addressed. The first challenge is aligning the functions and use of AI applications with the general goals of progress and sustainable development. This requires cooperation between different groups, such as institutions, policymakers, AI experts, engineers, and educators. The second challenge is providing access to AI applications and infrastructure, especially in underprivileged regions and developing countries where infrastructure is insufficient or unreliable. The third challenge is preparing teachers through training on AI in general and specifically on using AI for educational purposes. It also requires AI experts who can understand and appreciate teachers' work. The fourth challenge is developing and establishing appropriate and quality data systems. The fifth challenge is establishing ways to evaluate the effectiveness of using AI in teaching and schools with the help of continuous feedback and holistic research. Finally, the sixth challenge is ensuring respect for ethics, accountability, security, and transparency.

These challenges can be addressed through appropriate, well-established policies that define how, why, and under what conditions AI should be used in schools and teaching. These policies should reflect a vision for improving schools and communities with the help of AI. This vision should be appreciated and shared by all members of the school community (Fullan, 2007; Pedro et al., 2019).

AI IN EDUCATION

Modern societies are characterized by the rapid development of technology and knowledge, which is relevant to the function of AI. Any policy focusing on education for an AI-oriented society should reconsider teaching in terms of knowledge, skills, and attitudes. Learners need to be familiar with concepts, functions, and processes related to AI. They should also be competent in using AI and planning sessions involving its implementation for problem-solving. Lastly, they should be positive towards its use and open to the idea of contributing to its promotion and development. From another perspective, educational institutions should equip learners with competencies to use information and communication technology (ICT) – for managing, creating, reflecting, solving problems, and developing new knowledge. Moreover, they should develop competencies related to ICT that assist in decision-making, ensure balanced and healthy living, enhance understanding and respect for others, and support peaceful resolution of conflicts or challenges.

All these goals can be achieved if particular conditions are met. These include the provision of appropriate qualities on behalf of educators as well as an appropriate curriculum. This curriculum needs to focus on three different dimensions that teachers and learners need to emphasize. The first is technological literacy, which will help learners gain knowledge about ICT, AI, and how to use it efficiently. The second is knowledge deepening, which will help learners better understand knowledge gained from every subject and appreciate how it can be used to solve real-life problems. The third is knowledge creation, which will help learners contribute to the generation of knowledge that will lead to harmonious and prosperous societies (UNESCO, 2011).

These dimensions can be associated with the learning goals and outcomes that education for AI could set. Technological literacy pertains to cognitive goals. A primary cognitive goal might focus on learning about AI and its techniques, including understanding what AI is and is not, its basic features and components, and general terminology. Additionally, it could involve learning important historical information regarding its development. It could also encompass understanding how AI operates, including data management, sensor usage, and computer perception. A second cognitive goal could involve AI technologies and tools such as autonomous systems, chatbots, and language processing systems. A third cognitive goal might include learning about AI development, including design thinking and the product lifecycle. A fourth cognitive goal could involve understanding algorithms and their use in AI, particularly through computational processes. A fifth cognitive goal might focus on programming and its crucial role in AI. A sixth cognitive goal could be associated with data literacy, which involves understanding data collection, management, analysis, presentation, reporting, and usage to produce output. A seventh cognitive goal might relate to contextual problem-solving, discussing and evaluating AI's applicability to various practical problems. An eighth cognitive goal could involve integrating AI into other domains, explaining how AI can be used in everyday life and across different disciplines. A ninth cognitive goal might address ethics, including learning about AI's limitations, advantages, and disadvantages concerning bias, human rights, privacy, intellectual property, transparency, and security. Finally, a tenth cognitive goal might focus on the social implications of AI, learning about its general advantages and disadvantages for humans, its contribution to people's lives as individuals, citizens, and professionals, and its impact on the broader social context, including environmental issues, political matters, gender issues, fake news, and misinformation (UNESCO, 2022).

The second dimension, knowledge deepening, can be associated with skill or psychomotor goals. These goals can be similar to the cognitive ones. A primary psychomotor goal could involve AI and its techniques, including skills such as classifying objects, designing activities and tests, and selecting and interpreting resources or data. A second psychomotor goal could involve AI technologies, including designing, using, testing, and managing chatbots, systems, or autonomous robots. A third psychomotor goal might focus on AI development, including group work, designing AI projects, brainstorming, innovative thinking, and evaluating projects or activities. A fourth psychomotor goal could involve algorithms, including formulating algorithms, recognizing patterns, and organizing computational procedures. A fifth psychomotor goal might focus on programming, including creating codes, constructing scripts, developing applications, applying programming languages, and managing robots or hardware with relevant software programming control. A sixth psychomotor goal could involve data literacy and managing data and databases to support autonomous systems that execute functions such as decision-making. A seventh psychomotor goal might relate to contextual problem-solving, including defining a problem or task, developing strategies for solutions, and evaluating them. An eighth psychomotor goal could involve integrating AI into other domains, such as using AI to produce material for art or music. A ninth psychomotor goal might address ethics, including identifying risks, creating systems that protect ethics, privacy, or safety, and preparing guidance for citizens or developers on using AI ethically and prudently. Finally, a tenth psychomotor goal could focus on the social implications of AI, including evaluating, comparing, and analyzing AI developments and their impact on people's personal, social, or professional lives (UNESCO, 2022).

The third dimension, knowledge creation, can be associated with attitudes or affective goals. There are several groups of affective goals regarding AI teaching. One group includes personal affective goals. A primary personal goal is to develop an interest in ICT, explore AI tools, and create innovative solutions. A second personal goal is to develop persistence and resilience, including problem-solving with the help of programming and testing products or artifacts. A third personal goal is personal empowerment, which includes developing design thinking skills, researching data, and identifying risks. A fourth personal goal is reflection, which involves recognizing how AI has changed a person's life and work and the potential it offers. A fifth personal goal is the development of critical thinking, which includes planning problem-solving with AI, disseminating, evaluating, and justifying it. Finally, a sixth personal goal is entrepreneurship, which includes using AI to design innovative products, ideas, or services. Another group of affective goals is social, including collaboration, teamwork, and communication. Additionally, there is a group of societal affective goals, such as respect for others, personal responsibility, integrity, and tolerance regarding AI and related work or research. Finally, there are human affective goals, including developing an environmental mindset, learning how AI can influence the environment or sustainability, and taking action to mitigate any negative impact. These goals also include a commitment to equity, learning how AI can affect issues around equality, and taking action to limit inequalities (UNESCO, 2022).

AI IN SCIENCE EDUCATION

A first attempt to investigate the potential of AI in science education was made by Good (1987) from a theoretical perspective. Starting with the general observation that AI will bring shifts in learning paradigms, which will influence science teaching, the author emphasizes the impact of introducing intelligent systems in education and promoting the so-called intelligent computer-assisted instruction (ICAI). In science teaching specifically, this could impact problem-solving tasks or activities. The impact has three basic dimensions. The first is using AI to model the student and assist in eliciting learners' misconceptions, as well as gaining a deeper understanding of how knowledge is constructed, both generally and in specific situations, such as teaching individual students, small groups, or large groups. The second is using AI to model the teachers, helping students during the problem-solving process and creating opportunities for controlled student-teacher interaction. The third is using AI to model the learning environment, particularly as a simulation of the natural world or micro world for students to investigate and experiment with. In other words, AI can help students have hands-on experiences with topics they cannot engage with in their everyday lives. The main finding of this work highlights the importance of AI's potential to diagnose problems and the state of learners, as well as implement appropriate teaching strategies. These intelligent systems are being developed through continuous research validation and feedback, contrasting previously known information with new insights.

At the same time, Lippert (1987) pointed out that as future citizens need to catch up with the rapidly growing amount of knowledge and be competent in managing it, schools need to equip learners with the necessary qualities. This goal can be achieved by helping learners become familiar with problem-solving in mathematics and science subjects. Using expert systems and AI is therefore significant. Firstly, it involves active learning, which will likely be essential in future work environments. Secondly, by implementing activities that include problem-solving with expert systems, schools can help students better understand how knowledge is developed. For example, in science, expert systems can help learners engage in understanding forces, force combinations, and interactions. This can happen through discourse, hypothesis formation, experimentation, trial-and-error, explanation, presentation, and evaluation of data and performance. Thirdly, by seeing where the knowledge is used, they will appreciate it more and understand its meaning and effectiveness. Fourthly, by trying and using expert systems, they will become more familiar with them, their potential, and their risks. As the authors mention, it is important for appropriate technological tools and applications to be developed. These tools should consider various factors, including information technologies such as controlling functions, data entry, and analysis. They should also consider educational functions such as the cognitive processes through which students learn and the modes of instruction used in schools. Pilot implementation and evaluation of these tools in actual teaching situations are also crucial.

Al Darayseh (2023) conducted a study on science teachers' perceptions of using AI. Using a questionnaire distributed to 83 teachers in Abu Dhabi, the author aimed to examine the level of acceptance, the factors considered essential for effective teaching with AI, and the demographic variables, such as gender, academic qualification, and teaching experience, that might influence these perceptions. The findings indicated that acceptance depends on several correlated factors, including self-efficacy, stress and anxiety, expected benefits, ease of using AI applications, attitudes towards AI, and general behavior. There seemed to be no statistically significant difference due to demographic variables, likely attributed to state support with appropriate conditions, infrastructure, training, and support. Overall, the teachers in the sample showed a positive attitude towards using AI in science teaching. The general finding is that effective integration of AI in science education requires a strong level of technological literacy among teachers, which can be gained through appropriate training focusing on several areas. The first is theoretical knowledge of AI and its basic concepts. The second is effective practices for using AI in science classes that teachers can implement. The third is the inclusion of this topic in teacher-preparation courses. Finally, the fourth is the establishment of general guidelines for teachers, policymakers, and members of the educational community. These measures can increase awareness, self-confidence, and self-efficacy among teachers, enabling them to use AI effectively and routinely in science classes.

Jia et al. (2023) conducted a bibliometric study on articles researching the integration of AI in science education. The authors searched platforms to collect articles investigating specialized aspects, functions, and applications of AI as implemented in elementary and secondary science classes. The collection excluded articles that did not specifically use AI tools or were not based on empirical studies.

Through this search, 76 articles published from 2013 to 2023 were gathered. The findings indicate a general increase in the number of publications, despite a period of decline at the end of the 2010s. This decline can be attributed to factors such as the outbreak of COVID-19, which motivated researchers to investigate other areas. The main themes, concluded by keywords grouped into clusters, are 10: collaborative learning, robotics, computer science education, intelligent tutoring systems, elementary education, vocabulary, regression, theory of planned behavior, classroom teaching improvement, and explanation. The most popular AI techniques studied are automation, prediction, educational robots, intelligent tutoring systems, and machine learning. Most publications come from journals focusing on technologies in education, although some are from journals focusing on education studies or science education. They are mostly submitted by groups of researchers at universities. The countries with the greatest contributions are either English-speaking, such as the United States (USA), Canada, Australia, and the United Kingdom (UK), or non-English-speaking, such as China, Turkey, Japan, Germany, Italy, Finland, and Greece, with evident collaboration among countries.

Herdliska and Zhai (2023) conducted research involving 128 students from a high school in the USA. These students engaged in sessions using Google Teachable Machine, an AI application, to deliver scientific inquiry. The study emphasized teaching students how AI influences scientific work and methodology. Participants were first introduced to machine learning systems, AI, their potential, benefits, risks, and ethical dilemmas. They were then asked to plan a project involving scientific inquiry with the help of AI. After their plans were evaluated and approved, they executed them. The analysis focused on several points: understanding AI, developing projects, assessing the quality of data, developing algorithms, validating algorithms, and appreciating the limitations of AI. The findings show that although there was variation in student performance across these points, most developed a deep understanding of AI's potential and were able to use it practically. This study stresses the importance of including AI in mainstream science teaching as an essential skill for future citizens, who are expected to become familiar with digital tools and scientific inquiry. The authors explain that AI in teaching, particularly in teaching scientific inquiry, has many dimensions that must be investigated, including experimentation, validation, presentation, and social or ethical issues. They suggest that a change in the curricula might be necessary.

Kotsis (2024) published a study on integrating AI in elementary science teaching, emphasizing practical recommendations for effective implementation. AI is justified as useful for science teaching in many ways. It can analyze students' characteristics, strengths, weaknesses, interests, and other factors, assisting in individualized learning and instruction. Moreover, it can provide virtual labs and simulations that facilitate activities and experiments that would otherwise be difficult to conduct in a mainstream classroom due to cost or health and safety concerns. Additionally, teachers can provide adaptive assessment and feedback according to each student's pace and personality. Finally, AI-driven tools can make teaching more accessible and effective. However, certain conditions must be met to achieve these benefits. First, teachers need appropriate professional development, specializing in innovative teaching approaches using AI in science teaching. Second, teachers need to be familiar with data analytics to understand each student's needs, as well as curriculum design, lesson delivery, and evaluation. Third, there should be collaboration among teachers, facilitated by online platforms where they can exchange ideas and experiences. Lastly, there should be the provision of appropriate tools and resources, such as equipment, infrastructure, lesson plans, and curricula. These curricula should address misconceptions and ethical issues that may arise with the use of AI in science teaching.

Studies on AI in science education consistently emphasize the transformative potential of AI and the critical role of an AI-integrated curriculum in enhancing science education. Firstly, they highlight how AI fosters problem-solving skills and active learning. Good (1987) and Lippert (1987) emphasize ICAI and expert systems, which model students and teachers to diagnose issues and develop effective teaching strategies. Al Darayseh (2023), Kotsis (2024), and Herdliska and Zhai (2023) stress the importance of a curriculum that incorporates practical AI applications, demonstrating that effective AI use in classrooms requires thorough teacher training in AI concepts and practices. Secondly, the studies underscore the necessity of embedding appropriate technological tools and infrastructure within the curriculum. Lippert (1987) and Al Darayseh (2023) point out that successful AI implementation hinges on the availability of suitable AI applications and institutional support. This highlights the need for a curriculum designed to include these technologies and provide a robust support system. Thirdly, there is a consensus on the need for continuous research and curriculum evaluation. Good (1987) and Jia et al. (2023) highlight the ongoing development and validation of AI systems and the importance of empirical studies to understand the effective use of AI in science education. A dynamic curriculum that evolves with these findings ensures the relevance and efficacy of AI in education. Overall, these studies agree on the importance of a curriculum that familiarizes both teachers and students with AI, preparing them for future digital environments. Lippert (1987), Herdliska and Zhai (2023), and Jia et al. (2023) stress that understanding AI's potential and limitations is crucial for future citizens. Therefore, a curriculum that integrates AI across various educational levels is essential to developing digital literacy and scientific inquiry skills, ensuring that students and teachers are well-prepared for the future.

THE STUDY

Projects that conduct research into using AI in science education point out the importance of a well-structured curriculum. The curriculum needs to be structured appropriately to include clear goals, units, activities, and points that facilitate the involvement of AI in teaching and learning science. This involves various dimensions, such as learning science with the help of AI, learning about AI through science teaching, and understanding how AI has assisted scientific work and research (Herdliska & Zhai, 2023; Jia et al., 2023; Kotsis, 2024; Lippert, 1987). Although the role of the curriculum is justified, there is limited study examining whether current national curricula actually promote the implementation and familiarization of AI in science teaching across these dimensions.

This is the topic of the specific research. Such a study could provide significant insights into the possibilities that contemporary schools have from central governments to engage AI in science sessions, as well as the actual perceptions of the educational community regarding that matter. These points are directly or indirectly reflected in the goals, units, activities, approaches, and other components that make up a national curriculum. In other words, any attempt by contemporary teachers and schools to achieve learning outcomes related to AI in science teaching depends on the content of current curricula (Pedro et al., 2019). Therefore, this study is considered both innovative and significant for educators of science, digital technologies, or other specializations, as well as experts who work in or are involved in a relevant field.

To answer the basic question of whether AI is included in science curricula, it is necessary to specify what elements of AI and AI teaching could be incorporated. In other words, it is necessary to define what elements could be included in a science curriculum related to AI. These points could be relevant to the dimensions of AI in education. Technological literacy is the first dimension and involves digital awareness, policy awareness, knowledge about tools, integrating abilities, and classroom management. Teachers should have appropriate training and approval of the need for technological literacy so that they can deliver relevant knowledge to learners. Knowledge deepening is the second dimension and involves policy understanding, knowledge application, complex problem-solving, complex tools, and collaborative classroom management. Knowledge creation is the third dimension, and it involves policy innovation, complex social skills, self-management, highly complex analyzing technology, learning organization structure, and model-learner teachers (UNESCO, 2011, 2022). Bearing that in mind, the basic question of the study can be answered by researching whether the national curricula of science pay attention to technological literacy, knowledge deepening, and knowledge creation.

Therefore, the research questions for the study are, as follows:

1. Do the national science curricula contain goals, objectives, and activities about technological literacy around AI?
2. Do the national science curricula contain goals, objectives, and activities that emphasize knowledge deepening around AI?
3. Do the national science curricula contain goals, objectives, and activities that promote knowledge creation focused on AI?

By providing answers to these questions, it is possible to specify whether national science curricula contain elements regarding teaching about AI (UNESCO, 2022).

For this study, the national curricula of 21 different countries or regions were collected. These are Australia, Cyprus, Estonia, France, Finland, Greece, Hong Kong, India, Iceland, Ireland, Nepal, New Zealand, Norway, Ontario (Canada), Poland, Singapore, South Africa, South Korea, Sweden, the UK, and the USA. The selection was based on the criteria of language and accessibility. The research is qualitative in nature. The data came from the collected curricula. Document analysis was implemented. The documents, which in this case were the curricula, were examined carefully to find sections related to the research questions. As is common in qualitative research, this analysis was based on coding. Codes or labels that relate to the basic points, topics, or themes of the research questions were determined. Any text or quote from the document that related to these themes was classified under the relevant code. These codes were grouped into nodes. By collecting and analyzing the codes and nodes, it is possible to draw conclusions and provide insights into the findings (Cohen et al., 2017; Yin, 2015).

The nodes and codes should therefore reflect the basic themes and points of the research questions, which in this case are the elements of AI teaching that can be traced in national curricula of science subjects (UNESCO, 2022). For this study, three nodes have been selected. These nodes are technological literacy, knowledge deepening, and knowledge creation. The first, which relates to cognitive goals and knowledge, includes 10 codes. These are: AI learning and techniques knowledge; AI technologies and tools knowledge; AI development knowledge; algorithms knowledge; programming knowledge; data literacy knowledge; contextual problem-solving knowledge; integration knowledge; ethics knowledge; and social implications knowledge. Similarly, the second node, which relates to psychomotor goals and skills, has 10 codes. These are: AI learning and techniques skills; AI technologies and tools skills; AI development skills; algorithms skills; programming skills; data literacy skills; contextual problem-solving skills; integration skills; ethics skills; and social implications skills. Finally, the third node, which relates to affective goals and attitudes, has eight codes. These are interest; persistence and resilience; empowerment; reflection; critical thinking; entrepreneurship; societal; and human. Six of the eight codes in the last node represent the personal attitudes that curricula should focus on regarding teaching AI. The codes are presented in **Table 1**.

Table 1. Clear and concise explanation of each code used in the study

Code	Explanation
Knowledge codes	
1.01	'AI learning and techniques knowledge' – Understanding the foundational concepts and methods of AI.
1.02	'AI technologies and tools knowledge' – Familiarity with specific AI technologies and tools.
1.03	'AI development knowledge' – Knowledge about creating and developing AI technologies.
1.04	'Algorithms knowledge' – Understanding the principles and applications of algorithms in AI.
1.05	'Programming knowledge' – Knowledge of programming languages and coding related to AI.
1.06	'Data literacy knowledge' – Ability to understand and work with data in the context of AI.
1.07	'Contextual problem-solving knowledge' – Applying AI to solve real-world problems.
1.08	'Integration knowledge' – Integrating AI knowledge across different subjects and domains.
1.09	'Ethics knowledge' – Understanding the ethical implications of AI.
1.10	'Social implications knowledge' – Understanding the societal impacts of AI.
Skills codes	
2.01	'AI learning and techniques skills' – Practical skills related to AI learning and techniques.
2.02	'AI technologies and tools skills' – Proficiency in using specific AI tools.
2.03	'AI development skills' – Skills needed to develop AI solutions.
2.04	'Algorithms skills' – Practical skills related to creating and understanding algorithms.
2.05	'Programming skills' – Practical coding skills for developing AI applications.

Table 1 (continued).

Code	Explanation
2.06	'Data literacy skills' – Skills for interpreting and handling data in AI contexts.
2.07	'Contextual problem-solving skills' – Practical problem-solving skills using AI.
2.08	'Integration skills' – Ability to integrate AI knowledge and skills across various subjects.
2.09	'Ethics skills' – Skills for navigating ethical challenges in AI.
2.10	'Social implications skills' – Skills for understanding and addressing the societal impacts of AI.
Attitudes codes	
3.01	'Interest' – Fostering interest in AI and technology.
3.02	'Persistence and resilience' – Developing perseverance and resilience in AI.
3.03	'Empowerment' – Building confidence and self-efficacy in using AI technologies.
3.04	'Reflection' – Encouraging reflective practices about learning experiences and AI implications.
3.05	'Critical thinking' – Developing critical thinking skills regarding AI technologies and their applications.
3.06	'Entrepreneurship' – Fostering entrepreneurial skills and innovation using AI.
3.07	'Societal' – Understanding the broader societal implications of AI.
3.08	'Human' – Emphasizing human-centered aspects and impacts of AI.

Table 2. Table of codes and frequencies

Code	Frequency
Knowledge	
Code 1.1 AI learning and techniques knowledge	50
Code 1.2 AI technologies and tools knowledge	18
Code 1.3 AI development knowledge	10
Code 1.4 Algorithms knowledge	3
Code 1.5 Programming knowledge	2
Code 1.6 Data literacy knowledge	10
Code 1.7 Contextual problem-solving knowledge	23
Code 1.8 Integration knowledge	38
Code 1.9 Ethics knowledge	16
Code 1.10 Social implications knowledge	33
Skills	
Code 2.1 AI learning and techniques skills	67
Code 2.2 AI technologies and tools skills	19
Code 2.3 AI development skills	10
Code 2.4 Algorithms skills	3
Code 2.5 Programming skills	1
Code 2.6 Data literacy skills	12
Code 2.7 Contextual problem-solving skills	23
Code 2.8 Integration skills	34
Code 2.9 Ethics skills	18
Code 2.10 Social implications skills	32
Attitudes	
Code 3.1 Interest	14
Code 3.2 Persistence and resilience	6
Code 3.3 Empowerment	4
Code 3.4 Reflection	12
Code 3.5 Critical thinking	29
Code 3.6 Entrepreneurship	11
Code 3.7 Societal	57
Code 3.8 Human	46

An analysis of the science curricula based on these nodes and codes can provide insights into the components that promote teaching AI in science classes and perhaps the factors or constituents that teachers could or need to address to help learners become more familiar with AI through the relevant subjects (UNESCO, 2011, 2022).

The analysis was done with the help of an online qualitative research platform called QDAcity, which was appropriate for the study and accessible free of charge. Presentation of the codes can be achieved using online resources such as RawGraphs (Cohen et al., 2017; Yin, 2015).

FINDINGS

The findings of the study around the national curricula show that there is a comprehensive approach to integrating AI and ICT into education. National curricula worldwide emphasize the importance of equipping students with the necessary knowledge, skills, and attitudes to navigate and contribute to an AI-driven future. The analysis of frequencies, as shown in **Table 2**, reveals a strong focus on practical AI skills, interdisciplinary knowledge, ethical considerations, and societal impacts, highlighting a comprehensive approach to preparing students for the digital age. This aligns with the academic literature, which underscores the transformative potential of AI in education. Studies such as those by Good (1987) and Lippert (1987) emphasize the role of AI in fostering problem-solving skills and active learning through ICAI and expert systems. More recent research by Al Darayseh (2023), Kotsis (2024), and Herdliska and Zhai (2023) highlights the necessity of practical AI applications and thorough teacher training in AI concepts. The benchmarks from these studies provide a valuable context for understanding the importance of AI integration in modern curricula.

Knowledge Codes (1.01–1.10)

The analysis of code frequencies reveals significant insights into how different aspects of AI knowledge are emphasized in the curricula. 'AI learning and techniques knowledge' appears 50 times, indicating a strong emphasis on understanding AI learning methods and techniques within the curricula. This reflects the necessity for students to grasp the foundational concepts and theoretical knowledge related to AI, including how AI functions and the principles behind it. This focus ensures that students have a solid grounding in AI, preparing them to understand and utilize AI technologies effectively. 'AI technologies and tools knowledge' appears 18 times, highlighting the importance of familiarizing students with various AI technologies and tools. While it is less frequent than AI learning techniques, it underscores the necessity for students to be aware of specific tools and technologies they will encounter in AI applications (UNESCO, 2022).

'AI development knowledge' appears 10 times, suggesting a balanced emphasis on both using and creating AI technologies. This prepares students not only to utilize AI but also to contribute to its development and innovation. 'Algorithms knowledge' appears only 3 times, indicating that specific knowledge about algorithms might be integrated into broader AI topics like programming or data literacy rather than being a standalone focus.

Similarly, 'programming knowledge' appears 2 times, implying that programming skills are embedded within other ICT and AI learning topics, following a holistic approach to developing programming alongside other AI competencies.

'Data literacy knowledge' appears 10 times, reflecting its critical importance. Understanding and managing data is vital in AI contexts, and data literacy is essential for interpreting and analyzing data. 'Contextual problem-solving knowledge' appears 23 times, indicating a practical approach within the curricula, preparing students to use AI in various contexts, and enhancing their problem-solving capabilities. 'Integration knowledge' appears 38 times, highlighting the importance of integrating AI knowledge across different subjects and domains. This interdisciplinary approach ensures that students see the relevance and application of AI in various fields (Fullan, 2007; Perdo et al., 2019).

'Ethics knowledge' appears 16 times, underscoring the significance of teaching students about the ethical implications of AI. It prepares them to think critically about the responsible use of AI technologies and understand the moral considerations involved. 'Social implications knowledge' appears 33 times, indicating a significant focus on understanding the societal impacts of AI. Students are encouraged to consider how AI affects various aspects of society, including cultural, social, and economic dimensions, preparing them for thoughtful and responsible participation in a technology-driven world (UNESCO, 2011, 2022).

The importance of embedding appropriate technological tools and infrastructure within the curriculum is evident. The term 'artificial intelligence' itself appears in only a few curricula, indicating a broader focus on AI-related concepts rather than explicit mentions. This aligns with Lippert (1987), who highlights the importance of integrating AI implicitly through technological tools and infrastructure by discussing how ICAI and expert systems can model students and teachers to diagnose issues and develop effective teaching strategies, thereby enhancing educational outcomes. The necessity of practical AI applications and thorough teacher training, highlighted by Al Darayseh (2023) and Kotsis (2024), underscores the importance of ensuring that students are familiar with AI technologies and tools. Al Darayseh (2023) stresses that effective AI use in classrooms requires comprehensive teacher training in AI concepts and practices, ensuring educators are well-equipped to guide students through complex AI topics. Kotsis (2024) adds that incorporating practical AI applications into the curriculum not only enhances learning experiences but also prepares students for real-world challenges. These studies collectively suggest that a well-rounded curriculum, supported by robust technological infrastructure and informed by continuous teacher development, is crucial for leveraging AI's full potential in education, thus preparing students for the future.

Skills Codes (2.01–2.10)

In the analysis of skills codes, 'AI learning and techniques skills' appears 67 times, making it the highest frequency among all codes. This reflects a strong emphasis on developing practical skills related to AI learning and techniques. Curricula prioritize equipping students with hands-on skills, ensuring they can effectively engage with AI technologies and apply what they learn in real-world scenarios. 'AI technologies and tools skills' appears 19 times, indicating the importance of students becoming proficient in using specific AI tools and ensuring practical knowledge in navigating and utilizing these technologies.

'AI development skills' appears 10 times, highlighting the skills needed to develop AI solutions. This balanced emphasis suggests that while using AI technologies is important, contributing to their development is equally valued, fostering innovation and creativity among students. 'Algorithms skills' appears only 3 times, indicating that algorithmic skills are often integrated into broader topics such as programming or data analysis. This ensures that students understand algorithms in practical contexts rather than as isolated concepts (UNESCO, 2022).

'Programming skills' appears only once, suggesting that these skills are considered foundational and thus integrated into various other aspects of AI and ICT education rather than being a primary focus. 'Data literacy skills' appears 12 times, showing that data literacy is a critical skill essential for interpreting and handling data in AI contexts. Ensuring students have strong data literacy skills prepares them to work effectively with AI technologies.

'Contextual problem-solving skills' appears 23 times, indicating that practical problem-solving skills using AI are heavily emphasized. This prepares students to apply their AI knowledge to real-world challenges, enhancing their practical and analytical abilities. 'Integration skills' appears 34 times, reflecting the importance of interdisciplinary skills and showing that students are taught to integrate AI across various subjects. This skill set is crucial for applying AI in diverse contexts, promoting a holistic educational approach (Fullan, 2007; Perdo et al., 2019).

'Ethics skills' appears 18 times, indicating a balanced focus on ensuring students understand and practice responsible AI use. This prepares them to navigate the ethical challenges they may encounter in the field of AI. 'Social implications skills' appears 32 times, showing a significant focus on equipping students with the skills to understand and address the societal impacts of AI. This prepares them to consider and mitigate the broader consequences of AI technologies (UNESCO, 2011, 2022).

These findings are consistent with the emphasis on practical AI applications and the integration of suitable technological tools within the curriculum, as highlighted by studies such as Lippert (1987) and Al Darayseh (2023). Lippert's (1987) study underscores the transformative potential of embedding AI tools into educational practices, illustrating how these technologies can enhance learning experiences and foster active problem-solving skills. Al Darayseh (2023) emphasizes the critical need for incorporating practical AI applications, demonstrating that the availability of appropriate AI tools and infrastructure significantly boosts the effectiveness of AI integration in classrooms. Furthermore, the importance of thorough teacher training in AI concepts, as noted by Kotsis (2024) and Herdliska and Zhai (2023), is paramount. Kotsis (2024) highlights that educators must be well-versed in AI principles and practical applications to guide students effectively. Herdliska and Zhai (2023) stress that comprehensive training programs are essential for teachers to keep pace with rapid technological advancements and to impart relevant skills to students. The high frequency of skills related to AI learning and techniques found in the curricula reflects this need. This comprehensive approach ensures students are well-equipped to handle the complexities and ethical considerations of AI technologies, preparing them for future challenges in a technology-driven world.

Attitudes Codes (3.01–3.08)

For the attitudes codes, 'interest' appears 14 times, reflecting efforts to foster interest in AI and technology. While less frequent than skills and knowledge codes, it highlights the importance of engaging students and sparking their curiosity about AI. 'Persistence and resilience' appears 6 times, indicating a focus on developing these traits in students. Although it appears less frequently, it underscores the value of persistence and resilience in overcoming challenges and continuing to learn and innovate in AI.

'Empowerment' appears 4 times, showing that curricula aim to build students' confidence and self-efficacy in using AI technologies. This is crucial for fostering a sense of capability and ownership over their learning and application of AI. 'Reflection' appears 12 times, indicating that reflective practices are integrated into the curricula to encourage students to think critically about their learning experiences and the implications of AI. This fosters a deeper understanding and continuous improvement.

'Critical thinking' appears 29 times, highlighting a strong focus on developing critical thinking skills through AI education. Students are taught to analyze, evaluate, and make reasoned decisions about AI technologies and their applications. 'Entrepreneurship' appears 11 times, showing an emphasis on fostering entrepreneurial skills and encouraging students to innovate and create new solutions using AI. This prepares them for future opportunities in the tech industry and beyond.

'Societal' appears 57 times, underscoring the importance placed on understanding the societal implications of AI. Students are encouraged to consider how AI affects society and to think about their role in shaping its impact. 'Human' appears 46 times, reflecting a significant focus on human-centered aspects of AI, including user-centered design and the human impacts of technology. This ensures that students learn to develop and use AI in ways that are empathetic and considerate of human needs and values.

These findings support the need for continuous research and curriculum evaluation, as highlighted by Good (1987) and Jia et al. (2023). Good (1987) emphasizes the importance of ongoing assessment and refinement of AI systems to ensure they effectively enhance educational outcomes. Jia et al. (2023) underscore the necessity for empirical studies to validate the effectiveness of AI applications in educational settings, advocating for a dynamic curriculum that evolves with technological advancements and pedagogical insights. The emphasis on understanding AI's potential and limitations, as stressed by Lippert (1987), Herdliska and Zhai (2023), and Jia et al. (2023), highlights the critical role of educating students about both the benefits and ethical challenges of AI. Lippert's (1987) work illustrates how recognizing AI's limitations is as crucial as understanding its capabilities, fostering a balanced perspective in students. Herdliska and Zhai (2023) advocate for comprehensive education that includes ethical considerations, ensuring students are equipped to handle the societal implications of AI. This comprehensive focus on attitudes ensures that students develop not only technical skills but also the ethical and empathetic dispositions necessary for responsible AI use. By preparing students to navigate the broader implications of AI in society, the curriculum aims to create informed, thoughtful, and responsible future citizens.

Summary

The detailed analysis shows that modern curricula place a balanced emphasis on AI knowledge, skills, and attitudes. Practical skills related to AI learning and techniques, as well as understanding and integrating AI technologies, are heavily prioritized. Ethical considerations and societal impacts are also significant areas of focus, ensuring students are prepared to navigate the broader implications of AI. The curricula aim to foster critical thinking, problem-solving, and human-centered approaches, equipping students with a comprehensive skill set for the digital age. These findings are consistent with the academic literature, which highlights the transformative potential of AI in education and the critical role of an AI-integrated curriculum in enhancing science education (Al Darayseh, 2023; Good, 1987; Herdliska & Zhai, 2023; Kotsis, 2024; Lippert, 1987).

The diagram in **Figure 1** illustrates the distribution and frequency of various AI-related codes across three main categories: knowledge, skills, and attitudes. The most prominent code, 'AI learning and techniques skills,' appears 67 times, underscoring a significant emphasis on practical, hands-on AI skills in the curricula. This aligns with findings by Al Darayseh (2023) and Kotsis (2024), who highlight the critical need for practical AI applications in education. 'Contextual problem-solving knowledge' and 'integration knowledge' are also highly frequent, reflecting the importance of applying AI to solve real-world problems and integrating AI knowledge across different subjects. The relatively lower frequency of 'algorithms knowledge' and 'programming knowledge' suggests that these areas might be integrated into broader topics rather than being standalone focuses. The diagram also shows that 'societal' and 'human' attitudes are heavily emphasized, aligning with Lippert's (1987) and Jia et al.'s (2023) emphasis on understanding AI's societal and human implications. This comprehensive approach ensures that students develop not only technical proficiency but also the ethical and empathetic dispositions necessary for responsible AI use.

The arc diagram in **Figure 2** illustrates the distribution of AI-related codes across knowledge, skills, and attitudes, highlighting 'AI learning and techniques skills as the most prominent. This visual emphasizes the importance of practical AI skills, aligning with Al Darayseh (2023) and Kotsis (2024), who stress the necessity of hands-on AI applications in education.

CONCLUSIONS

The integration of AI in education, particularly in science curricula, is a multifaceted endeavor that aligns with the rapid technological advancements characterizing modern societies. The findings of this study underscore a comprehensive approach in national curricula towards embedding AI-related knowledge, skills, and attitudes, preparing students to thrive in an AI-driven future. This conclusion synthesizes the detailed analysis of how AI is addressed within various educational frameworks, drawing parallels with existing literature to highlight key insights and recommendations.

Regarding knowledge integration, the emphasis on AI-related knowledge within the curricula is evident through the frequent mentions of 'AI learning and techniques knowledge' and 'AI technologies and tools knowledge.' These aspects are crucial for providing students with a foundational understanding of AI, encompassing its basic principles, functions, and the diverse

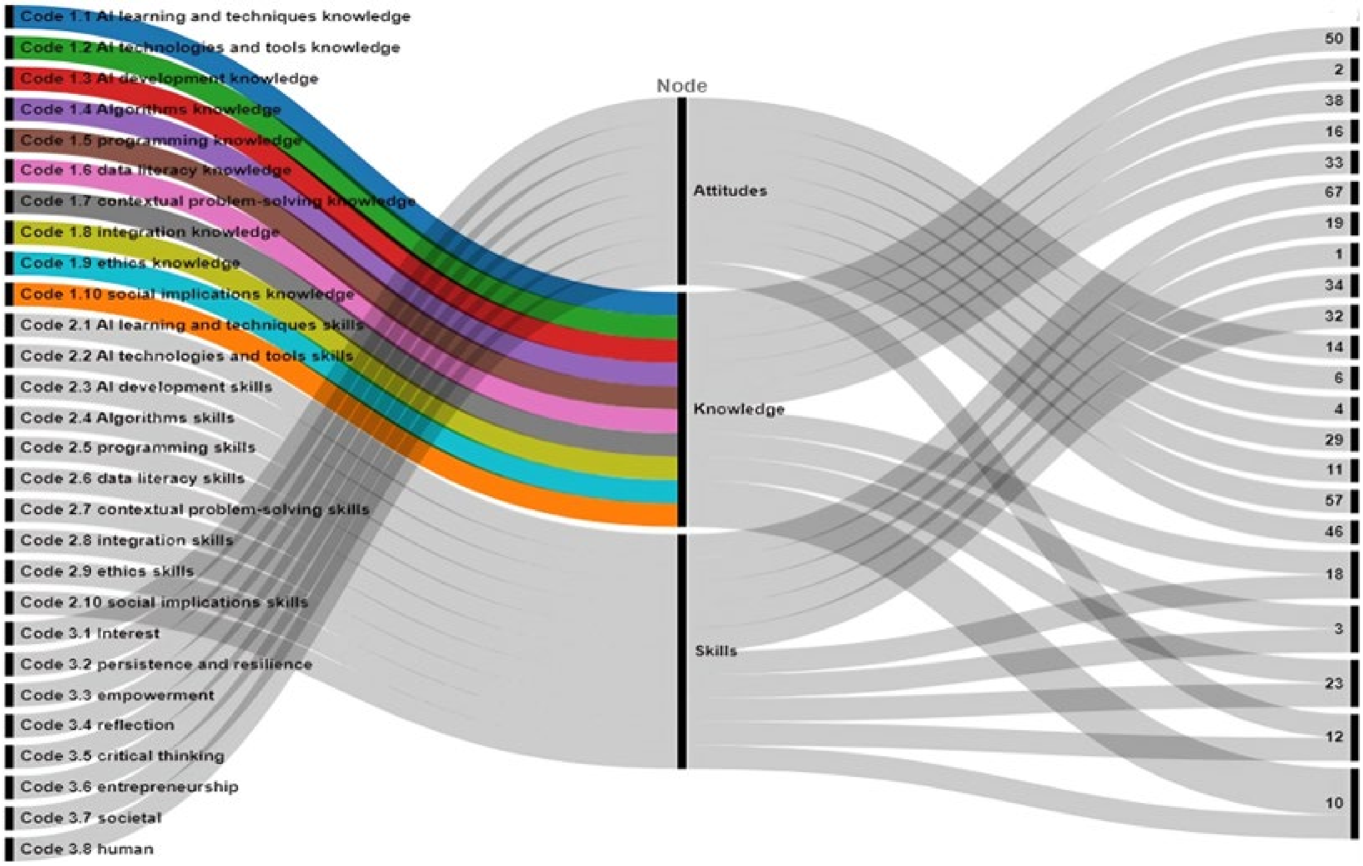

Figure 1. Diagram of the code and distribution of frequencies (Generated by the author using RAWGraphs, https://www.rawgraphs.io)

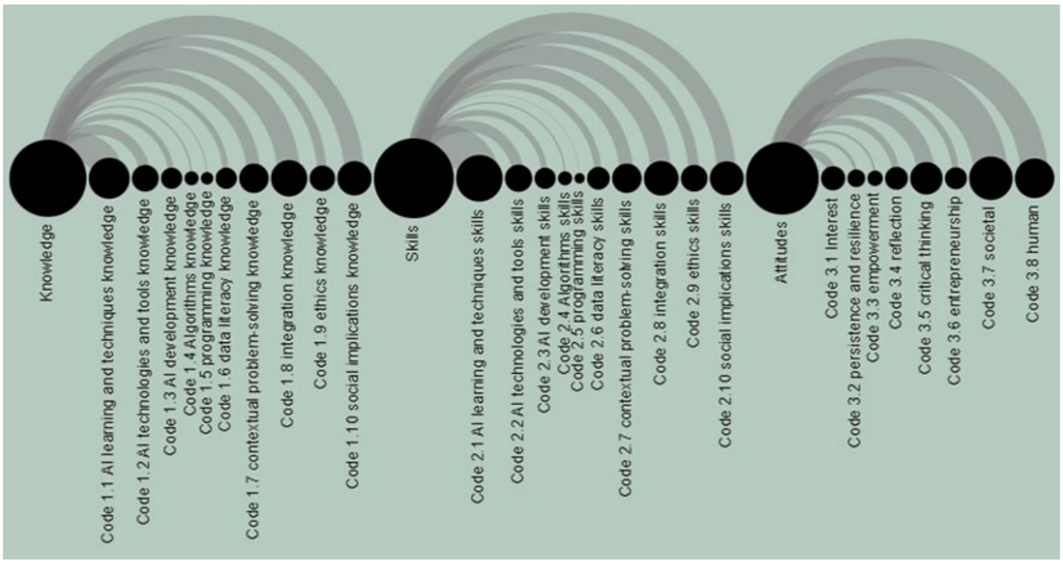

Figure 2. Distribution of codes (Generated by the author using RAWGraphs, https://www.rawgraphs.io)

technologies associated with it. The analysis reveals that while AI-specific terminology may be limited, broader AI-related concepts are embedded within the educational content. This aligns with the perspective of Lippert (1987), who underscores the importance of integrating AI implicitly through technological tools and infrastructure.

For instance, the high frequency of 'contextual problem-solving knowledge' and 'integration knowledge' highlights the importance of applying AI to solve real-world problems and integrating AI knowledge across various subjects. This interdisciplinary approach ensures that students perceive AI not just as a standalone subject but as an integral part of their overall education. This is consistent with the findings of Al Darayseh (2023), who emphasizes the necessity of practical AI applications for enhancing educational outcomes.

Moreover, the inclusion of 'ethics knowledge' and 'social implications knowledge' in the curricula reflects a balanced approach, preparing students to think critically about the responsible use of AI technologies and their societal impacts. This aligns with the recommendations of Good (1987) and Jia et al. (2023), who stress the need for continuous research and curriculum evaluation to ensure that AI integration remains relevant and effective.

Regarding the development of practical AI skills, there is a significant focus within the curricula, as evidenced by the high frequency of 'AI learning and techniques skills.' This emphasis on hands-on, practical skills ensures that students can effectively engage with AI technologies and apply their knowledge in real-world scenarios. This practical approach is crucial for fostering innovation and creativity among students, as highlighted by Kotsis (2024) and Herdliska and Zhai (2023).

Skills such as 'contextual problem-solving' and 'integration skills' are also prominently featured, reflecting the importance of interdisciplinary skills in applying AI across various subjects. This holistic educational approach is essential for preparing students to navigate the complexities of an AI-driven world, as emphasized by studies such as Lippert (1987) and Al Darayseh (2023). The inclusion of 'data literacy skills' and 'ethics skills' further underscores the importance of equipping students with the capabilities to handle data responsibly and navigate the ethical challenges posed by AI technologies.

Regarding the development of positive attitudes towards AI, there is a critical aspect of the curricula: fostering interest, persistence, and resilience among students. The emphasis on 'interest' and 'critical thinking' highlights the importance of engaging students and encouraging them to think analytically about AI technologies and their applications. This aligns with the findings of Lippert (1987) and Herdliska and Zhai (2023), who advocate for comprehensive education that includes ethical considerations and the societal implications of AI.

The frequent mentions of 'societal' and 'human' attitudes reflect a significant focus on understanding the broader impacts of AI on society. Students are encouraged to consider how AI affects various aspects of human life and to develop the empathetic dispositions necessary for responsible AI use. This comprehensive focus on attitudes ensures that students not only acquire technical skills but also develop the ethical and empathetic dispositions necessary for responsible AI use.

The findings of this study are consistent with the existing literature on AI in education. Good (1987) and Lippert (1987) highlight the transformative potential of AI in fostering problem-solving skills and active learning through ICAI and expert systems. These technologies model students and teachers to diagnose issues and develop effective teaching strategies, thereby enhancing educational outcomes.

More recent studies by Al Darayseh (2023), Kotsis (2024), and Herdliska and Zhai (2023) emphasize the necessity of practical AI applications and thorough teacher training in AI concepts. These studies collectively suggest that a well-rounded curriculum, supported by robust technological infrastructure and informed by continuous teacher development, is crucial for leveraging AI's full potential in education. The emphasis on embedding appropriate technological tools and infrastructure within the curriculum, as highlighted by Lippert (1987) and Al Darayseh (2023), underscores the importance of ensuring that students are familiar with AI technologies and tools. This comprehensive approach is essential for enhancing learning experiences and preparing students for real-world challenges.

This study is limited by the scope of the curricula analyzed, as it may not fully capture the diversity of AI integration across all educational contexts. Additionally, the reliance on document analysis without empirical validation may affect the comprehensiveness of the findings.

Based on the findings of this study, several recommendations can be made to enhance the integration of AI in national science curricula. First, there is a critical need for comprehensive teacher training programs that focus on both theoretical knowledge and practical applications of AI. Teachers should be equipped with the skills to integrate AI technologies effectively in their teaching practices, as highlighted by Al Darayseh (2023) and Kotsis (2024). Second, curriculum developers should consider integrating AI-related content explicitly and implicitly across various subjects. This includes embedding AI concepts in existing subjects and creating standalone AI courses to provide a balanced and comprehensive AI education. Third, it is essential to include ethical considerations and societal implications of AI in the curriculum. This prepares students to think critically about the broader impacts of AI and use AI technologies responsibly, as emphasized by Lippert (1987) and Jia et al. (2023). Fourth, ongoing research and curriculum evaluation are necessary to ensure that AI integration remains relevant and effective. This involves empirical studies to validate the effectiveness of AI applications in educational settings and continuous feedback to refine AI systems, as highlighted by Good (1987) and Jia et al. (2023). Fifth, an interdisciplinary approach to AI education is crucial. Integrating AI knowledge and skills across various subjects helps students understand the relevance and application of AI in different fields, as reflected in the frequent mentions of 'contextual problem-solving' and 'integration skills.' Finally, developing positive attitudes towards AI, such as interest, critical thinking, and empathy, is essential. Curricula should include activities and content that foster these attitudes, preparing students to navigate the broader implications of AI in society, as highlighted by Herdliska and Zhai (2023).

The integration of AI in education, particularly in science curricula, is a crucial step towards preparing students for the challenges and opportunities of the digital age. The findings of this study highlight a comprehensive approach to AI education, emphasizing the knowledge, skills, and attitudes necessary for students to thrive in an AI-driven future. These findings are consistent with the academic literature, underscoring the transformative potential of AI in education and the critical role of an AI-integrated curriculum in enhancing science education. By following the recommendations outlined in this study, educators and policymakers can create a robust and effective AI education framework that prepares students for the future (Fullan, 2007; Pedro et al., 2019; UNESCO, 2011, 2022).

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