

# Adoption and pedagogical use of generative artificial intelligence in K-12 mathematics/science/language classrooms: Challenges and opportunities

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## Article Info:

Received 19 March 2026

Revised 05 April 2026

Accepted 16 April 2026

Published 26 April 2026

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## Abstract

Generative artificial intelligence in K-12 mathematics, science, and language classrooms has already presented major opportunities of personalized learning, automatically provided feedback, curriculum development, and student interaction, and posed multiple questions about ethical AI, academic dishonesty, teacher preparedness, algorithm bias, and student data security. With the prevalence of large language models, generative AI-driven learning aids and multimodal learning platforms that have begun to be popular in schools, more individuals are interested in learning about the pedagogical utilization, utility, limitations, and implications of Generative AI in school learning. This literature review is based on the PRISMA framework that provided a systematic inspection of the current research of the adoption and pedagogical integration of Generative AI in K-12 mathematics education, science education, and language education. The review conducted to synthesize the evidence on the identification of the dominant themes in research, patterns of implementation, and gaps in current scholarship. Special focus was put on adaptive learning, intelligent tutoring systems, automated assessment, teacher professional development, multilingual learning, differentiated instruction and human-AI collaboration. The results demonstrate that personalized learning, cognitive scaffolding, inquiry-based learning, project-based learning, formative assessment, and self-regulated learning can be greatly enhanced in mathematics, science, and language classrooms with the help of Generative AI. It is concluded that responsible AI systems, enhanced teacher education, fair access and evidence-based pedagogical models balancing the innovativeness with human regulation are the needed components of future-ready deployment of Generative AI in K-12 education.

**Keywords:** Generative artificial intelligence, Artificial intelligence, STEM education, Digital pedagogy, K-12 education, Teacher.

## 1. Introduction

The fast-developing Generative artificial intelligence is one of the most important advances in modern K-12 education, especially in mathematics education, science education, and language education. Generative AI has created new possibilities in AI-assisted learning, adaptive learning, personalized learning, and multimodal learning using large language models, conversational agents, intelligent tutoring systems, and automated feedback platforms unlike earlier forms of educational technology which were more concerned with content delivery (or more simply administrative automation) [1]. Generative AI tools are already finding their role in schools, being used to aid lesson planning, learning assessment, collaborative learning, inquiry-based learning, project-based learning, and development of literacy. The ease of use of technologies like the AI chatbots, text and image generators, virtual tutoring tools, etc. has sparked the use of educational technology in various levels of education and subject matter, bringing excitement yet confusion to the future of teaching and learning. In recent global discourses, it is highlighted that the idea of Generative AI can be used to transform people learning quality and effectiveness in terms of applying it to facilitate human-AI interdependence, student interaction, and teacher professional judgment instead of substituting it.

The relevance of this subject can be observed especially in the teaching of K-12 mathematics, science and language disciplines since these areas require varied types of reasoning, communication and cognitive scaffolds. Generative AI can be used in mathematics teaching to explain things step-by-step, support a learner in computational thinking, and deliver a modified learning experience to less and more able students. It can support inquiry-based learning, virtual experimentation, immersive learning, and real-time interpretation of scientific data in science education. It may reinforce language learning in language teaching, the development of literacy, multilingual education, the learning of vocabulary, reading comprehension, the quality of writing, and conversational fluency. There is an growing body of evidence that shows that Generative AI can be used to help students with special educational needs, offer adaptive feedback to various students, and make educational content more accessible to various students in different languages and contexts. Meanwhile, some worries have been voiced regarding the possibility of overreliance on AI-generated answers, shallow learning, lack of critical thinking, and the possibility of false mastery, in which learners can seem successful without truly learning the material on a conceptual level. According to current research, specifically-designed AI educational tools can generate better learning effects than generic AI chatbots due to their foundation on pedagogical theory and cognitive science.

The current state in the field of Generative AI in K-12 education can be described as ad hoc innovativeness and wide-spread implementation. The adoption of Generative AI in the classroom is set to become more popular among schools, educators, and policymakers, but many schools are not ready because of the lack of teacher preparedness and readiness, the absence of AI literacy, and the absence of an effective policy framework [1-3]. Recent systematic reviews suggest that most studies in K-12 education on Generative AI have been short term classroom studies, teacher attitudes and perspectives and AI as a lesson planning, automatic assessment and student support tool. Nevertheless, the literature is not well balanced in pertinent areas and mathematics and language education have received more coverage as compared to science education and interdisciplinary learning. According to existing literature, it is also evident that many educators are informally employing Generative AI without formally provided institutional support, and there are important issues regarding generative AI and ethical AI, generative AI, responsible AI, explainable AI, data privacy, academic honesty, algorithmic discrimination, and fairness in education which will inform the decision to adopt. A growing number of arguments by international bodies claim that AI regulatory frameworks, competencies, and teacher-focused practices on integration are necessary to maintain sustainability and ethics. UNESCO and OECD advice also note that teachers should always keep the center of the classroom decision making process since education is based on the relationship, judgment, inventiveness and human touch which are not automated.

Regardless of the increasing literature base, a number of significant research gaps can still be perceived. First, the synthesis of the current application of Generative AI as applied in various curriculum areas of mathematics, science, and language classrooms in K-12 education are limited. A lot of literature on AI according to its application in general educational settings does not compare it to subject-specific pedagogical integration, curriculum innovation, and learning outcomes. Second, long-term educational outcomes, such as the influence of Generative AI on self-regulated learning, teacher agency, critical thinking, creativity, and future-related skills in the long run, are not given sufficient attention. Third, it is not well-evidenced as to whether it has been applied equitably in low-resource contexts where the digital divide and inequality in access to technology might exacerbate existent education disparities. Lastly, despite the common accepted importance of teacher professional development and AI literacy, research on effective development of timely engineering skills, ethical reasoning, and pedagogical competence as critical to long-term human-AI collaboration is limited. The recent literature indicates the need to conduct more longitudinal, comparative and evidence-based researches which do not only seek to establish whether Generative AI is being applied, but how, why and in what circumstances it enhances the quality of education. It is against this backdrop that this literature review aims at considering the adoptions and pedagogical applications of Generative AI in K12 mathematics, sciences, and language classes with specific attention to opportunities and challenges, as well as future trends. This review aims to reveal the most frequently encountered themes within literature, define the effectiveness of Generative AI in teaching and learning, analyze the barriers associated with use in terms

of ethics and implementation, and suggest directions in future research through the use of PRISMA framework. Much corresponds to the contribution of the paper: interdisciplinary approach and consideration of three core areas of subject, its orientation to new processes with high capacity of future references and focus of the data on teacher preparedness, responsible AI and classroom innovation and education transformation. This review synthesizes the evidence on the topics of pedagogical integration, adaptive learning, and digital pedagogy, and AI governance that can guide researchers, teachers, and policymakers to develop balanced, fair, and student-centered models of the adoption of Generative AI in K-12 education.

## **2. Methodology**

This is a systematic literature review that was written using the Preferred Reporting Items for Systematic Reviews and Meta-Analyses guidelines (PRISMA) of 2020 to make it transparent, reproducible, and rigorous in the identification, screening, and synthesis of pertinent empirical literature regarding the adoption and pedagogical use of generative artificial intelligence in K-12 mathematics, science, and language classrooms. Pursuing a global search approach, four prominent academic databases, including Scopus, Web of Science, IEEE Xplore, and PubMed, were searched using a comprehensive search strategy to cover all publications published between January 2019 and December 2025, a timeframe that was chosen intentionally to capture the volume of publication and academic discussion around generative AI tools in education, especially since the popular release of large language model-based The Boolean search strings employed in Scopus and Web of Science included combinations such as ("generative artificial intelligence" OR "generative AI" OR "large language model" OR "ChatGPT" OR "GPT-4" OR "Bard" OR "Gemini") AND ("K-12" OR "primary school" OR "secondary school" OR "elementary school" OR "high school" OR "middle school") AND ("mathematics education" OR "science education" OR "language learning" OR "classroom instruction" OR "pedagogical integration" OR "teaching and learning"), as well as supplementary strings such as ("AI-assisted learning" OR "AI-powered tools") AND ("student outcomes" OR "teacher adoption" OR "challenges" OR "opportunities" OR "curriculum integration") AND ("K-12" OR "school education"), with additional field-specific variants applied in IEEE Xplore and PubMed to account for their disciplinary indexing conventions. A preliminary search of databases revealed 3,741 records listed (Scopus: 1,284; Web of science: 1,057; IEEE Xplore: 876; PubMed: 524) on which 47 more records were subsequently added by citation search and grey literature screening of institutional and governmental educational technology reports. After automated deduplication and filtering out records identified by automation tools as either ineligible (n = 198) or simply delete records due to any number of reasons, including the obvious presence of off-topic subjects in the title or abstract (n = 414), 3,176 unique records passed to the title/abstract screening step, after which 2,738 had been identified as not meeting the criteria of addressing The other 438 database obtained reports and 47 other obtained reports were referred to full-text retrieval, of which 31 and 5 could not be obtained and making 407 database obtained reports and 42 other obtained reports eligible Fig. (1). The full-text exclusions were based on the exclusion criteria of being non-K-12 education-focused (n 112), lacking focus on the target subject areas of mathematics, science or language (n 89), lack of specific examination of generative AI tools (n 76), non-empirical or opinion-based (n 54), not published within the 2019 2025 time In the end, 71 studies that fit all the inclusion criteria (peer-reviewed empirical research, mixed-method studies, and qualitative research) were retained to be included in thematic synthesis and analysis in the given review.

## **3. Results and discussions**

### *3.1 Artificial intelligence techniques*

#### Large Language Models and Transformer-Based Architectures

Transformer-based architectures and large language models are the most prevalent tools of Generative AI that can be applied to K-12 education at the present moment. Deep learning, natural language processing and attention mechanisms are the key models that result in human-like responses,

information summarization, responses to questions as well as instructional content generation [2,4]. Transformer models can also be used in mathematics education, science education, and language education with conversational AI applications providing students with explanations, help solving problems, explaining concepts, and interactive tutoring. Large language models have been shown to be specifically useful in adaptive learning and differentiated instruction because of their capacity to comprehend the context, produce coherent text, and over-compliment the learner. These methods are being actively incorporated in AI-assisted classrooms at K-12 levels where learners are able to ask questions, give feedback, and explore subject matter on their own time. Transformer-based models are also associated with allowing teachers with the possibilities of automatizing lesson planning, quiz generation, rubric design and adaptation of the work material to the abilities of learners of varying skills. The success of these models is however very reliant on these qualities: swift quality, area-specificity, and educator control as hallucinated data and faulty results are significant issues in educational establishments.

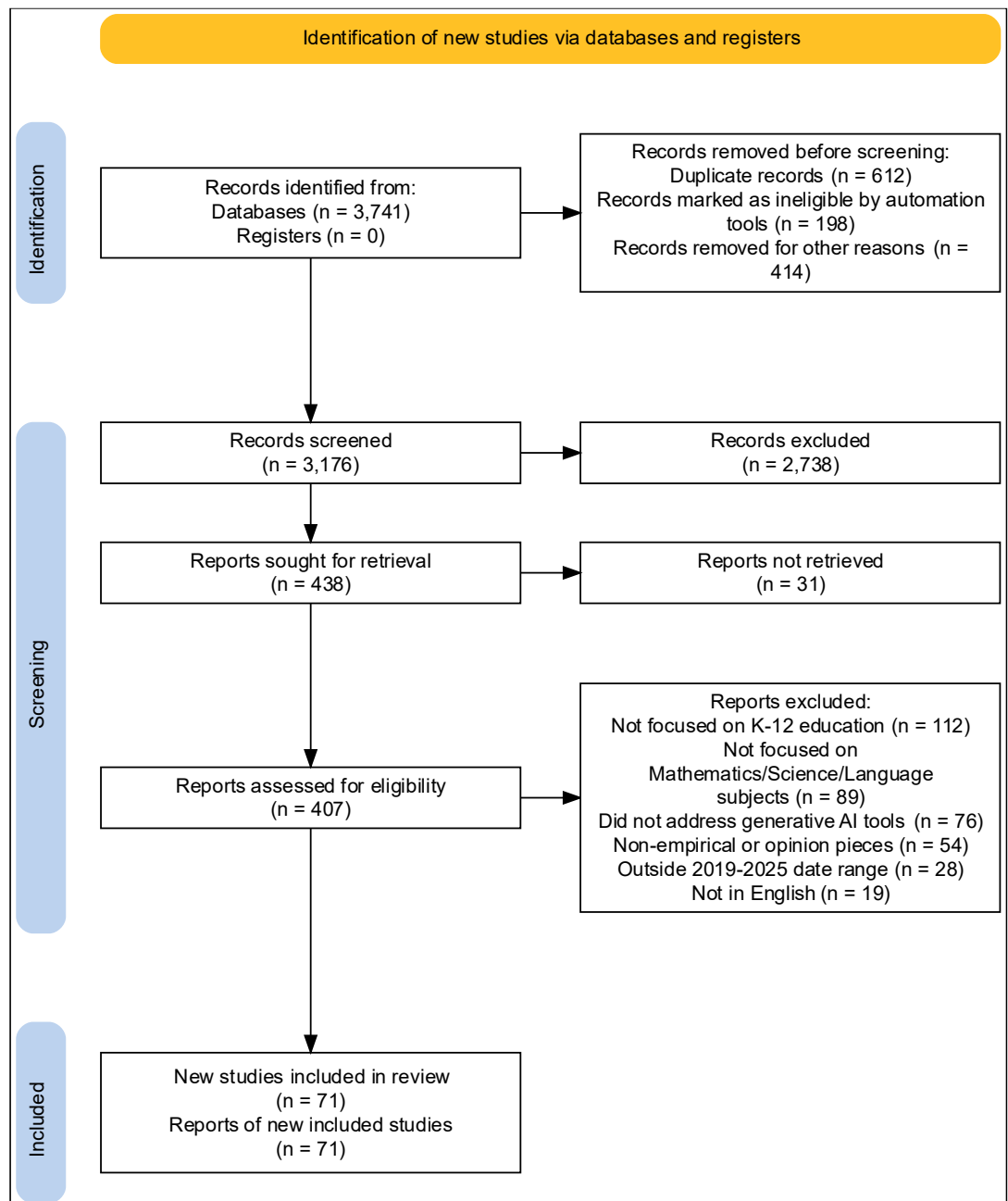


Fig. 1 PRISMA Framework

### Natural Language Processing for Educational Interaction

NLP has emerged as a baseline AI method of enabling communication, the acquisition of literacy, learning in multiple languages, and classroom interaction. Using NLP techniques, systems can interpret written and oral speech, find patterns of grammar, analyze sentiment, identify fallacies, and respond to the user personally. NLP assists in writing, fixing grammar, learning vocabulary, reading, understanding, and speaking fluently in language education. Education NLP has been applied to word problems, explanation of equations in ordinary language, translation of symbolic expressions into language increasingly in the field of mathematics education. NLP can be applied in science education by improving the ability of learners to read complex scientific materials, develop summaries, and discuss the vocabulary of science using an interactive conversation. Semantic analysis, contextual understanding, automatic summarization, cross-lingual translation, emerged as new datasets in the NLP field, but they are specifically useful in multilingual classrooms and in heterogeneous educational settings. NLP systems are advancing and can now serve inclusive education by helping learners with reading problems, language barriers, and problems with communication.

### Intelligent Tutoring Systems and Virtual Tutors

Intelligent tutoring systems, virtual tutors are one of the most popular forms of AI practices in K-12 education classes, as they offer personalized attention, which resembles one-to-one learning. These systems are a combination of machine learning, knowledge tracing, learning analytics, and adaptive learning algorithms that determine the performance of the students and suggest the proper instructional pathways. Mathematical instruments Intelligent tutoring systems have the potential to identify errors, offer step-by-step support, and increase or decrease the complexity of problems based on the student progress in mathematics learning. Virtual tutors can assist in science education by assisting with laboratory simulation, scientific inquiry, and problem-solving with interactive inquiry and real-time comments. Virtual tutors in language education help a student in pronunciation, reading fluency, writing quality and even conversation. New advances in Generative AI have allowed these tutoring systems to become more conversational, empathetic, and context-sensitive, allowing students to interact more closely with AI systems. The tools are especially useful in large classrooms where the teachers might not be able to give all learners individualized attention.

### Adaptive Learning and Personalized Learning Algorithms

Generative AI in pedagogy of K-12 education focuses on adaptive learning and learning classification algorithms to personalize learning. These methods are based on predictive analytics, recommender systems, and machine learning in adapting the educational material, assessment activities, and feedback to the needs of individual learners [5-8]. In mathematics teaching, adaptive systems may determine if a student needs extra help in algebra, geometry, arithmetic or problem-solving. Personalized learning algorithms may suggest individual simulations, experiments, or scientific readings, which are used in science education, according to performance and the interests of students. These systems may be adapted to target the reading passages, writing prompts and vocabulary activities in language education based on level of proficiency and speed of learning. The increasing popularity of adaptive learning technologies in the classroom is indicative of a more generalized perspective on student-centered teaching and differentiated instructional applications. Self regulation learning is also facilitated through individualized learning systems to enable students track their learning progress, their strengths and weaknesses and have learning goals.

### Knowledge Tracing and Predictive Analytics

Predictive analytics and knowledge tracing are novel AI technologies that can enable an educator to know how students learn, as they advance in learning. An example of knowledge tracing models is based on quiz, assignments, classroom activity, and digital learning data that can be utilized to guess how much a student has mastered a particular concept. Predictive analytics builds on this method by revealing trends that can tell the possibility of future performance, dropout, disengagement or learning challenges. Knowledge tracing can be used in mathematics education to identify repeating mistakes in fractions, algebraic reasoning or geometry. Predictive analytics have applications in science education

to identify areas in which the students have weaknesses in scientific inquiry, experimentation, or data analysis. These tools can be used to track the reading fluency, the writing progress in language education, and the acquisition of vocabulary. Learning analytics and predictive analytics help teachers intervene at an earlier stage and have a more focused amount of help available. Through these methods, the schools can also make better use of their resources and develop intervention plans in students who are likely to perform poorly in school.

#### Automated Feedback and Automated Assessment Systems.

The K-12 classrooms are shifting towards automated feedback, automated assessment systems to ease the work of teachers and enhance speed. The AI methods are based on the processing of natural language, the learning of machines, and the generation of texts in order to analyze the answers given by students and give them feedback in real time. Automated assessment systems can be used in mathematics education to assess numerical responses, detect calculational errors, and justify errors. They are able to evaluate lab reports, short-answer answers and scientific reasoning in science education. Automated feedback devices are also common in language teaching and learning to correct grammar and score an essay, analyse vocabulary and improve writing. The main benefit of automated assessment is that students are able to receive immediate feedback as opposed to waiting till the teacher reviews their work. This immediacy facilitates formative assessment, self-managed learning, and progressive improvement. There are however fears are reliability, fairness and transparency of automated grading systems especially where such systems are used in high stakes tests.

#### Conversational AI and Chatbot Technologies

Chatbot and conversational AI have experienced a rise in K-12 education as they provide interactive, accessible, and scalable support to learners. Generative AI chatbots are able to answer questions or provide clarifications to students, offer study advice and walk students through activities [6,9]. Chatbots can provide explanations of mathematical formulas, equations, and multistep visualizations in mathematics classrooms. Conversational AI can also be used to simulate scientific inquiry, answer questions related to experiments, and explain scientific phenomena in science classes. Chatbots i.e., are used in language classrooms to aid speaking, conversational fluency, pronunciation and writing support. More modern forms of conversational AI have more recently enhanced contextual memory, emotional recognition, and the ability to support multiple languages, thus becoming more useful in various educational institutions. Simultaneously, teachers should make sure that the messages between chatbots are monitored and comply with the learning requirements since imprecise and inappropriate answers can have a harmful effect on the learning process.

#### Multimodal AI and Image Generation Techniques

The combination of text, images, audio, video, and interactive media is changing the nature of interaction between the students and learning material because of multimodal AI and image generation. Multimodal learning (or multimedia) learning environments are especially useful in the learning process of the K-12 education due to their ability to cater to other learning styles and to simplify abstract information. Image generation can assist mathematics learners in modeling geometry, graphs, fractions, and spatial connections. Multimodal AI may be used in science education to make simulations, diagrams, and virtual experiments and generate scientific illustrations to enhance conceptual understanding. In language teaching, the tools are capable of producing storyboarding, visual aids and multimedia recordings that boost originality and literacy growth. Other current multimodal Generative AI advances are text-to-image generators, image captioning, speech-to-text, and video generation, which all present good opportunities in developing future classroom uses. The techniques are particularly effective with the students who have learning disabilities or language barriers as they give them a variety of access to information.

#### Speech Recognition and Voice-Based AI Systems

Voice-based AI systems and speech recognition are growing in relevance in K-12 classrooms as students can now communicate with the educational materials using oral speech. These technologies employ

machine learning, natural language process, and deep learning to transform speech into text, identify pronunciation patterns, and offer real-time verbal feedback [10]. In language, speech recognition helps in the training of pronunciation, oral fluency, listening comprehension, and learning a language. Voice based learning may be applied in mathematics education to assist younger students in explaining steps of solving a problem orally and be guided in their response by a conversation. In science education, speech-enabled tools may be useful in experiments, may be used in giving oral instructions and aid the accessibility of physically challenged learners. Voice-based AI can improve the inclusive education as well helping students who might have difficulties with typing, reading or writing. These technologies are bound to take a bigger part in immersive learning, multilingual learning, and accessible education as they become more advanced.

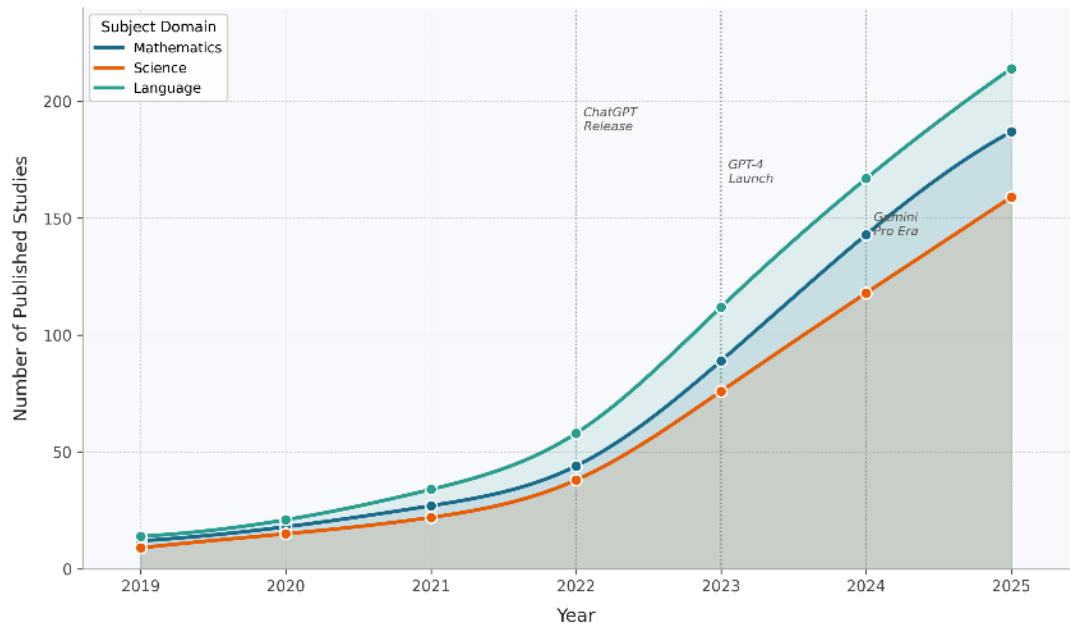


Fig. 2 Temporal Trends in GenAI Research Publications Across K-12 Subject Domains (2019-2025)

Fig. 2 is a smoothed line plot traces the annual volume of peer-reviewed studies on generative AI in K-12 Mathematics, Science, and Language classrooms from 2019 to 2025, with cubic spline interpolation applied to highlight trajectory curvature rather than raw point-to-point volatility. Vertical reference lines annotate three landmark events -- the release of ChatGPT, the launch of GPT-4, and the emergence of Gemini Pro -- contextualizing the exponential surge in publication volume that began in 2022. Language consistently registers the highest publication count across years, reflecting the natural synergy between LLMs and linguistic skill development. The accelerating upward curves from 2023 onward underscore the field's emergence as a high-growth research domain, making this visualization particularly well-suited to literature review papers arguing for urgency in policy-level responses to GenAI in compulsory education.

#### Recommender Systems and Curriculum Personalization

Recommender systems are becoming more popular in educational technology systems to recommend learning resources, assignments, videos, reading and activities that students can relate to their needs. These systems recommend content using predictive analytics, collaborative filtering, and machine learning to identify and suggest content based on student needs, performance, and learning history. Recommender systems can be used in mathematics education, where one can generate students with recommended exercises on a particular topic, like fractions, algebra, or geometry. They may prescribe experimentation, simulations and project based learning in science education. Recommender Systems can be used in language education to customize reading materials, writing assignments, and vocabulary lists. Personalization of the curriculum by use of recommender system is useful in engaging the students

and in ensuring that the learners are not overwhelmed or underchallenged. There is, nevertheless, some worry that over-reliance on recommender systems could curtail or characterize the liberty of the student or portray students to pathways of restricted content.

#### Explainable AI and Ethical AI Techniques

Explainable AI and ethical AI methods are becoming generally accepted as important elements of technological implementation in the K-12 education system. Explainable AI is defined as systems capable of justifying their decisions, predictions or advice to make the assertions understandable by teachers and students. Explainability is especially necessary in educational settings since educators must be made aware of why an AI system suggests particular content, forecasts performance in the students, or recognizes learning gaps. Ethical AI is based on justice, transparency, responsibility, and responsible technology use. Issues of academic integrity, biased algorithms, surveillance, data privacy, and unequal access are emerging as so-called red flags when it comes to Generative AI in schools. Science, language classrooms, and mathematics would need ethical AI solutions that would guarantee these learners all equitable chances, including not being put in a disadvantageous position due to prejudiced algorithms or faulty datasets. Responsible AI, AI governance and human-centered educational design will probably receive more critical attention in future research.

#### Human-AI Collaboration and Teacher Augmentation

Human-AI cooperation becomes one of the most significant theoretical frameworks of generative AI usage in the K-12 education. Instead of replacing teachers, AI methods are now more and more perceived as teacher enhancement that can enable teachers to save time, personalize their teaching and make better-informed decisions [10-12]. Generative AI can assist teachers in creating lesson plans, assessments, teaching content, analyzing student performance, and assist classroom management. AI can be used in mathematics education to detect the misconceptions of teachers and develop specific interventions. It can be used in teaching science by facilitating the establishment of simulations, experiments, and inquiry-related tasks. It can help in writing as well as generating feedback and multilingual communication in language education. Implementation of classroom innovation is most likely to rest on the ability of teachers and AI systems to work together in aiding students in learning. The readiness of teachers, AI literacy, and professional development thus become critical in ensuring that teachers are able to make such technologies confident and responsible.

#### Immersive Learning, Extended Reality, and Emerging Generative AI Systems

The next phase of educational transformation in K-12 classrooms is immersive learning, extended reality, and emerging systems of Generative AI. Virtual reality and augmented reality technologies along with longer reality technologies are increasingly integrated with Generative AI to make learning highly interactive. Immersive environments can be used in mathematics learning to create experiences in three-dimensional geometry, patterns, and data visualization. In science teaching, virtual laboratories, science exploration, and natural phenomenon simulation can be enhanced with the help of the extended reality. Immersive learning environment in language education may provide the simulation of reality in conversation and the creation of a culturally immersive setting of learning a language. The new AI systems are also getting more multimodal as well as emotionally intelligent as well as able to create real time personalized learning experiences. The implications of these trends are that the future of K-12 education include both more advanced syntheses of Generative AI, immersive learning, and human-AI partnership that would bring about new possibilities in engaging students, building their skills, and equipping them to operate in the future.

### *3.2 Artificial intelligence methods*

#### Large Language Models and Transformer Models

The most significant current developments in AI that have shaped Generative artificial intelligence in K-12 education are the large language models and transformer models. These approaches are based on deep learning, neural networks, and attention mechanisms to process language, respond, summarize,

and facilitate interactive learning [7,13-16]. Transformer models can be used in mathematics education to explain equations, give step wise solutions, and direct learners through tasks that require computational thinking. These practices in science education may produce scientific explanations, data interpretation, and simplification of complex concepts to diverse age groups. Large language models in language education aid in the development of literacy, correction of grammar, vocabulary, writing, and multilingualism. The growing popularity of systems based on transformers show that Generative AI can go beyond the non-interactive educational applications and develop the conversational, context, adaptive learning systems. The rising importance of these models in education is that they allow such a personalization of teaching to adjust to the requirements of learners on the fly and to help supplement teaching with automated text-generation, and lesson planning. Recent studies are beginning to focus more on the idea that dedicated educational large language models are much more successful than general-purpose systems since they are tailored to the objectives of the curriculum, age-specific pedagogy, and assessment systems.

#### Natural Language Processing and Educational Communication

NLP is now one of the most broadly used AI approaches in K-12 classrooms since it allows machines to read, comprehend, and create natural language. NLP technologies aid conversation AI, automated response, scoring essays, text summarization, semantics analysis, sentiment analysis, and language translation. In the teaching of mathematics, NLP can be used to teach students how to solve word problems in equations and interpret mathematical reasoning by providing simple explanations. Natural language processing applied in the education of science can assist students in summarizing articles in science, investigating disciplinary language and dialoguing where questions and answers can be asked about experimentation and observation. NLP techniques come in particularly handy in language learning since they enhance reading instruction, suitable grammar, writing achievement, orality, and multilingual interaction. The new NLP systems are progressively accommodating cross linguistic learning systems and learning inclusion by allowing students whose Linguistic background is different to gain access to learning resources in various languages. Such possibilities are especially applicable in multilingual learning classrooms at K-12 level where students might possess varying languages and cultural backgrounds. The role of the NLP systems in communication, accessibility, and literacy development is likely to increase in the future as they will be more context-aware and emotionally intelligent.

#### Adaptive Learning and Personalized Learning Systems

One of the oldest AI techniques in education is intelligent tutoring system and virtual tutors, as it provides one-to-one/adaptive/personalized instruction. Based on these systems, machine learning, knowledge tracing, predictive analytics, and conversational AI are utilized to detect student strengths, weaknesses, and preferences in learning. In mathematics education, algebra, arithmetic, geometry, fractions, problem-solving, intelligent tutoring systems have the potential to specialize (to offer the necessary support), including, but not limited to, diagnosing misconceptions and varying the level of difficulty. Virtual tutors used in science education facilitate inquiry-based learning, experimentation and learning concepts via interactive explanations and problem-solving guidance. These systems are common in language education in terms of training pronunciation, feedback of writing, vocabulary growth and comprehension of reading. The recent development of Generative AI enabled these systems to become more conversational, understanding, and able to continue educational conversations longer. They can more and more produce hints as opposed to straight-forward answers, which in their turn maintains critical thinking and self-regulated learning. Nevertheless, scholars also observe that tutoring systems experience difficulties connected with scalability, assessment, and design involving pedagogy.

#### Personalized Learning Systems and Adaptive Learning.

The significance of the AI in learning lies in adaptive learning and individualized learning systems, which allow an individual student to be taught the content depending on their needs, performance, and preferences. The techniques rely on recommender systems, predictive analytics and learner modeling in order to personalize activities, assignments and feedback [2,17-19]. Adaptive learning systems help identify which subjects of mathematics an individual student might require more experience with, like

multiplication, algebraic equations or geometry, in mathematics education. Personalized learning systems may suggest simulations, experiments, and scientific texts to the student that support his or her level of understanding in science education. Within the context of language teaching, adaptive systems may individualize reading passages, vocabulary activities, grammar activities, and writing prompts based on the abilities of students. Of particular importance is personalized learning since classrooms are becoming very diverse in the terms of ability levels, learning style, and the educational background. Differentiation, self-regulated learning, and student engagement can thus be aided using the adaptive systems because they will not be exposed to too difficult or too easy content. These systems will probably be personalized even further in the future by multimodal data, behavioral analytics, and emotional recognition.

#### Knowledge Tracing and Predictive Analytics

The use of knowledge tracing and predictive analytics as methods of AI is increasingly common to learn how students learn over time and who might require more assistance. Knowledge tracing models are models to estimate the mastery of specific skills or concepts by a student based on the patterns recorded in quizzes, assignments, classroom interactions, and online activities. Predictive analytics goes even deeper and predicts future performance, disengagement risks, and patterns that are likely to cause underperformance. In mathematics education, predictive analytics may detect patterns in the mistakes in algebra, fractions, and geometry. These techniques can be used in science education to identify students who have some difficulties with laboratory work, scientific reasoning or inquiry learning. Knowledge tracing can track vocabulary development, reading comprehension, writing development, and oral communication in language learning. Such approaches are useful since they enable educators to act sooner and offer more specific assistance. They further aid in the learning analytics as they assist school in determining the instructional methods that are most effective on particular groups of learners. Predictive analytics is likely to grow in importance as greater numbers of schools and educational institutions adopt educational technology to promote fair and informed decision-making.

#### Automated Feedback and Automated Assessment

Automated feedback and automated assessment are also gaining significance as AI tools since they will lower teacher work requirements and allow more student learning to be evaluated more promptly and continuously. The systems employ the natural language that can process, machine learning and text generation to evaluate assignment, essays, quizzes and short-answer responses. In mathematics teaching, automated evaluation is capable of detecting arithmetic errors, wrong operations, and lack of rationalization. These methods can be used to analyze laboratory reports, scientific explanations and open-ended answers in science education. Automated feedback systems are commonly used in language education, including grammar correction, scoring essay, and spelling analysis as well as writing improvement. The significant benefit of automated feedback is that they offer instant feedback and the student will be able to make corrections and even do it faster. It promotes formative assessment, self-directed learning, and ongoing development of skills. Nevertheless, fairness, transparency, and explainability continue to be raised, particularly when automated assessment involves taking place in high-stakes situations. The scientists are becoming more insistent that automated systems need not replace teacher judgment but should supplement it.

#### Conversational AI and Educational Chatbots

Some of the fastest emerging AI processes are conversational AI and learning chatbots that enable students to get explanations, feedback, and learning support whenever they need it through on-demand access to these processes. Generative AI chatbots can give answers, describe things, inform and direct students to study materials, and show them through learning activities [3,20-23]. Examples in mathematics education Chatbots in mathematics can be used to find the solution of equations, give explanations, and also assist in multi-step logical thinking. Conversational AI can also be traditionally applied to simulate scientific inquiry, answer scientific inquiry questions about experiments and give interactive explanations of scientific phenomena in science education. Chatbots are particularly practical in language education in conversational practice, training in pronunciation, grammatical support, and communication in more than one language. The recent developments in conversational AI

comprise context memory, emotion recognition and the capability to maintain more extended and consistent communication. The advances result in chatbots being more interactive and helpful to student learning. Still, the problem of excessive dependence on the responses made by chatbots, the probability of misleading information, and the potential to avoid effective struggle and critical thinking exist.

#### Multimodal AI, Computer Vision, and Image Generation

Multimodal AI, computer vision, and image generator are also becoming of significant importance as AI tools as they allow students to access educational information in a variety of formats: text, picture, audio, video. Computer vision in mathematics education, Computerized interpretation of graphs, geometric shapes, and handwritten equations, can assist the student to understand and interpret diagrams, geometrical forms, and equations. The techniques of image generation can be used to provide a visual representation of mathematical constructs, so the concepts that are difficult to comprehend become simpler. Multimodal AI can be used in science education to construct diagrams, scientific illustrations, simulations, as well as virtual experiments, which enhance conceptual knowledge. Image generated and multimedia storytelling could be used to promote creativity, development of literacy and acquisition of vocabulary in language learning. The methods can be applied especially with students who have learning disabilities, are avaricious to the language, or have varied learning preferences as they offer more than one avenue of accessing information. With the continued advances in multimodal Generative AI, it should be able to facilitate immersive learning, project-based learning, and inquiry-based learning in more interactive formats.

#### Speech Recognition and Voice-Based AI

Due to the capability of developing speech recognition and voice-based AI, these systems are increasingly popular in the K-12 level of education, as it enables students to connect with educational content by speaking. By applying deep learning and natural language processing, these technologies turn speech into text and examine pronunciation as well as offer verbal feedback. Speech recognition has been employed in language learning especially in pronunciation, listening comprehension, oral fluency, and multilingualism. Voice-based AI (in mathematics education) can be used to assist younger learners in verbalizing their thinking processes and getting feedback on their conception of the processes being taught. Voice assistants can also be used in science education through laboratory work, verbal explanation of scientific concepts, and hands-free assistance during an experiment. The speech recognition also adds to the issue of accessibility as it benefits those students who struggle with typing, reading or writing. Voice-based AI will probably become increasingly significant in the field of inclusive education and collaboration between humans and AI as voice recognition becomes more accurate and information-aware.

#### Recommender Systems and Learner Modeling

Recommender systems and learner modeling are AI techniques used to tailor the educational process or student behavior and performance in accordance with recommendations of learning resources, learning activities, and interventions. Such systems apply machine learning, collaborative filtering, and predictive analytics to discover the type of content that is most suitable to a particular learner [9,24-26]. Recommender systems can be used in mathematics education to recommend targeted practice activities on a particular subject, e.g. fractions, equations, or geometry. They can prescribe experiments, simulations, videos, or readings in science education related to the interests and level of achievement of a student. In language learning, recommender systems have the potential to customize reading resources, vocabulary activities as well as writing assignments. The modeling of learners is particularly useful since it enables teachers to develop a clearer picture of the student likes, motivation, and learning developments. There is, however, concern that high dependence on recommender systems can restrict learning possibilities or buttress prevailing prejudices in the educational material.

#### Explainable AI, Ethical AI, and Responsible AI

Explainable AI, ethical AI, and responsible AI are also gaining strength as a relevant type of AI practice as they all involve transparency, fairness, and accountability of the educational technologies.

Explainable AI is dedicated to the idea of keeping teachers and students aware of how AI systems take decisions, recommend, or assess performance. Explainability becomes very important in K-12 education since teachers have to understand why an AI tool suggests a certain learning activity or why it considers certain students at risk. Ethical AI contends with making decisions about the algorithmic bias, academic integrity, surveillance, privacy, and unfair access to technology. It is becoming more common that scholars call on designers to create AI systems that safeguard student rights, minimize bias, and increase fairness in their design. Responsible AI also involves governance systems, educator supervision, and policies which govern how AI technologies are utilized in a manner that grabs educational values and human agency. Such concerns are coming to the center of a debate about educational transformation as the adoption of AI without any ethical restrictions will widen the already existing inequalities and lessen the trust towards educational technology.

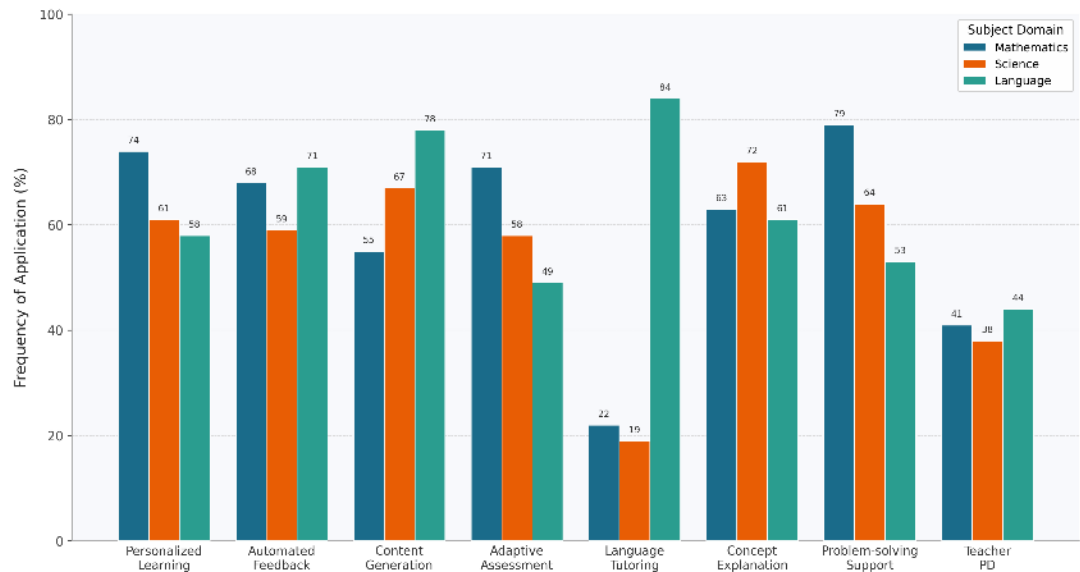


Fig. 3 Frequency of GenAI Application Types Across K-12 Subject Domains

Fig. 3 shows grouped bar chart quantifies how frequently eight distinct GenAI application categories - including personalized learning, automated feedback, adaptive assessment, language tutoring, and teacher professional development -- are reported across Mathematics, Science, and Language classroom studies. Each cluster of three bars corresponds to one application type, with subject domain encoded by a consistent color scheme. Value labels atop each bar facilitate direct numeric comparison without requiring readers to consult the y-axis. The visualization reveals that problem-solving support is the dominant application in Mathematics, content generation leads in Science, and language tutoring is almost exclusively reported in Language classrooms, reflecting domain-specific pedagogical affordances of generative AI. These cross-domain asymmetries are of direct relevance to curriculum designers, edtech developers, and policymakers aiming to align AI tools with disciplinary learning objectives.

#### Human-AI Collaboration and Teacher Augmentation

Human-AI partnership and teacher augmentation is the significant change in perceptions of AI practices in K-12 schools. Instead of substituting the teachers, Generative AI is increasingly offered as a platform, which helps teachers with decision-making, workloads, and improving the quality of instructions [27-29]. The AI systems can help teachers create lesson plans, quizzes, analyze the performance, and design differentiated instruction, as well as give automated feedback. AI has the potential to assist teachers in mathematics education to detect misconceptions and develop specific interventions. Similarly, it may be used in science education to develop simulations, experiments, and project-based learning activities. Artificial intelligence can aid in language education writing lessons, reading intervention, and bilingualism. Recent studies keep stressing that teachers will still be the major focus in educational procedures as learning is always about relationships, nurturing, innovativeness, and professional analysis. Cooperation between teachers and the AI systems is bound to be the most effective models of

education instead of complete automation, though. The readiness of teachers, AI literacy, and professional development will be required to facilitate the effectiveness and accountability with which all educators will be able to use these methods.

### *3.3 Artificial intelligence technologies*

#### Large Language Models and Transformer-Based Technologies

The most conspicuous Generative AI technologies currently used in K-12 communication instruction based on mathematics education, science education, and language teaching are large language models and transformer-based technologies. These technologies are based on deep learning structures, neural networks, and attention mechanisms to interpret the context, predict language patterns, and come up with the responses that are human-like. Transformer-based systems find extensive application in K-12 classrooms in the question answering system, text summarization system, lesson planning system, automated feedback system and conversational tutoring. These technologies assist in explaining equations, providing problem-solving instructions and in computational thinking as applied in mathematics education. In science learning, they aid learners in comprehending scientific understanding, summarizing laboratory results, and deciphering complicated terminologies. Large language models can particularly be useful in language education in the areas of grammar correction, vocabulary generation, literacy instruction, multilingual instruction, and writing aids. They are very useful in adaptive learning and differentiation instructions because of their age-relevant and individualized explanations. Emerging educational research highlights that most educational large language models are more effective compared to general-purpose systems since those built are aligned with curriculum goals, pedagogy, and developmental requirements. Similar results are also reflected in findings of OECD studies which reveal that educational large language models have the best applications in assisting learning and teacher judgment as opposed to substituting cognitive effort and classroom interaction.

#### Intelligent Tutoring Systems and Virtual Tutor Technologies

Some of the most common investigated and implemented educational technologies in the K-12 environment are intelligent tutoring systems and virtual tutor technologies. These technologies are machine learning, knowledge tracing, predictive analytics, and conversational AI in combination to offer students personalized instructional support [30-32]. Intelligent tutoring systems in mathematics education have been used to diagnose the misconceptions in arithmetic, fractions, algebra, and geometry and to adapt curriculum task difficulty based on performance of the learners. Virtual tutors assist with inquiry-based learning, virtual experiments and mastering concepts in science education by asking guided questions and providing real-time explanations. Virtual tutoring technologies offer learning assistance in pronunciation, grammar, writing, reading fluency and trying oral communication in language education. New advancements in Generative AI have seen intelligent tutoring systems be more conversational, empathetic and understand context to enable them sustain more academic conversations and offer customized hints rather than answers. Simultaneously, recent studies indicate that large language models are not beneficial enough to facilitate responsible tutoring due to their inability to monitor the progress of the learner on a long-term basis. Hybrid tutoring technologies that include deep knowledge tracing, learner modeling and large language models are hence assuming a growing significance.

#### Natural Language Processing Technologies

NLP technologies form the basis of using Generative AI to pedagogical purposes since educational systems need to understand, analyze, and generate human language. NLP technologies find extensive applications to score essays, summarize texts, check them with respect to grammar, translate languages, perform sentiment analysis, semantic analysis, and provide automatic feedback. In mathematics education NLP has the potential of converting word problems to equations and verbal explaining mathematical procedures. Applications of NLP technologies in science education allow students to recap scientific literature, learn scientific words, and communicate with AI via natural language

dialogue. These technologies are particularly significant in language education in the areas of reading comprehension, vocabulary acquisition, quality of writing, oral fluency and multi lingual communication. The sophistication of NLP technologies has also enhanced their capabilities of assisting students with language barriers, learning disabilities or with limited literacy levels. According to the current trends, the future technologies of NLP will be more emotion-conscious, situation-sensitive, and able to help the cross-lingual communication in more diverse classrooms.

#### Adaptive Learning Platforms and Personalized Learning Technologies

Individual learner-centric and personalized learning technologies and adaptive learning platforms are largely adopted to offer personalized learning experiences in response to the needs, interests and performance of the individual learners. Predictive analytics, recommender systems, learner modeling, and behavioral data are applied in these technologies to optimize lessons, assignments, and feedbacks [9,33-35]. Adaptive platforms may also be used in mathematics education, suggesting specific exercises to students who appear to have issues with particular areas like algebra, geometry, or fractions. Personalized learning technology may be utilized in science education to present simulations, readings, and experiments that match the level of knowledge and interest of a student. Adaptive systems in language education can be used to tailor vocabulary activities, grammar activity, passages of reading, and prompts to write. The growing popularity of the adaptive learning technologies is also connected with the general trend in the direction of student-centered learning, self-regulated learning, and differentiated instruction. Recent studies have recommended adaptive tutoring and individual generation of content as some of the brightest applications of Generative AI in the context of human-centered pedagogy, respectively custom-crafted to advance equity, teacher control, and learner agency.

#### Conversational AI and Educational Chatbot Technologies

The technologies of conversational AI and chatbots are quickly becoming essential components of the educational technology of K-12 since they offer quick and interactive, scaling assistance to students. Chatbots used in education may resolve questions, describe phenomena, propose resources and direct learners on assignments. Chatbots can be applied in mathematics education to assist students to solve equations, learn formulas, and reason in multi-step problems. Conversational AI can be used in science education to replicate scientific investigation, respond to questions regarding experiments, and describe the scientific phenomena using easy to understand language. Chatbots are common in learning languages, conversational practice, pronunciation training, grammar correction and multilingual communication. In conversational AI, recently, more powerful contextual memory, emotional awareness, and the capacity to maintain more coherent and personalized communication have been improved. Nonetheless, it is also feared that students might get too reliant on chatbots, rely on them to avoid critical thinking, or be misinformed without strict supervision of the systems. OECD guidance focuses on the principle of integrating chatbot technologies with explicit pedagogical objectives and teacher oversight instead of active shortcuts in getting tasks done.

#### Learning Analytics, Predictive Analytics, and Knowledge Tracing Technologies

The importance of learning analytics, predictive analytics, and technology of tracing knowledge is becoming increasingly relevant since they enable the educator to learn how the students learn in the long term. The technologies gather and process data related to assignments, quizzes and the interaction, and digital learning environments in order to establish the mastery of learners and forecast their performance [36-38]. In math education, predictive analytics may allow detecting patterns in error in fractions, algebra, and geometry. Knowledge tracing technologies can be used to identify the nature of student problem in either scientific inquiry, laboratory work or conceptual argument in science education. The kinds of technologies that could be used in language learning include vocabulary, writing, reading, and speaking fluency. The technologies of learning analytics are so useful in particular because they enable teachers to take early intervention steps, to customize teaching, and to offer special assistance to learners with difficulties. New research has also given more emphasis on integration of analytics technologies with human judgment in order to enable teachers to use patterns in a way that would be meaningful, ethical, and contextually appropriate.

### Automated Assessment and Feedback Technologies

K-12 classrooms are also starting to adopt the more automated assessment and feedback technologies due to their lessening teacher workload and the immediate feedback that students get regarding their work. These tools apply natural language processing, machine learning and text generation to review assignments, quiz, essays and short answer responses. In mathematics teaching, there is the use of automated evaluation techniques to know of wrong computations, lack of reasoning and possible fallacies. These technologies may be applied in science education to assess lab reports, scientific arguments, and short answer explanations. In language teaching, automated feedback systems incorporate the scoring of essay, grammatical corrections, spelling, vocabulary, and the enhancement of the writing process. Among the primary benefits of automated assessment, it enables formative assessment and self-regulated learning as it provides students with the chance to revise and correct their work in the immediate future. Nevertheless, it is recommended to be concerned with the fairness, transparency, and reliability of automated grading systems, especially in test of high stakes. Existing evidence would propose that automated feedback technologies will work best when supplemented with teacher judgment, and not substitute it.

### Multimodal AI, Computer Vision, and Image Generation Technologies

Multimodal AI, computer vision, and image generators are gaining significance due to the ability to engage students with educational content regarding various formats, e.g. text, images, audio, video, and interactive simulations. Computer vision technologies in the field of mathematics can be used to identify handwritten equations, comprehend graphs, draw geometric shapes. The image generation technologies have the ability to generate diagrams, charts, and explanations visually that can be used to explain abstract concepts to the students. Multimodal AI could be used in science education to aid virtual experiments, scientific visualization, laboratory simulation, and interactive diagrams. Image generation technologies have the potential to generate visual cues, storyboards and multimedia stories in language education in support of literacy and creativity. The learning disabled, language challenged or other learning preference students find multimodal technologies especially helpful since they offer multiple means of receiving information. Recent studies have cited multimodal learning analytics and multimodal Generative AI as potential key advances to the future of educational technology, since they enable the incorporation of all types of interaction with students into more tailored and interactive learning processes.

### Speech Recognition and Voice-Based Technologies

Voice-based technologies and speech recognition are gaining popularity in K-12 classes since they enable children to communicate with learning systems by speaking. These technologies are based on natural language processing, deep learning and speech analysis, to transform speech to text, to identify pronunciation patterns and to give verbal feedback [3,39-41]. Speech recognition technologies find extensive applications in language education and are used in the process of training pronunciation, listening comprehension, oral fluency, and multilingual learning. Voice-based systems may be used in mathematics education to assist younger students who can speak out their reasoning as well as get support in a conversational form. Speech-enabled technologies can also be used in science education to offer verbal instructions in an experiment, respond to spoken questions, and assist physically disabled learners. Voice technologies are another technology that is used in inclusive learning since students who have difficulty in reading, typing or writing can use voice technologies. These technologies will be used to increase their contribution to immersive learning, accessibility, and human-AI collaboration as they become more accurate and context-aware.

### Virtual Reality, Augmented Reality, and Immersive Learning Technologies

The technologies of virtual reality, augmented reality and immersive learning are the next evolution in education in classrooms in the K-12. Generative AI is becoming more and more combined with these technologies to develop the most interactive learning environments. Immersive technologies can be used in teaching mathematics to students to learn three-dimensional geometry, data visualization, and spatial reasoning. Virtual reality might be used in science education to facilitate laboratory simulation,

scientific inquiry and complex systems discovery (ecosystem, atoms or planetary motion). Immersive learning technologies are able to provide real conversational and culturally rich virtual environments in language learning. Immersive learning combined with Generative AI is especially promising, as it is going to allow altering the scenario in real-time, providing personalized feedback, and making the project-based learning more engaging. Current research indication in education implies that immersive technologies could gain even greater prominence in enhancing student motivation, creativity, and future proof skills.

#### Robotics and Embodied AI Technologies

K-12 education is slowly beginning to embrace robotics and embodied AI technologies due to its physical and interactive learning experiences, which are supplementary to online tools. Through hands-on activities, educational robots may facilitate collaborative learning, computational thinking, STEM education, and problem-solving [36,42-44]. Robots may be used in instructions of mathematics, where measurement, geometry, coding, logical reasoning are taught. Robotics can facilitate inquiry-based learning, engineering design, and experimentation in the teaching of science. Social robots in language education: There are numerous applications of social robots that may be used in language teaching as conversational practices, storytelling, and pronunciation. The so-called embodied AI technologies are considered especially promising as they combine the physical interaction with digital intelligence, which makes the learning process more engaging and memorable. Studies of tutoring systems are increasingly considering robot tutoring systems together with computer based intelligent tutoring systems, which may suggest that classrooms of the future have the potential to feature a combination of conversational AI, robotics and multimodal technologies.

#### Explainable AI, Ethical AI, and Responsible AI Technologies

Explainable AI, ethical AI, and responsible AI technologies are becoming necessary since they respond to the transparency, fairness, and accountability of learning systems. Explainable AI technologies can enable teachers and learners to learn how AI systems make recommendations, grade assignments or learners. Some of the ethical AI technologies are aimed at avoiding algorithmic bias, safeguarding students and achieving fair access to digital devices. The governance of AI technologies, surveillance systems, and protection, which help align AI tools with educational values and human rights is also a responsibility of AI technologies. UNESCO guidelines always point to the fact AI in education must safeguard the rights of learners, human agency, and the autonomy of a teacher. Associated issues that are raised in literature focus on scholarly honesty, monitoring, information security and the possibility of well-constructed AI systems reinforcing status quo. Consequently, explainable AI and responsible AI technologies are becoming regarded as prerequisites of sustainable educational change.

#### Human-AI Collaboration Platforms and Teacher Augmentation Technologies

The application of human-AI collaboration platforms and teacher augmentation technologies are coming in as some of the most significant educational technologies since they establish AI as a help but not a replacement of teachers. The technologies are used by educators to create lesson plans, generate quizzes, analyze performance of students, design differentiated instruction and give feedback more effectively. Technologies of teacher augmentation can be used in mathematics education to discover misconceptions and create targeted interventions [40,45-47]. They may be useful in science education in the establishment of simulation, project-based learning, and laboratory work. In language education, AI may help in instruction in writing, supports reading, multilingual communication, and vocabulary growth. Recent educational studies have been emphatic that the future of Generative AI in education relies on hybrid human-AI, which denote the maintenance of teacher autonomy, learner agency, and professional judgment. Educators are also necessary since they offer emotional support, creativity, classroom management, and moral principles that are not reflectable to use of technology alone.

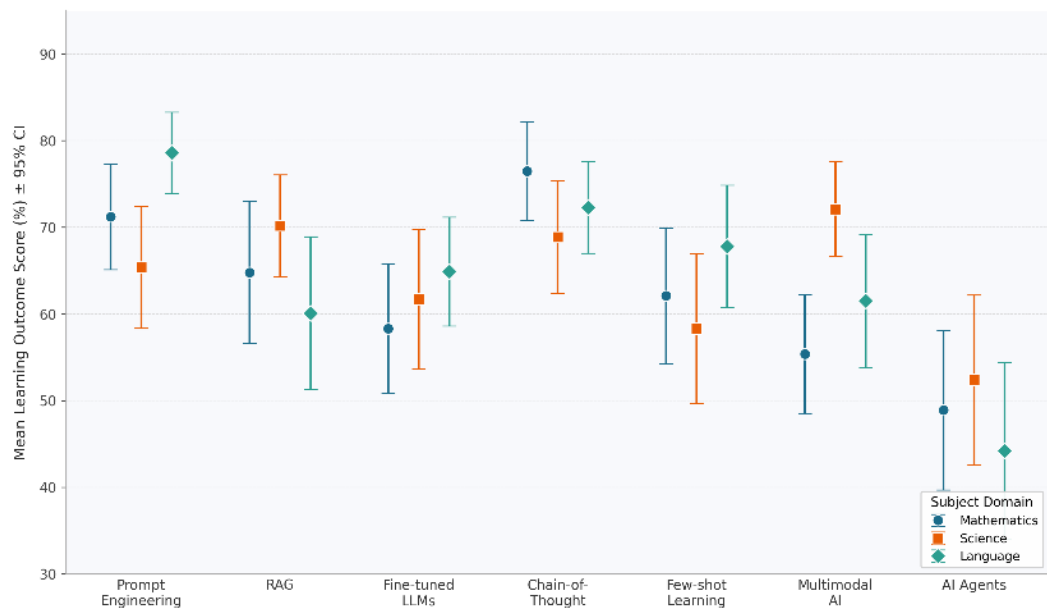


Fig. 4 Mean Learning Outcome Scores by GenAI Technique and Subject Domain (95% CI).

Fig. 4 visualizes error bar plot compares mean student learning outcome scores (with 95% confidence intervals) achieved through seven prominent GenAI techniques -- Prompt Engineering, Retrieval-Augmented Generation (RAG), Fine-tuned LLMs, Chain-of-Thought prompting, Few-shot Learning, Multimodal AI, and Agentic AI systems -- across the three K-12 subject domains. The 95% confidence intervals, calculated as 1.96 times the standard error of the mean, convey both the central tendency and the statistical precision of each estimate, a convention aligned with the reporting standards of high-impact journals in education technology and learning sciences. Chain-of-Thought prompting emerges as the strongest technique for Mathematics, while Multimodal AI achieves the highest score in Science, and Prompt Engineering dominates in Language settings. The comparatively wide confidence intervals for AI Agents reflect the nascent and heterogeneous nature of agentic deployment in K-12 contexts, signaling a productive frontier for future controlled experimental research.

### 3.4 Artificial intelligence models

#### GPT Models and Autoregressive Large Language Models

Autoregressive large language models such as GPT models have been the new dominant models of AI that gets applied to K-12 mathematics education, science education, and language education through the use of Generative artificial intelligence. The models produce text and predict the next token in a sequence resulting in the ability to generate coherent descriptions, answer questions, summarize ideas, and facilitate personalized learning. The value of the GPT-based systems in particular lies in the fact that they may be useful in supporting conversational AI, intelligent tutoring systems, automated feedback, and adaptive learning in a range of subject fields. GPT models are applicable in mathematics to explain formulae, reasoning step by step and help solve problems. In science education, they are able to summarize the scientific concepts, make sense of data and come up with inquiry-based learning tasks. GPT models have been popular in grammar correction, essay writing, reading comprehension, and multilingual learning in language education. Newer multimodal variants of GPT have also been able to handle images, speech, and audio and could be applied in visual problem-solving and voice-based tutoring. The increasing educational importance of GPT models can be explained by a high degree of flexibility, increase in size, and features to assist students and teachers in real-time. Nonetheless, studies are becoming more vocal on the need to closely monitor GPT models since they have been prone to creating hallucinations, factual inaccuracies, and high confidence responses.

## Transformer Models and Attention-Based Architectures

Most current Generative AI in the education domain relies on transformer models as their underlying software. These models are founded on the mechanisms of attention with the help of which they can determine the significant relationships between words, pictures, and situational information [3,48-50]. The transformer-based architectures are particularly relevant in the K-12 education as they are able to handle long series of the information and keep the context of the interaction and also multimodal learning. Transformer models are applicable in mathematics education, where word problems, explanations of equations, and analysis of mathematical reasoning can be solved. Such models may be used in science education to disseminate scientific readings, create summaries, and assist in map making concept. Transformer architectures in language education make it possible, through complex grammar analysis and machine translation, writing assistance, and conversational style. The popularity of transformer models has seen the creation of more advanced learning applications that integrate text, speech, images and video in one learning space. They are the key to the future of adopting educational technology with their capacity to facilitate contextual comprehension and adaptive reactions.

## BERT, XLNet, and Bidirectional Language Models

BERT, the XLNet and other bidirectional language models are significant since they act upon context in both directions instead of trying to predict only the next word. This renders them particularly good in activities like reading comprehension, semantic analysis, sentiment, question answering, and automated assessment. BERT-based systems have the potential to examine the sentence structure in language education, identify grammatical mistakes, and facilitate literacy building. Bidirectional models in mathematics education may make a sense of complex word problems and determine the connection between verbal and numerical data. These models can find applications in science education through the analysis of scientific texts, determining the main concepts and the vocabulary building. XLNet was better placed to handle language understanding tasks because it brought opposing changes to the previously existing transformers through the fusion of autoregressive learning and bidirectional context. Such models are still used to design educational AI systems since they have powerful contextual reasoning features, and are also much more efficient than certain larger generative models.

## T5 and Encoder-Decoder Models

Other encoder-decoder models such as T5 are gaining importance in fields of educational AI since they assume that all language tasks are text-to-text problems. These are particularly useful models in translation, summarization, question generation, scoring of essays and automated feedback [5,8,51-52]. In language teaching T5 models may be used in K-12 to translate texts between languages, simplify complex reading materials and to create exercises. In mathematics education encoder-decoder models that can translate symbolic equations into plain-language descriptions and create practice questions. In science education, the models have the ability to summarize scientific articles, concept explanation and development of age specific content to learners at various levels. T5 models are useful in adaptive learning systems since they can be fine-tuned to a number of diverse tasks due to their flexibility. They are also especially applicable in classrooms that are becoming more diverse due to the need to support multilingual learning and individualized instructions.

## PaLM, Gemini, and Foundation Models

A newer generation of AI models incorporating as well as multimodal functionality and large scale training is PaLM, Gemini, and other foundation models. These models can handle text, pictures, audio, and video messages so that they can be used to facilitate more engaging and interactive learning. Multimodal foundational models are applicable in mathematics education within examination of graphs, handwritten equations, data picturesque, etc. They are able to comprehend diagrams, scientific illustrations and simulated laboratory set ups in science education. These models may be used in the fields of language teaching in terms of speech recognition and pronunciation training and story-telling on a multimedia level. The Gemini and similar models prove very helpful as they combine the textual and visual comprehension within one system, which is why they can be used in multimodal learning contexts. PaLM was also good in reasoning, translating and arithmetical skills especially when used in

conjunction with chain-of-thought prompting. The capabilities imply that foundation models will become more and more significant in K-12 schools in the future when students will be subjected to various types of information at the same time.

#### Multimodal Large Language Models

The Multimodal large language models are becoming one of the most potent category of AI models in K-12 education since they have the ability to process and generate various types of content at once, including text, images, audio, and video. The models have found application especially in mathematics education since they assist in the analysis of diagrams, handwritten equations, graphs and geometry problems as well as written explanations. Multimodal models are able to analyze scientific illustrations, laboratory images, and experimental data in the science education. They are able to integrate text, images and speech in language instruction to encourage literacy growth, narration, and pronunciation. Recent studies in education indicate that multimodal large language models can particularly be useful with students experiencing learning disability, language barriers or varied learning preferences due to the fact that they offer more than one route to information. Nevertheless, multimodal models have issues regarding the accuracy, computational cost, and interpretability as well. Research articles about multimodal tutoring show that we still have not reached the point where such systems outperform qualified human tutors in certain aspects like pedagogical sequencing and errors diagnosis.

#### Deep Knowledge Tracing Models

Deep knowledge tracing models are specialized AI models that are used to track the progress of understanding the student as time progresses. These models are based on machine learning and sequencing data analysis to determine whether a particular concept or a skill has been mastered by a learner or not [9,53-55]. Deep knowledge tracing can be used in mathematics education to diagnose the recurring errors in the areas of fractions, algebra and geometry. These models can also be used in teaching science to track the way in which the students acquire scientific reasoning, experimental skills and conceptual knowledge. Deep knowledge tracing may be used to monitor vocabulary development, mastery of grammar and reading comprehension in the field of language education. Deep knowledge tracing models are more credible to predict the long-term learner improvements than general-purpose large language models, which are not educational predictors. Recent studies indicate that these models are more effective than large language models in terms of being more temporal consistent, more accurate and mastery estimative, and are also necessary to responsible tutoring and adaptive learning.

#### Recommender Models and Personalized Learning Models

Recommender models are actively applied in K-12 to customize the learning process through the recommendations of the activities, exercises, readings, and interventions students need. With these models, predictive analytics, collaborative filtering and learner profiling is utilized in determining the best content to be assigned to an individual student. Recommender models can also be used in education of mathematics, where they are used to recommend practice problems to a student that focus on outstanding weaknesses. In the learning of science, they are able to prescribe scientific experiments, simulations, and project based learning activities. Individual learning models can propose vocabulary lists, reading passages, and writing prompting materials in a language with a suitable level of proficiency in the context of language teaching. The significance of these models is that they advocate differentiated instructions, independent learning, and student interaction. Scientists however warn that the overuse of recommender models can potentially limit access to varied content and further strengthen already present prejudices in academic routes.

#### Speech Models and Audio-Based Language Models

The use of speech models and audio based language models is gaining importance in K- 12 classrooms as it enables students to communicate to the education system using spoken language. They are speech recognition, text-to-speech generation, and audio analysis-based models that offer conversational tutoring and pronunciation assistance. Speech models come in particularly handy in language teaching in the areas of listening comprehension, oral fluency, pronunciation training, and bilingual education.

Voice-based models can be applied in mathematics education to instruct younger learners on thinking processes, as well as, teach them how to express those steps through words. Audio-based models in science education may serve both as giving verbal instructions during laboratory work and serving as an aid with accessibility needs of students. In current trends with speech AI frameworks, it is possible to note that future learning systems will be increasingly equal in terms of audio, text and visual inputs, and thus, the process of learning. Such integration will ensure that learning environments are more interactive, inclusive and responsive to the diverse student needs.

#### Open-Source Models and Local Educational Models

Open-source AI models, including LLaMA and systems that can be deployed locally, are increasingly becoming significant in K-12 education due to their increased flexibility, reduced costs and improved data privacy. Educational institutions and schools are raising their interest to local models due to the fact that it enables the data of students to be housed in the institutions instead of being forwarded to third-party providers [56-58]. The open-source models may also be tailored towards curriculum alignment, multilingual education and regional educational requirements. Local educational models can also be customized in mathematics, science and language classes in order to address particular subjects, grade levels, and instructional styles. The models are particularly applicable in situations where the schools are interested in greater control over privacy, transparency and explainability. Simultaneously the open-source models can be more demanding in terms of technical knowledge and computational power, which can be of a disadvantage to smaller schools. Recent trends hint at eco-system of education in the future that would incur both proprietary and open models based on the institutional requirements and infrastructure.

#### Grade-Specific Educational Models

Grade-specific educational models constitute a standing separate category of AI models due to the increase in the number of scholars who appreciate that learners in age-specific levels need different levels of complexities, vocabularies, and instruction design. These models are developed precisely to meet the curriculum expectations, age content and cognitive progression. Grade-specific models in mathematics education can produce exercises whose material is corresponding to the level of numerical reasoning or understanding of algebra in the student. They are able to modify scientific explanations in line with the level of development in science education. They can help in making the texts easy to read, change the vocabulary, and tailor the reading comprehension activities in language education. The increased popularity of grade-specific models can be viewed as an indication of a more general movement towards responsible AI and child-centred architecture in K-12 education. These types of models have a strong likelihood of gaining more significance in the future since they minimize the chances of exposing learners to improper, too complex or misleading information.

#### Hybrid Human-AI Models and Responsible Tutoring Models

Hybrid human-AI models are now considered to be the best strategy in regards to K-12 education since they would be flexible in terms of Generative AI and reliable due to the traditional model of learners and their expertise applied by teachers. These models combine large language models with a knowledge tracking system, predictive analytics, recommender system, and teacher supervision. Hybrid tutoring may offer adaptive support in mathematics education but with correct records of student achievement. With science education, teachers can integrate simulations, multimodal content and teacher feedback to generate more learning experiences. In language teaching, hybrid models may be used to aid writing support, training pronunciation and multilingual learning and make sure that teachers are at the core of the teaching experience. Existing literature is strongly in favor of the notion that big language models do not alone suffice to do responsible tutoring since they are not able to persistently model learners over time. The future of AI in education is hence, perhaps a hybrid system, enhancing the merits of various AI systems with human judgment, ethical principles, and pedagogical skills.

### *3.5 Artificial intelligence applications*

#### Personalized Learning and Adaptive Learning Applications

The most common applications of Generative artificial intelligence to K-12 mathematics and science education as well as language education are personalized learning and adaptive learning. Generative AI systems may be used to study the performance of learners, reveal the gaps in their knowledge, to tweak instructional materials automatically based on personal needs, preferences, and progress [59-60]. Mathematics education Adaptive learning applications may produce specific practice problems, scaffold equations that are complicated, and offer an increased level of difficulty based on student preparation. These systems can mimic simulation of laboratories, scientific readings and other activities involving inquiry in science teaching. Adaptive platforms in language instruction offer the option of giving vocabulary exercises, grammar tasks, reading passages and writing prompts based on the proficiency of the learner. Learning applications that are personalized have become widely accepted as needed in differentiated instruction due to the presence of diverse students in classes in terms of academic levels, learning style and or language. Recent research claims that adaptive learning systems driven by Generative AI need to be optimally effective because they are built to address the educative purpose and mentoring them to be oriented towards articulate pedagogical objectives as opposed to being generic chatbots.

#### Intelligent Tutoring Systems and Virtual Tutor Applications

Among the most powerful applications of Generative AI to K-12 classrooms are intelligent tutoring systems and virtual tutor applications since they offer students a type of personalized instruction which is similar to one-to-one teaching. These systems integrate conversational AI, knowledge tracing, predictive analytics, and automated feedbacking, to direct the students through issues, identify errors in thinking, and prescribe actions. Intelligent tutoring systems in mathematics education may be used to assist in arithmetic, fractions, algebra, geometry, word problems, etc., through step-by-step explanations and strategic hints. In education science Virtual tutors may be used to support scientific inquiry, design of experiments and interpretation of results as a result of interaction. Virtual tutors aid learners in pronunciation, grammar, literacy building, writing skills, and fluency in conversation, in the language education context. According to recent research findings, AI-based tutoring technologies usually enhance student performance and learning, but this depends on the quality of instructional design and the participation of instructors. Education-based tutoring applications based on the learning science seem to have better results compared to general-purpose AI chatbots.

#### Automated Feedback and Assessment Applications

Generative AI finds significant use in automated feedback and evaluation as it diminishes the teacher workload other than offering real-time feedback about performance to the student. Generative AI is applicable in mathematics education to automatically mark answers based on numerical results, discriminate common mistakes, and elucidate wrong thinking [9,61-63]. The automated assessment tools can be used in the education of sciences to assess lab reports, scientific arguments and short answers explanations. These systems have been very useful in language teaching particularly in scoring essays, correcting grammar, dissecting spelling, evaluating vocabulary and polishing writing. Independent assessment is helpful in formative assessment and self-regulated learning due to automated feedback many times students can quickly revise their work and could not be left waiting to have their work commented by the teacher. Nevertheless, there are also concerns about fairness and transparency as well as overreliance on algorithmic assessments with increased use of automated assessment. Majority of the studies that are being conducted today indicate that automated evaluation is a supplement of teacher evaluation, as opposed to its total elimination.

#### Lesson Planning, Curriculum Design, and Teacher Augmentation Applications

Teachers are finding more and more applications in generating lessons, curriculum, worksheets, quizzes, rubrics and instructional materials through generative AI. The significance of these teacher augmentation applications, in particular, is the lessening of the administrative load on the administrator

and the more open time of the teacher to face-to-face interaction with the students. Teachers working in the field of mathematics education can rely on AI systems to make up practice problems, visual representations of their explanation, and differentiated tasks that can be offered to the students with different abilities. Generative AI can be used in science education to assist a teacher in creating a laboratory experiment, simulation, project-based learning problem (project-based learning), and inquiry-based lesson. In linguistic learning, educators are able to create reading texts, writing to-s, vocabulary tests, and multilingual educational contents. According to the recent reports, teachers are one of the users of Generative AI the most active ones; they tend to use these programs to become efficient and reduce workload. According to frequent teacher users, the first category of time saved every week, is often on the areas of planning and marking of tasks. Meanwhile, teachers note that even AI-generated materials need human assessment to be adequately accurate and of quality and comply with the requirements of the curriculum.

#### Conversational AI and Educational Chatbot Applications

The use of conversation AI and educational chatbot programs is becoming more frequent due to the fact that they enable students to have access to on demand support and explanation, as well as interactive conversations [64-66]. Chatbots in mathematics education have been shown to be useful in explaining mathematical formulae, solving equations, and walking a student through a multi-step argument. Conversational AI application in science education may be used to answer a scientific question, describe a laboratory procedure, and facilitate the inquiry-based learning. Chatbots are popular in language teaching, where they are applied in speaking practice, auto-correction, vocabulary building and communication across languages. In current trends in chatbot systems, there is this-called contextual memory, emotional identification, and more natural speaking skills, as a result of which they become more interactive with students. Nevertheless, teachers are worried about the fact that the excessive use of chatbots can decrease critical thinking, problem-solving, and effective struggle. Studies are sounding alarm that high heavy reliance general-purpose AI-based tools in the learning process may make learners fail in performing when they are eventually called up to do tasks on their own without AI-assisted services.

#### Multimodal Learning and Content Generation Applications

Multimodal learning and content creation are also blistering platforms to apply Generative AI given that the learning environment offers learners to engage with text, pictures, audio, video, and simulations. Generative AI has the potential to generate graphs, geometric drawings, stepwise visualisations, and animation of mathematical concepts in mathematics education [6,67-69]. Scientific illustrations, virtual experiments, interactive simulations and data visualizations have been used as multimodal applications in science education. Generative AI has the capability of creating images, storyboards, multimedia narratives, and audio-based activities in language education that enhances the development of literacy and creativity. The multimodality content generation is also very useful to students with learning disabilities, language barrier as well as the students with different learning preferences as it offers more than one way to access information. According to emerging studies, multimodal AI applications will grow in significance in the classroom during future periods since they are capable of being used in highly engaging, inclusive and immersive educational practices.

#### Learning Analytics and Predictive Analytics Applications

Learning analytics and predictive analytics are also becoming key uses of Generative AI because they enable an educator and educational institutions to discover the trends in student performance and intervene earlier when the challenges are noted. All these applications process the mark of assignments, exam results, classroom attendance, and online communications to determine the progress of the learners and highlight problem areas. Predictive analytics can spot the same mistake made over and over in mathematics education in fractions (algebra, geometry, etc). Learning analytics would help in science education to discover students with a weakness in inquiry learning, experimenting or conceptual learning. These tools may be used in language education to track the reading fluent, vocabulary and writing quality, and speaking. The predictive analytics software comes in handy especially when it comes to detecting students who might soon get disengaged or perform poorly and prescribing specific

actions. According to recent reports, superior AI platforms could be incorporated into classes and classrooms in the coming few years, which will involve referencing student needs and necessities in real-time and looks after classroom instructional assistance more efficiently.

#### Multilingual Learning and Language Support Applications

Some of the most valuable uses of Generative AI in language learning include multilingual learning and language support due to the fact that multilingual students can break linguistic barriers and learn the material in different languages. AI applications will be able to translate writings and make reading books easier, pronounce words, and come up with a bilingual explanation [70-73]. The latter is particularly significant in a multilingual classroom where the applications assist both the students with different backgrounds and offer more interesting engagement. Culturally responsive examples, adaptive reading passages and conversational practice can also be offered by generative AI depending on the level of language proficiency. In mathematics and science education Multilingual artificial intelligence can be used to translate technical vocabulary, to simplify word problems, and to simplify complicated concepts in a more understandable way to English language learners. These applications will be favored as the classrooms continue to get more linguistically diverse and as the schools are attempting to make education more equitable.

#### Inquiry-Based Learning and Project-Based Learning Applications

Significant pedagogical uses of Generative AI include inquiry-based learning and project-based learning since these methodologies will motivate students to investigate, explore, and create instead of remembering information. Generative AI can be used to assist students in designing experiments, creating hypotheses, analyzing data, and delving into the scientific findings in science education effectively [19,74-76]. AI systems can be used in mathematics education to support open-ended problems, applications in the real world and group research. Generative AI may assist students in language education to generate stories and presentations, as well as multimedia projects and debates. Such applications are especially useful since they allow thinking critically, being creative, collaborative, and future-relevant. Recent studies indicate that Generative AI works best when it is an imaginative collaborator or virtual research assistant and not a tool to give direct solutions. This change of inquiry-based and project-based applications of AI is also characteristic of the even wider trends in digital learning and student-centered learning.

#### Immersive Learning and Extended Reality Applications

Generative AI is also being incorporated with immersive learning and extended reality applications to develop high interaction levels of education. It becomes possible to have virtual reality, augmented reality, and AI-driven simulations that would help to make students interact with complicated ideas in more experiential terms. Utilities in Three-dimensional geometry Three-dimensional geometry can be taught using immersive applications in math education, data visualization and spatial reasoning. In science studies, virtual lab environments make simulated environments to be available to students who learn about a virtual laboratory, a virtual ecosystem, a virtual planet, or a virtual chemical reaction. During language education, immersive learning may provide the appearance of real conversational situations and culturally diverse environments to learn a language. According to recent review, AI-enhanced extended reality applications are a relatively recent but potentially promising area of K-12 education, particularly of STEM education. Such technologies will have a more significant part in future classrooms as they may enhance the engagement, motivation, and understanding of the concepts.

#### Educational Robotics and STEM Applications

Another relevant field of Generative AI applications in the K-12 classroom is educational robotics and STem applications since they merge computer-driven thinking, learning with hands-on experiences, and problem-solving in small groups. Robotics activities may be used in mathematics education as an aid to geometry, measurement, coding, and logic. Robots may be used to investigate engineering, experimentation and scientific inquiry in science education. Generative AI can also be useful in robotics projects and assist students in writing code and troubleshooting bugs, as well as in brainstorming design

ideas. Project-based learning and collaboration with future-ready skills are particularly useful as it can be encouraged with the help of those applications. As per research, robotics is a smaller yet expanding subdivision of AI application in K-12 STEM education, in which there is potential of interdisciplinary learning and genuine problem-solving experience.

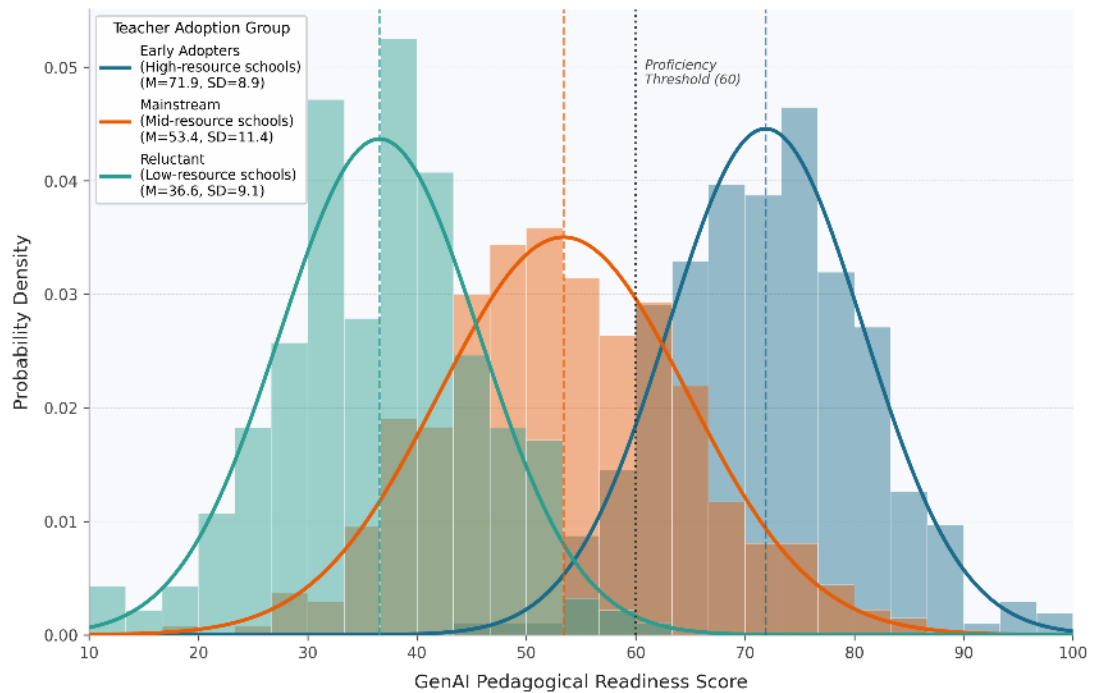


Fig. 6 Distribution of GenAI Pedagogical Readiness Scores Across K-12 Teacher Adoption Groups

Above Fig. 6 explains density histogram overlaid with fitted normal kernel density curves illustrates the distributional shape of composite GenAI pedagogical readiness scores among three empirically distinct teacher profiles -- Early Adopters in high-resource schools, Mainstream adopters in mid-resource schools, and Reluctant adopters in low-resource schools. A vertical proficiency threshold line at 60 points partitions the score continuum into below-proficiency and above-proficiency zones, providing a practical reference point grounded in educational measurement literature. The distribution for Early Adopters is visibly right-shifted and tighter, reflecting both higher mean readiness and lower inter-individual variability, while the Reluctant Adopters curve is broadly distributed and left-leaning, indicative of systemic capacity gaps likely associated with digital infrastructure inequality and limited professional development access. This distributional framing situates individual teacher readiness within structural school-level determinants, which positions the figure as particularly valuable for papers engaging with equity-focused and sociotechnical dimensions of GenAI adoption in compulsory schooling.

#### AI Literacy, Ethical AI, and Responsible Use Applications

AI literacy, ethical AI and responsible use are currently embraced as vital educational applications due to the need of students to have knowledge of how AI functions, its constraints, and understanding of how to utilize it safely. Schools start to teach AI literacy in the math, science, and language courses to teach students about the algorithmic bias, academic honesty, data security, and responsible AI practices [77-79]. Ethical AI education is most crucial, since without proper monitoring, Generative AI can produce misleading information through biased results and pose a threat to privacy. The students should also be advised on situations when they should turn to AI, when to make independent decisions, and how to assess the validity of the AI-generated content. According to recent findings, the rapidly growing field of AI literacy is becoming popular, and governments, educational institutions, and technology-focused organizations are investing in AI literacy training of both educators and learners. Nevertheless, it still requires more explicit frameworks that could consider innovation and human judgment, equity and educational values as balanced.

#### 4. Discussion

The literature review results show that Generation artificial intelligence has emerged as one of the most revolutionary influences on K-12 education, especially mathematics education, science education and language education. The use of large language models, intelligent tutoring systems, conversation AI, multimodal learning platforms and adaptive learning systems have grown exponentially due to the growth of emphasis on GenAI by schools as a means of personalized learning, differentiated instruction and transforming education. In all three subject areas, Generative AI is useful to facilitate automated feedback, lesson planning, inquiry-based learning, project-based learning, multilingual learning, and self-regulated learning. Recent advances indicate that schools and other learning establishments are no longer using generic chatbot apps but more specialized, curriculum conforming AI, which is expected to reinforce teacher judgement, student interaction, and classroom innovation. Meanwhile, the fast increase in the use of educational technologies has also raised the issue of ethical AI, information privacy, bias in algorithms, academic honesty, and teacher preparedness, so responsible governance of AI has become a significant component of further application. Recent studies indicate that educational Generative AI systems can best be efficient when they are as purpose-built to learn, centered on pedagogical concepts, and linked to human regulation instead of using them as entirely autonomous technologies.

Table 1. Summary of Artificial Intelligence Applications, Techniques, Methods, and Opportunities in K-12 Education

Sr. No.	Application Area	Techniques / Methods / Technologies / Models	Opportunity and Future Direction
1	Personalized learning	Adaptive learning, recommender systems, predictive analytics	Customized instruction for individual learner needs
2	Mathematics tutoring	Intelligent tutoring systems, large language models	Stepwise explanations and computational thinking
3	Science inquiry	Conversational AI, virtual laboratories	Interactive experimentation and inquiry-based learning
4	Language learning	Natural language processing, speech recognition	Multilingual learning and conversational fluency
5	Writing support	Large language models, automated feedback	Grammar correction and literacy development
6	Automated assessment	Machine learning, text analytics	Faster grading and formative assessment
7	Lesson planning	Teacher augmentation, content generation	Reduced teacher workload and improved efficiency
8	Curriculum innovation	Generative content tools, multimodal AI	More engaging and updated learning materials
9	Classroom analytics	Learning analytics, predictive analytics	Early identification of struggling students
10	STEM education	Robotics, project-based learning	Future-ready skills and computational thinking
11	Science simulations	Virtual reality, augmented reality	Immersive and experiential learning
12	Mathematics visualization	Image generation, graphing tools	Better conceptual understanding
13	Reading support	NLP, adaptive reading platforms	Improved reading comprehension
14	Vocabulary development	Chatbots, language models	Personalized vocabulary instruction
15	Collaborative learning	Human-AI collaboration, digital pedagogy	Increased teamwork and peer interaction
16	Accessibility support	Speech-to-text, text-to-speech	Inclusion for diverse learners
17	Teacher feedback	Automated feedback systems	Faster and more targeted responses
18	Project-based learning	Generative AI tools, multimodal learning	Creative and interdisciplinary projects
19	Multilingual education	Translation models, NLP	Better access for linguistically diverse students
20	Student engagement	Gamification, conversational AI	More interactive classroom experiences
21	Inquiry-based learning	Virtual tutors, AI simulations	Stronger critical thinking skills
22	Knowledge tracing	Predictive analytics, learner modeling	Continuous monitoring of learner progress
23	Digital pedagogy	Blended learning, hybrid learning	Flexible and technology-enhanced instruction
24	AI literacy	Responsible AI education	Better understanding of ethical AI use

Among the patterns that have been the most significant in the job of the literature is the rise of adaptive learning, personalized learning, and intelligent tutoring systems that have been emerging in K-12 classrooms. Many AI-assisted learning systems have been applied in mathematics education to deliver step-by-step explanations, computational support, automated grading, and subject-specific remediation of fractions, algebra, geometry, and problem solving topics. Generative AI can be used in science education to aid scientific inquiry and interpretation of data, laboratory simulations, and learners in virtual environments and multimodal AI tools. Large language models and natural language processing technologies have found common application to language education, and are used with support and development of literacy and multilingual education, grammar correction, conversational practice, and writing aids. We have seen that such applications have gained particular relevance in the classrooms where the needs of different learners can be met since teachers can teach differently and provide more personalized assistance. Recent research however suggests that a termination of the short term benefits linked to AI assisted learning do not necessarily carry over into long term conceptual learning when students are assessed in the future without the aid of AI. This problem, according to researchers, has also been termed as false mastery in which students make it literally seem as though they are excelling in AI-powered assignments only to fail to present logical independent reasoning and the ability to solve problems independently later.

Table 2. Summary of Challenges, Risks, and Future Directions of Generative AI in K-12 Education

Sr. No.	Challenge	Impact on Education	Future Direction
1	Academic integrity	Increased cheating and plagiarism risks	Redesign assessments for authentic learning
2	False mastery	Superficial understanding of concepts	Promote independent problem-solving
3	Algorithmic bias	Unequal recommendations and outcomes	Use diverse and inclusive training datasets
4	Data privacy	Risk of student information misuse	Strengthen privacy regulations and governance
5	Teacher readiness	Low confidence in AI use	Expand teacher professional development
6	AI literacy gaps	Misuse of AI tools by students	Integrate AI literacy into curriculum
7	Digital divide	Unequal access to technology	Improve infrastructure and equity policies
8	Overreliance on AI	Reduced critical thinking	Encourage balanced human-AI collaboration
9	Inaccurate outputs	Misleading or false information	Require teacher review and fact-checking
10	Prompt engineering limitations	Poor AI performance due to weak prompts	Train teachers and students in prompt design
11	Assessment validity	Difficulty measuring authentic learning	Use project-based and inquiry-based assessment
12	Ethical AI concerns	Potential harm and unfairness	Adopt responsible AI frameworks
13	Lack of transparency	Difficulty understanding AI decisions	Increase explainable AI adoption
14	Teacher workload	Time needed to learn new systems	Provide institutional support and resources
15	Student dependency	Reduced creativity and self-regulation	Encourage guided AI use
16	Curriculum misalignment	AI tools not matching standards	Develop curriculum-aligned educational AI
17	Language bias	Poor performance for multilingual learners	Expand multilingual datasets
18	Accessibility issues	Exclusion of some learner groups	Design inclusive AI systems
19	Technology fatigue	Reduced student motivation	Balance digital and face-to-face learning
20	Cybersecurity risks	Exposure to online threats	Strengthen school cybersecurity policies
21	Cost barriers	High expense of AI implementation	Invest in affordable open-source solutions
22	Lack of governance	Inconsistent school policies	Create national AI guidelines
23	Teacher resistance	Slow adoption of new technologies	Promote participatory design and collaboration
24	Weak evidence base	Limited long-term impact studies	Conduct longitudinal and comparative research

The other significant topic, which can be seen in the literature, is the increased interest in teacher augmentation instead of teacher replacement. Generative AI is being utilized by teachers in lesson planning, curriculum development, quiz generation, rubric development, grading, and automated feedback [6,80-84]. Such teacher-facing applications have been shown to be of utility especially in terms of minimizing workload, saving some of the time and the teacher is in a better position to spend more time in the classroom interaction, relationship building and pedagogical decision making. Simultaneously, there are consistent findings that teacher readiness, AI literacy, and professional development are the key obstacles to a successful implementation. Not many teachers are confident in timely engineering, evaluation of AI, data privacy, and responsible AI. Moreover, educators tend to complain that they are not sure how to incorporate Generative AI into teaching and remain academically valid and with meaningful assessment patterns. Current research also shows readiness among teachers

to use AI systems that are pragmatic, adaptable, fair, and strict but remind that AI must perform as a helper and not a substitute of expertise. The findings also indicate that should the new educational policy focus on the development of teachers, participative design, and models of human-AI collaboration that empower teachers make competent decisions concerning the use of technology.

Also emphasized in the literature is the fact that the future of Generative AI in the field of K-12 education will largely hinge on the schools dealing with ethical AI, explainable AI, academic integrity, and equity in education. The presence of an algorithmic bias, privacy concerns, untrue content creation, and unequal treatment of technology are characterized as the major issues in the numerous studies and could increase the digital divide. The schools with low resources might not be able to receive the most advanced learning systems that provide AI assistance, though more sophisticated personalized learning technologies may be available to schools with a more developed infrastructure. It is equally possible that algorithmic bias will produce unfair results when AI is trained on a small set of data that is not representative of a wide range of learners, languages or cultural backgrounds. The issue of academic integrity is also of high priority as the Generative AI can be employed to write tasks, paraphrase, and come up with essays in a manner that complicates authentic evaluation. The new learning policy seems to question this with the current trend of stressing the need to reshape assessment in a manner that advantage creativity, collaboration and reflection of cognitive process as opposed to only evaluating the end products.

In sum, the general discourse indicates that Generative AI does not need to be considered as an ordinary technological innovation but in a more general context change of digital pedagogy, curriculum innovation, and transformation of education. There is a strong likelihood that in the future, classrooms will have a greater focus on multimodal learning, conversational AI, immersive learning, predictive analytics, teacher augmentation tools. Nevertheless, teacher agency, innovation in students, and human judgment will be the most successful educational models. The focus on prompt engineering and chatbot utilization should be replaced by critical thinking, AI literacy, critical ethical reasoning, and skills that will be used in the future in schools. The need to investigate the long-term effect of Generative AI on self-regulated learning, student motivation, metacognition, creativity, and human-AI collaboration is also increasing. New information indicates that the future of education will not only lie on how successful schools become in adopting Generative AI technologies, but on how purposefully they will balance innovation, equity, responsibility, and authentic learning.

## **5. Conclusions**

As shown in this literature review, the use of Generative AI in the form of adoption and pedagogy in mathematics, science, and language classrooms on K-12 level is changing the teaching and learning experience at steep rates. The synthesis of the research based on the PRISMA framework teaches that Generative AI vacillation is no longer associated with experimental educational technology applications but it gradually becomes a part of regular classroom innovation, adaptive learning, and digital pedagogy. The evidence is consistent throughout mathematics education, science education and language education: AI-assisted pedagogies, large language models, multimodal learning environments and intelligent tutoring environments have the potential to enhance personalised learning, formative assessment, automated responses, cognitive scaffolding and student engagement. These technologies also endorse divergent instruction, collaborative learning, self-regulated learning, and evaluation of learning; thus, enabling educators to better meet the diverse learner requirements. The review also states that the educational worth of Generative AI varies in different disciplines. Generative AI can improve the ideas of computational thinking, problem-solving, series of reasoning, and conceptual comprehension in mathematics education via real-time assistance and adaptive clarifications. In science learning, AI facilitates inquiry-based learning, project learning, virtual experimentation, immersion learning, and data interpretation and allow students to interact with scientific concepts more interactively. Generative AI application in language teaching is also used in developing literacy, learning multiple languages, writing language, vocabulary, reading, and conversation to make language learning more individualized and approachable. Generative AI has been interdisciplinary in nature, thus making

it an effective instrument in enhancing not only STEM learning but also communication abilities on a larger level in K-12 institutions.

Although these opportunities exist, the review mentions a number of endured obstacles that can hinder a sustainable implementation. The readiness of teachers is also one of the most critical issues because most of them are not AI-literate, prompt-engineered, and pedagogically trained teachers to gain classroom integration. Issues of ethical AI, responsible AI, explainable AI, algorithmic bias, academic integrity, and data privacy remain a factor that informs institutional attitudes towards adoption. Moreover, inequitable access to digital infrastructure, insufficient investment, and the digital divide can exacerbate educational disparities in the event of Generative AI implementation without an equitable strategy. These items demonstrate why it should be emphasized that the methods of formulating AI governance, curriculum design, and teacher professional development strategies are developed to enable both innovation and accountability. Further studies must go beyond descriptive studies on the adoption of technology to longitudinal, comparative, and the evidence-based research on the learning outcomes of various age groups, fields of study, and education environments. The examination of the long-term effects of the collaboration of humans and AI in relation to student creativity, critical thinking, metacognition, emotional development, and future-prepared related skills need a specific study. Culturally responsive AI systems, learning in multiple languages, designing inclusive education, and the contribution of Generative AI to serving the needs of students with diverse learning requirements are other areas of study that should be explored in further studies. The future of Generative AI in K-12 education will be determined by how educators, policymakers, and technology makers can develop balanced, ethical, and student-centered models of pedagogical integration that are most effective in transforming the education process, yet that maintain the dominant role of teachers in the learning process.

#### **Conflict of interest**

The authors declare no conflicts of interest.

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