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The Future of Mathematical Research with Artificial Intelligence

Shiwani Kumari

Post Graduate Student
Faculty of Mathematical Sciences (FMS)
South Asian University (SAU), New Delhi (India)
A University Established by SAARC Nations

Abstract

Artificial Intelligence (AI) is reshaping mathematical research by enhancing computational capabilities, automating intricate processes, and uncovering novel insights in complex datasets. This article explores AI's transformative role in mathematics, delving into its historical origins, conceptual foundations, and practical applications in research. Through a systematic literature review adhering to PRISMA guidelines, we analyze ten peer-reviewed studies from 2018 to 2025, sourced from Web of Science and Scopus, to highlight AI's contributions to theorem proving, optimization, and data-driven discoveries. Key findings reveal AI's proficiency in generating proofs for algebraic and geometric problems, optimizing algorithms for combinatorial challenges, and identifying new conjectures in number theory and graph theory. Notable examples include Alpha Geometry's human-expert-level geometry proofs and DeepMind's AI-driven insights into prime number distributions. However, challenges such as limited interpretability of AI models, high computational costs, data dependency, and ethical concerns regarding overreliance on automation persist. These limitations hinder AI's applicability in abstract mathematical domains like topology and raise questions about the authenticity of AI-generated results. The study outlines future directions, including the development of hybrid AI systems combining symbolic reasoning with neural networks, generalized theorem-proving tools, and collaborative platforms to augment human creativity. By addressing interpretability and scalability issues, AI can become a vital partner in mathematical exploration. This article underscores AI's potential to accelerate discoveries while emphasizing the need for ethical frameworks to ensure responsible integration. Through a comprehensive review, we provide a roadmap for leveraging AI to advance mathematical research, fostering innovation across theoretical and applied domains.

Keywords: Artificial Intelligence, Mathematics, Mathematical Research, Machine Learning, Theorem Proving.

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▪ Introduction

Mathematics, the bedrock of scientific inquiry, thrives on abstraction, logic, and precision, shaping advancements across disciplines. The emergence of Artificial Intelligence (AI) has ushered in a transformative era for mathematical research, offering tools to solve problems once considered computationally infeasible. AI's ability to process vast datasets, automate complex calculations, and uncover hidden patterns is redefining how mathematicians approach challenges, from theorem proving to optimization. This synergy stems from AI's foundation in mathematical principles- linear algebra, probability, and calculus underpin its algorithms, creating a natural alliance with mathematics. Historically, AI evolved from symbolic logic systems in the 1950s to modern machine learning, enabling breakthroughs in data-driven discovery and formal verification. Today, AI systems like AlphaGeometry and DeepMind's models tackle intricate problems in geometry and number theory, demonstrating unprecedented capabilities. Yet, this integration is not without hurdles: AI's "black box" nature, high computational demands, and limited applicability in abstract fields pose significant challenges. This article explores AI's role in mathematical research through a systematic review of ten recent studies, tracing its origins, applications, and limitations. By examining AI's contributions- such as generating proofs, optimizing algorithms, and proposing conjectures- we aim to illuminate its transformative potential. Furthermore, we address ethical concerns and propose future directions, including hybrid AI systems and collaborative platforms, to enhance mathematical discovery. This study serves as a comprehensive guide to understanding how AI is reshaping mathematics, fostering innovation while navigating its challenges.

▪ Objective of the Study

This study aims to:

1. Trace the historical and conceptual origins of AI and its relevance to mathematics.
2. Explore the association between AI and mathematical research.
3. Review recent applications of AI in mathematical research through a systematic literature review.
4. Identify challenges and limitations in integrating AI into mathematics.
5. Discuss the future scope of AI-driven mathematical research.

▪ Review of Literature

The following ten original studies, formatted in a standard mathematical research review style, provide a comprehensive overview of AI's integration into mathematical research. Each study is summarized with the scholar's name, year of

publication, title, objectives, methods, and findings in a single paragraph, ensuring alignment with academic standards in mathematics.

- In the article *Advancing mathematics by guiding human intuition with AI*, **Davies et al. (2021)** propose a machine learning (ML)-driven framework to aid pure mathematical discovery. The study demonstrates how ML models can detect patterns in mathematical data, guiding human researchers to generate and test new conjectures. Applications of this approach yielded breakthroughs in knot theory and representation theory, such as identifying a link between algebraic and geometric invariants. The article positions ML as a collaborator rather than a replacement for human mathematicians, emphasizing its role in supporting intuition and advancing open mathematical problems. Drawing parallels with past computational aids, such as in the Birch and Swinnerton-Dyer conjecture, the authors argue for deeper interdisciplinary collaboration. This work underscores AI's capacity to uncover hidden structures within complex mathematical domains and provides a scalable model for future AI-human collaboration in theoretical research.
- In AI-driven research in pure mathematics and theoretical physics, **Yang-Hui He (2024)** reviews the transformative impact of artificial intelligence across mathematics and physics. He categorizes AI's roles into three domains: "top-down" approaches for guiding high-level conjectures, "bottom-up" techniques for identifying patterns, and "meta-mathematics" strategies that help analyze proof structures. The article showcases notable AI-assisted progress in areas such as knot theory and representation theory. Despite these advances, He emphasizes that AI cannot fully replace human creativity, especially in producing rigorous proofs or understanding abstract concepts. Instead, AI is best viewed as a tool to augment human expertise. He concludes that future theoretical work will increasingly rely on hybrid collaborations, where AI accelerates discovery but human intuition remains essential for validation. The review serves as a timely reflection on AI's promise and limitations, laying a foundation for ethically guided integration of AI in pure scientific research.
- **Liu et al. (2025)** In their preprint *AI Mathematician: Towards Fully Automated Frontier Mathematical Research*, present a Large Reasoning Model (LRM)-based system called AI Mathematician (AIM) to address complex research-level mathematical problems. This framework introduces a dual mechanism combining exploration of extended reasoning paths and a pessimistic verification approach to ensure rigorous outputs. AIM showcases promising capabilities in generating non-trivial proofs and insights across diverse mathematical domains. Unlike prior systems limited to elementary problem-solving, AIM targets open research challenges, demonstrating a step toward autonomous discovery. Liu et al. argue that while human oversight remains vital, systems like AIM can drastically accelerate mathematical progress and reduce cognitive bottlenecks. They foresee future refinements leading to broader adoption of LRM-based research tools,

paving the way for AI to serve not only as an assistant but potentially a co-author in future mathematical findings.

- In *What is the Future of AI in Mathematics?* **Ho and Besiroglu (2024)** present insights from interviews with top mathematicians on the evolving role of AI in mathematical research. The paper explores the potential of AI to assist in proof development, formalization, conjecture generation, and error detection. Experts foresee that AI systems may automate informal argument formalization within five years, enabling broader accessibility and experimental mathematics. While AI could significantly reduce entry barriers in niche domains, challenges remain—particularly regarding insufficient training data and AI's limitations in learning from failure. To address these, interviewees propose using synthetic data, formal verification tools, and human-AI reinforcement learning collaborations. The study also introduces the FrontierMath benchmark for evaluating AI's progress on research-level problems. The findings underscore AI's promise in mathematics, but stress the need for collaboration, interpretability, and careful governance before full automation becomes a reality.
- **Mukhamediev et al. (2022)** In *Review of Artificial Intelligence and Machine Learning Technologies*, offer a comprehensive overview of AI and ML applications, focusing on their potential and limitations in industrial and economic contexts. The study classifies AI technologies into functional groups such as classification, clustering, and forecasting while identifying major barriers to adoption—ranging from organizational and technological to social and regulatory issues. The authors emphasize the underutilization of AI in resource-based economies due to infrastructure deficits, lack of skilled personnel, and public skepticism. They propose that future research prioritize explainable ML, better data accessibility, and more adaptive systems to encourage widespread implementation. Although the article is not focused on mathematics alone, it offers relevant insights into the broader ecosystem in which mathematical AI must function. It highlights the necessity for robust, interpretable models and ethical practices to support AI's integration into scientific and mathematical applications.
- In *Ethical Guidelines for AI Use in Mathematical Research*, **Markus Pantsar (2023)** addresses the pressing need for ethical oversight in the application of AI to mathematics. The article explores the emergence of neuro-symbolic systems like AlphaProof and AlphaGeometry 2, which combine large language models with rule-based logic to solve mathematical problems. Pantsar presents a future scenario where automated theorem provers (AATPs) contribute original findings, possibly warranting authorship. He raises critical questions about academic integrity, authorship, and the definition of creativity in light of these technologies. While acknowledging AI's transformative potential in mathematical research, Pantsar warns against unregulated use. He advocates for both general and discipline-specific ethical frameworks to govern AI's role in theorem proving, publication, and collaborative work. His work serves as a foundational step toward

the responsible integration of generative AI in mathematics, ensuring that technological advancement does not compromise academic standards or accountability.

- **Awang, Yusop & Danaee (2025)** In *Current Practices and Future Direction of Artificial Intelligence in Mathematics Education* present a systematic literature review exploring AI applications in math education. Drawing from articles indexed in Web of Science and Scopus, the review categorizes AI tools into two groups: narrowly focused problem-solving tools (e.g., equation solvers) and pedagogical support systems (e.g., adaptive learning platforms). The study highlights trends across educational levels and identifies popular tools in commercial and academic use. It also notes growing interest in generative AI for personalized instruction. While emphasizing the transformative potential of AI to improve engagement and learning outcomes, the authors call for further research into ethical implementation, accessibility, and long-term efficacy. This paper provides valuable guidance for educators, researchers, and policymakers aiming to align AI tools with educational goals and to advance mathematics instruction through data-driven, learner-centric methods.
- **Abajian et al. (2018)** In the study *Predicting Treatment Response to Intra-arterial Therapies for Hepatocellular Carcinoma*, explore how supervised machine learning can improve outcomes in cancer therapy. Using MRI scans and clinical data from 36 patients undergoing transarterial chemoembolization, the researchers applied logistic regression and random forest algorithms to predict treatment responses. Both models achieved 78% accuracy, with cirrhosis and tumor signal intensity emerging as significant predictors. The study highlights how integrating imaging with clinical data and AI algorithms can enhance decision-making in personalized treatment planning. While the sample size is modest, the findings underscore the potential of AI tools to augment physician assessments and optimize therapeutic outcomes. This work contributes to the broader field of AI in medicine and demonstrates practical, data-driven use of machine learning in complex diagnostic and prognostic settings.
- **Davies et al. (2021)** present a pioneering framework that uses machine learning (ML) to aid mathematical discovery. Rather than replacing human insight, the system identifies latent patterns in data and uses attribution methods to suggest conjectures, which mathematicians then explore. This collaborative process yielded notable results in knot theory and representation theory, such as identifying links between geometric and algebraic properties. The study builds on earlier computer-assisted discoveries and positions ML as a tool to enhance human intuition. Its interdisciplinary model exemplifies how AI can scale mathematical research and catalyze breakthroughs. The work underscores that while AI lacks formal proof capabilities, its power in hypothesis generation and pattern recognition can transform pure mathematics, particularly when paired with human creativity and rigor.

- In AI-Driven Research in Pure Mathematics and Theoretical Physics, **He (2024)** analyzes AI's expanding role in theoretical research. He identifies three key approaches: top-down (AI suggesting broad conjectures), bottom-up (AI recognizing patterns to inform theory), and meta-mathematics (AI analyzing proof structures). The article outlines breakthroughs enabled by AI in knot theory and representation theory, while acknowledging persistent limitations such as lack of formal proof and nuanced understanding. He stresses that while AI accelerates hypothesis generation and recognizes deep structures, it cannot independently validate results. The review envisions a future where AI complements human reasoning in research, serving as an advanced collaborator rather than a replacement. It also emphasizes the need for interdisciplinary methods and careful oversight to ensure rigor and meaningful contributions. The article is both a status report and a roadmap, highlighting AI's promising but evolving place in theoretical sciences.

▪ **AI Association with Mathematics**

The interplay between Artificial Intelligence (AI) and mathematics is profound, as the two fields are intricately linked through their shared reliance on abstraction, logic, and structured reasoning. At its core, AI is built on mathematical foundations, with disciplines like linear algebra, probability theory, calculus, and optimization forming the backbone of its algorithms. This symbiotic relationship enables AI to enhance mathematical research while drawing on mathematical principles to advance its own capabilities. Linear algebra, for instance, underpins neural networks, where matrices and vectors represent data transformations and weights, enabling models to learn complex patterns. Probability theory drives Bayesian inference and decision-making in AI systems, crucial for applications like uncertainty modeling in statistical analysis. Optimization techniques, such as gradient descent, are central to training machine learning models, minimizing error functions to improve predictive accuracy. Conversely, AI empowers mathematical research by automating computationally intensive tasks, uncovering hidden structures in data, and accelerating problem-solving across diverse domains.

In mathematical research, AI's contributions are transformative. Automated theorem proving exemplifies this synergy, with systems like Lean and Coq leveraging machine learning to generate and verify proofs for complex theorems in algebra and geometry. These systems rely on formal logic, a mathematical construct, to ensure correctness while using AI to predict proof steps, reducing human effort. For example, AI can explore vast search spaces to identify viable proof paths, a task that scales exponentially in complexity without computational aid. In optimization, AI enhances algorithms for problems like the traveling salesman problem or scheduling, using reinforcement learning to find near-optimal solutions efficiently. Mathematical

constructs like graph theory and combinatorics guide these algorithms, while AI's ability to iterate and learn refines their performance. Data-driven mathematics is another key area, where AI analyzes large datasets to uncover conjectures in number theory or graph theory. Neural networks, grounded in linear algebraic operations, identify patterns that lead to novel hypotheses, such as new properties of prime numbers or graph connectivity.

AI's pattern recognition capabilities, rooted in statistical mathematics, enable discoveries in fields like number theory, where analyzing integer sequences can reveal unexpected relationships. For instance, AI models trained on sequence databases have proposed conjectures about prime gaps, later verified by mathematicians. In applied mathematics, AI enhances simulations in areas like fluid dynamics, using partial differential equations to predict outcomes from incomplete data. Symbolic computation tools, such as Mathematica, integrate AI to solve complex differential equations, relying on mathematical formalisms to ensure accuracy. These applications highlight how AI leverages mathematical structures to push boundaries in research, from theoretical explorations to practical problem-solving.

The association also extends to AI's ability to bridge pure and applied mathematics. In pure mathematics, AI aids in exploring abstract structures, such as topological invariants, by applying machine learning to high-dimensional data. In applied domains, AI optimizes real-world systems, like coding theory for error-correcting codes, using mathematical optimization principles. This dual role underscores AI's versatility, driven by its mathematical underpinnings. However, the relationship is not without challenges. AI's reliance on large datasets can be a limitation in pure mathematics, where data may be sparse or abstract. Additionally, the "black box" nature of many AI models, particularly neural networks, raises interpretability issues, as their reasoning processes are not always aligned with mathematical rigor. Despite these hurdles, the mathematical foundation of AI ensures its continued relevance, enabling iterative improvements through techniques like hybrid symbolic-neural systems.

This association is further strengthened by AI's ability to augment human intuition. By automating routine calculations and exploring vast combinatorial spaces, AI allows mathematicians to focus on creative and conceptual tasks. For example, in combinatorics, AI can generate candidate solutions for complex designs, which mathematicians then refine. The mathematical rigor embedded in AI algorithms ensures reliability, while their adaptability fosters innovation. As AI evolves, its integration with mathematics will deepen, driven by advancements in computational power and algorithmic design. This partnership not only accelerates discoveries but also redefines the boundaries of mathematical inquiry, making AI an indispensable ally in exploring the infinite landscape of mathematics.

▪ Application of AI in Mathematical Research

Artificial Intelligence (AI) is revolutionizing mathematical research by introducing powerful tools to tackle complex problems across various domains. One key application is **automated theorem proving**, where AI systems like Lean and Coq use machine learning to generate and verify proofs for intricate theorems in algebra, geometry, and logic. For instance, AlphaGeometry (2024) combines natural language processing and symbolic reasoning to solve Euclidean geometry problems at a human-expert level, streamlining proof development. **Optimization** is another critical area, where AI employs reinforcement learning to enhance algorithms for combinatorial problems, such as the traveling salesman problem, achieving near-optimal solutions faster than classical methods. In **data-driven mathematics**, AI analyzes vast datasets to uncover novel conjectures, particularly in number theory and graph theory. DeepMind's 2023 work on integer sequences identified new patterns in prime number distributions, sparking fresh research avenues. **Symbolic computation** benefits from AI integration in tools like Mathematica, which simplifies complex symbolic expressions and solves differential equations efficiently, aiding applied mathematics. Additionally, AI enhances **mathematical modeling** in fields like fluid dynamics, predicting outcomes from partial data using neural networks trained on equations like Navier-Stokes. Recent examples include AI-assisted combinatorics (2022), where neural networks optimized error-correcting codes, improving efficiency in coding theory by 20%. AI also supports problem-posing, with generative models creating novel mathematical challenges, though often lacking research-grade depth. These applications leverage AI's ability to process large datasets, automate repetitive tasks, and identify patterns, significantly accelerating research. By bridging theoretical and applied mathematics, AI enables discoveries that were previously computationally infeasible, transforming how mathematicians approach problem-solving and hypothesis generation.

▪ Challenges

Despite its transformative potential, integrating AI into mathematical research faces significant hurdles. **Interpretability** remains a major issue, as neural networks often produce “black box” results, obscuring the reasoning behind their outputs, which conflicts with mathematics' emphasis on transparent logic. For example, AI-generated proofs may be correct but lack human-readable explanations, complicating validation. **Data dependency** poses another challenge, as AI models require large, high-quality datasets, which are often scarce in pure mathematics domains like topology, where abstract structures dominate. **Computational cost** is a barrier, with training complex models demanding substantial resources, limiting accessibility for smaller research groups. For instance, DeepMind's number theory models (2023) required extensive computational power, raising scalability concerns. **Ethical concerns** arise from

overreliance on AI, potentially diminishing human intuition and creativity in mathematical discovery, which could lead to a loss of authenticity in results. Additionally, AI's **limited scope** restricts its impact, as current applications excel in specific areas like algebra and geometry but struggle in abstract fields like category theory due to their complexity and lack of structured data. Ensuring AI aligns with mathematical rigor while addressing these challenges requires ongoing innovation in model design and ethical frameworks.

▪ Conclusion

Artificial Intelligence (AI) is revolutionizing mathematical research by introducing unprecedented capabilities in theorem proving, optimization, and data-driven discovery. Systems like AlphaGeometry, which solves complex geometry problems at a human-expert level, and DeepMind's AI, which uncovers novel conjectures in number theory, exemplify AI's transformative impact. These advancements, supported by machine learning and symbolic computation, enable mathematicians to tackle computationally intensive problems, automate repetitive tasks, and explore new hypotheses with remarkable efficiency. AI's ability to analyze vast datasets and optimize algorithms has accelerated progress in fields like combinatorics and fluid dynamics, bridging the gap between theoretical and applied mathematics. However, challenges such as the lack of interpretability in neural networks, high computational costs, and data dependency limit AI's applicability, particularly in abstract domains like topology. Ethical concerns about overreliance on AI also raise questions about preserving human intuition and authenticity in mathematical discovery. Despite these hurdles, the future of AI in mathematics is promising, with potential advancements in hybrid systems combining symbolic reasoning and neural networks to enhance transparency and generality. Collaborative AI platforms, such as open-source tools like Lean and Coq, can foster global research efforts, while ethical frameworks will ensure responsible integration. By addressing current limitations, AI can evolve into an indispensable partner, augmenting human creativity rather than replacing it. This synergy will drive innovation, enabling mathematicians to explore uncharted territories and solve problems previously deemed intractable. As AI continues to evolve, its role in mathematical research will expand, redefining the boundaries of the discipline and paving the way for groundbreaking discoveries that blend computational power with human insight.

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