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The Contemporary Relevance of Al-Farabi's Musical Theory in Interdisciplinary Studies and the Malaysian Educational Context

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Abstract

This paper examines Al-Farabi's music theory and explores its relevance in interdisciplinary education, particularly within the Malaysian context. The objectives focus on analyzing his philosophical and scientific perspectives on music and proposing ways to incorporate these principles into modern educational practices. This paper adopts a qualitative, literature-analysis research design based on historical and philosophical documents and evidence. It draws on historical texts, scholarly interpretations, and curriculum analyses, emphasizing Al-Farabi's integration of cosmological, psychological, mathematical and pedagogical dimenisons of music. Findings reveal that his holistic approach positions music as a tool for cognitive development, emotional regulation, ethical refinement, and cultural identity. The paper also demonstrates practical applications, including connecting musical structures to mathematical foundations, supporting emotional well-being through music, and incorporating local musical traditions into the curriculum. The conclusion advocates for integrating Al-Farabi's theories into the Malaysian curriculum to promote interdisciplinary learning, cultural appreciation, and holistic development, demonstrating the timeless relevance of his ideas in contemporary education.

Keywords: *Al-Farabi, music theory, holistic development, interdisciplinary approach, Malaysian education*

INTRODUCTION

The integration of music and the arts represents one of the most influential developments in contemporary education (Escala et al., 2024; Li & Sun, 2023). Music, as reconceptualized by Small (1998), refers to an active practice, or "musicking" (p. 9) in which people engage with sound through performing, listening, composing, and sharing within social and cultural contexts. The arts more broadly, according to scholars like Eisner (2002), consist of human creative expressions, including visual arts, drama, dance, and music, that nurture imagination, critical thinking, and emotional growth. However, music and the arts remain underutilized in many educational curricula (Murphy, 2023). Fragmentation of disciplines in schools often leads to compartmentalized learning (Carla et al., 2017), where students fail to see the natural connections among philosophy, science, mathematics, and culture (Abedin et al., 2017). This disconnection limits holistic learning and reduces opportunities for students to develop creative, reflective, and morally grounded capacities. In Malaysia, for example, current curricula emphasize technical and assessment-driven outcomes, which can marginalize arts-based learning and interdisciplinary approaches (Gani & Halim, 2024).

Historical and philosophical perspectives offer conceptual tools to address these challenges. Classical Islamic thinkers, in particular, developed integrative frameworks that connected music, mathematics, ethics, and human psychology (Elzamzamy et al., 2024; Granot & Shair, 2019). These frameworks are relevant today, as they provide a coherent rationale for holistic education and interdisciplinary integration (Firdaus et al., 2020). Music, in this context, is more than an aesthetic practice; it functions as a medium for ethical formation, emotional regulation, and cognitive development (Tercan, 2020). The psychological and mathematical dimensions of music highlight its potential to enhance analytical reasoning, pattern recognition, and emotional balance in learners (Maarif et al., 2018).

Among these thinkers, Al-Farabi (c. 873–950 CE) stands out as a philosopher, scientist, and music theorist whose work exemplifies interdisciplinary integration (Tercan, 2020). He connected philosophical reasoning with scientific and artistic knowledge, framing music as a tool for intellectual, emotional, and ethical cultivation (Islamov 2021; Rauf et al., 2013). Al-Farabi's approach contrasts with modern compartmentalized models, which often treat arts education as peripheral. Studying his thought helps educators see how music can connect different areas of knowledge, which will nurture both students' thinking and emotional growth.

Looking back at Al-Farabi's work allows us to see how music possesses a lasting ability to connect people across cultures and fields of knowledge. This paper therefore adopts a historical and philosophical analytical approach to examine Al-Farabi's philosophical, scientific, and pedagogical perspectives on music, analyze the interdisciplinary dimensions embedded in his work, including cosmological, psychological, mathematical, and cultural elements (Maarif et al., 2018; Nurysheva & Tercan, 2021), and evaluate their relevance to contemporary Malaysian education. It also proposes practical educational applications that honor both Islamic heritage and local musical traditions such as *gamelan* and *dikir barat* (Abdul Rahman, 2025; Fitriah et al., 2025; Wong & Augustine, 2017). This paper positions Al-Farabi's thought as a meaningful conceptual resource for promoting interdisciplinary learning, emotional well-being, and culturally responsive pedagogy. It explicitly connects his philosophical ideas to holistic educational outcomes, showing how they can guide teaching and learning in practice.

OBJECTIVES OF THE PAPER

The objectives of this paper are to examine Al-Farabi's philosophical, scientific, and pedagogical perspectives on music, analyze the interdisciplinary dimensions embedded in his music theory, including its cosmological, psychological, mathematical, and cultural elements, and explore how these principles can be meaningfully integrated into Malaysia's contemporary education system. The paper further aims to evaluate the relevance of Al-Farabi's holistic understanding of music for cognitive development, emotional regulation, ethical refinement, and cultural identity, and to propose educational applications that support creative, multicultural, and interdisciplinary learning. A qualitative analysis approach, grounded in literature analysis and historical textual interpretation, is well suited to these goals because the paper focuses on conceptual inquiry, the interpretation of classical sources, and the synthesis of scholarly perspectives. This approach allows for descriptive and interpretive inquiry, making it possible to examine Al-Farabi's ideas and consider their potential adaptation within modern pedagogical contexts.

METHODOLOGY

This paper adopts a qualitative, literature-based analytical approach grounded in historical and philosophical sources. It focuses on examining and interpreting primary texts by Al-Farabi alongside relevant secondary scholarly works. The analysis integrates philological close reading, historical contextualization, and thematic synthesis to reconstruct Al-Farabi's philosophical and scientific perspectives on music and to explore their relevance for interdisciplinary education in Malaysia. This approach is appropriate because the paper addresses conceptual meanings, intellectual traditions, and interpretive frameworks embedded in classical texts rather than measurable variables. The interpretive nature of qualitative textual analysis enables a deep and context-sensitive understanding of Al-Farabi's ideas and facilitates their potential application within contemporary educational discourse.

DATA SOURCES AND DATA ANALYSIS

Data Sources

Sources of data for this paper consist primarily of Al-Farabi's treatises, books, essays, extant manuscripts, and reliable translations, supplemented by peer-reviewed secondary literature such as monographs, journal articles, book chapters, and historical analyses, as well as additional historical sources that help situate his ideas within their broader intellectual and cultural context. Data collection follows an iterative strategy in which initial readings of secondary works may reveal further primary sources, prompting additional searches in archives or digital manuscript repositories; all adjustments to search terms, source repositories, and inclusion criteria are systematically recorded in an audit trail. Engagement with the material is intensive and document-centered, with each primary text read closely, annotated, and examined in relation to other writings, while archival or manuscript consultation and comparison across translations are carried out when necessary to ensure accuracy and depth of interpretation.

Data Analysis

Data analysis proceeded through four interconnected stages. First, close textual and interpretive analysis was applied to primary texts to identify key concepts, philosophical arguments, technical musical classifications and references to education. Second, thematic coding was conducted on excerpts from primary and secondary works to derive recurring themes such as cognitive development, emotional regulation, cultural formation, mathematical structure and interdisciplinary learning. Codes were refined iteratively and organised into higher-order categories. Third, comparative and contextual analysis examined Al-Farabi's ideas across multiple works and situated them within the broader scientific, cosmological and pedagogical frameworks of his era. Finally, a synthesising stage integrated insights across all sources to develop a coherent interpretation of Al-Farabi's music theory and its potential application within Malaysia's multicultural and interdisciplinary educational landscape. The analysis was supported by systematic note-taking, memo writing and documentation of interpretive decisions.

FINDINGS

The findings of this paper are organised around key thematic dimensions of Al-Farabi's thought. It first outlines his biographical background, before analysing his theory of music in terms of its philosophical principles and practical applications. Subsequently, the paper delineates the cosmological, psychological, mathematical, and pedagogical dimensions of his music theory, demonstrating the depth and integrative nature of his intellectual contributions.

The Biography of Al-Farabi

Al-Farabi was one of the influential figures in the history of Islamic thought, known for his interdisciplinary scholarship that integrated philosophy, science, and the arts. He was born around 872 CE in the city of Farab, located in modern-day Kazakhstan. Al-Farabi's early education reflected the rich intellectual traditions of the Islamic Golden Age (Islamov, 2021). He later moved to Baghdad, a thriving center of knowledge, where he studied under prominent scholars such as Abu Bishr Matta ibnu Yunus and immersed himself in Greek philosophy, particularly the works of Aristotle and Plato (Rauf et al., 2013). Al-Farabi, known as the Second Master, provides insights that can guide scholars in understanding the principles underlying his philosophical thought and political works. Al-Farabi's philosophy, especially his extensive analyses of individual works by Plato and Aristotle, established his reputation as the greatest philosophical authority next to Aristotle. However, scholars have critiqued Al-Farabi for his perceived dependence on Greek philosophical sources. Richard Walzer, in his extensive commentary on al-Madīnah al-Fāḍilah (The Virtuous City), sought to trace Al-Farabi's ideas to specific Greek predecessors, often hypothesizing lost or obscure works (Mahdi, 1990). Critics argue that this approach overemphasizes Greek influence, distracts from Al-Farabi's original contributions, and underestimates the impact of the Islamic context in which he wrote. Later commentators like Al-Ghazali (2000/1095) in his *Tahāfut Al-Falāsifah* (Incoherence of the Philosophers), challenged the integration of Greek philosophy into Islamic theology.

Al-Farabi stood as an Islamic scholar who systematically explored the theory and principles of music, as his work has significantly influenced the development of music music theory within the Islamic intellectual tradition, informing subsequent musical thought in medieval Islamic cultures. (Tercan, 2020). It is widely believed by music researchers that Al-Farabi's approach to philosophy and music's truth knowledge is inspired by Ancient Greek musical thought, particularly the work of Pythagoras and Aristoxenus, whose ideas about intervals, scales, and the scientific basis of music were incorporated and reinterpreted in his *Kitāb al-Mūsīqā al-Kabīr*. His idea of music, which sheds light on future music and is a reference, has not lost its importance. Having processed the science of music within the framework of universal laws, Al-Farabi placed music on a scientific and philosophical basis. We can see traces of music's thoughts on the interaction of music on the human mind, as well as studies on the knowledge of functionality between the feature, the heart, the brain and other organs. Al-Farabi's writings on music theory made a significant contribution to the ideas of musics in the Islamic geography and have long served as a main reference (Al-Farabi, 1968, 1969, 1998).

His masterpiece, *Kitāb al-mūsīqī al-kabīr* (The Great Book of Music), stands out as one of the most comprehensive works on music theory from the medieval Islamic world (Al-Farabi, 1998). It includes the philosophy of music, relationship between language and music, musical instruments details, melody, rhythm and vocal intonation (Firdaus et al., 2020). This work demonstrates Al-Farabi's belief in the interdependence of music with cosmology, mathematics and human psychology. He viewed music not merely as an art form but as a science capable of revealing deeper truths about the universe and the human condition (Khalaf Allah, 2020).

Al-Farabi's view of music combines precise theoretical analysis with philosophical insight (Al-Farabi, 1998). He then emphasized the mathematical foundations of musical harmony, yet he expanded these ideas by incorporating insights from Islamic cosmology and ethics (Maarif et al., 2018). His theories encompassed the mathematical principles governing musical intervals, the emotional and psychological effects of melodies, and the pedagogical methods for teaching music. Strong-Wilson et al. (2020) emphasized that Al-Farabi's integration of these diverse elements marked a significant advancement in the field, influencing subsequent generations of scholars in both the Islamic and Western worlds.

The relevance of Al-Farabi's work extends far beyond his era. In the modern context, his theories offer valuable insights into the interdisciplinary nature of music and its role in education, therapy, and cultural preservation. The universality of his ideas has inspired scholars across cultures, and his emphasis on music's ethical and emotional dimensions aligns with contemporary efforts to use music for societal well-being (Rauf et al., 2013). However, it is important to acknowledge that, historically, music was a controversial subject within Islamic thought, with figures such as Al-Ghazali questioning its moral and theological permissibility (Al-Ghazālī, 2000/1095, 1982). Despite these debates, Al-Farabi's principles provide a framework for integrating music thoughtfully into educational and cultural programs, particularly in contexts like Malaysia, where diverse musical traditions can benefit from a balance between scientific, philosophical, and ethical considerations.

Al-Farabi's Theory of Music: Philosophical Principles

Al-Farabi's theory of music, as presented in his *Kitāb al-mūsīqī al-kabīr (*The Great Book of Music*),* is a comprehensive examination of the art and science of music, an interpretation supported by modern scholars such as Nurysheva and Tercan (2021). He defined music as both a theoretical discipline and a practical art, emphasizing its dual role in intellectual exploration and emotional expression. Influenced by Greek philosophers like Pythagoras, Plato, and Aristoxenus (Maarif et al., 2018), Al-Farabi regarded music not merely as an aesthetic or entertainment activity, but as a reflection of cosmic order, an audible manifestation of the harmony that pervades the universe. He viewed music as a reflection of cosmic harmony and a tool for achieving emotional and spiritual balance. In his philosophical system, the principles governing music mirror the universal laws, and listening to or performing music cultivates moral, emotional, and spiritual refinement in individuals. Alignment of the soul with these harmonies enhance inner balance, self-discipline, and ethical sensibilities (Carr, 2006).

This philosophical understanding of music directly connects to his utopian vision in *Al-Madina al-Fadila* (The Virtuous City), where the ideal society is structured to promote the virtuous development of citizens (Al-Farabi, 2012). Just as music harmonizes the soul, the social and political institutions of the Virtuous City are designed to harmonize human behavior with reason and virtue. Music thus becomes a microcosm of Al-Farabi's broader ethical and political philosophy. The cultivation of virtue in the individual through music parallels the cultivation of justice, wisdom, and happiness in society as a whole. In this way, the ethical and spiritual function of music supports the moral architecture of the ideal city, helping citizens achieve personal virtue and, collectively, societal harmony. Music serves as both a tool of education and a symbol of cosmic and social order, bridging the individual's emotional life with the ethical structure of the community.

In *The Republic*, Plato (1943) explicitly emphasizes his formative power of music, arguing that musical training is a more potent instrument than any other because rhythm and harmony find their way into the inward places of the soul. For Plato, musical education was not merely aesthetic but ethical, enhancing inner balance, gentleness, and moral discipline through orderly patterns and harmonious structures. In *Falsafah Aristutalis* (Philosophy of Aristotle), Al-Fārābī (1969) extends the Platonic framework by integrating it with Islamic philosophical and ethical principles, positioning music as a major component of education, moral refinement, and cultural transmission. Situating Al-Farabi within the broader Islamic philosophical tradition is challenging, as his harmonization of Plato and Aristotle does not fully conform to the later historiographical views of Islamic philosophy that potray it as a seamless blend of Greek and Islamic doctrines. While Plato emphasizes music's ethical power within a Greek framework, Al-Farabi adapts this concept to reconcile philosophical insights with Islamic moral and cultural principles.

Al-Farabi's Theory of Music: Practical and Technical Applications

Building upon these philosophical foundations, Al-Farabi elaborated detailed technical and practical aspects of music. The main aspects of Al-Farabi's theory include his analysis of music, particularly his elaboration on the concept of *maqam* (plural: *maqamat*) system, explaining how different arrangements of tones evoke specific emotions. *Maqam* is a melodic material used in Arabic music that has a lot of melodical details such as unequal and microtonal intervals, and special pitches (Yöre, 2012). His mathematical precision in discussing intervals and tetrachords demonstrates his commitment to merging science with art. Nicholson (2021) stated in his study of instruments, Al-Farabi focused on the *oud*, providing detailed guidance on its tuning and performance.

Al-Farabi further divided music into two categories: theoretical and practical (Nurysheva & Tercan, 2021). He described practical music as the application of sound principles using various musical instruments. In contrast, theoretical music focuses on the concepts of composition and the artistic process involved in creating music. He classified musical instruments by their sound production methods, reinforcing their practical importance in realizing theoretical concepts. Through these contributions, Al-Farabi linked the theoretical understanding of music with its practical applications, enriching both the study and practice of music.

Al-Farabi also explored the psychological and therapeutic effects of music, asserting its ability to influence human emotions and behaviors (Nurysheva & Tercan, 2021; Yuldashev, 2024). Music, through its intricate structure and the emotional qualities of different sounds, can evoke a wide range of feelings and states of mind. He drew on the Greek concept of *ethos*, arguing that specific modes can inspire courage, calm anxiety, or restore emotional balance. This position closely parallels the views articulated by Plato and Aristotle, who maintained that music possesses an intrinsic moral and spiritual force capable of cultivating harmony and order within the soul (Whitfield, 2010).

Al-Farabi's theory of music is characterized by a systematic approach that integrates philosophy, mathematics, cosmology, psychology, and pedagogy.

Cosmological Dimension

Al-Farabi believed that the universe itself is a harmonious system, governed by mathematical and musical principles. He saw music as a reflection of this cosmic order, with musical intervals mirroring the celestial movements and harmonies of the spheres. Al-Farabi, like many ancient Greek philosophers, believed in the "Harmony of the Spheres". This concept suggests that the planets and stars emit sounds as they orbit around the Earth, creating a celestial symphony (Farmer & George, 1925). Unlike a literal interpretation of planets producing audible sounds, he understood this harmony as a symbol of divine order, reflecting the wisdom of God and influencing the human soul indirectly (Al-Farabi, 1964). In Islamic thought, this aligns with the belief that creation reflects divine order: the cosmos operates according to God's laws, and its harmony points to His perfection (Sūrah al-Mulk, 67: 3–4). Some modern scholars, such as Nurysheva and Tercan (2021), interpret his work as associating different musical notes with the four elements which are earth, water, air, and fire. This idea is not explicitly stated in his works but it aligns with Islamic philosophical and medical traditions that emphasize harmony between the universe and human nature (Syeed, 2022).

Psychological Impact

Al-Farabi explored the emotional and spiritual dimensions of music, emphasizing its capacity to influence human behavior and emotions. He categorized melodies according to their effects, such as joy, sorrow, or contemplation, and linked these effects to specific societal and individual needs. His discussion on the Pythagorean concept of the "Harmony of the Spheres" and its connection to music therapy is noted in *Kitab al-Siyasa* (Al-Farabi, 1964). He stated, "*When earthly music comes closest to the harmony of the celestial spheres, it profoundly affects the human soul, making it joyful and strong*" (Farmer & George, 1925). This implies that music can uplift the spirit, enhance emotional well-being, and even increase vitality (Nurysheva & Tercan, 2021). Al-Farabi's belief that music could be used therapeutically resonates with modern applications of music in mental health practices (Al-Farabi, 1998). Aristotle also proposed that music can serve as a 'spiritual remedy' for 'mental illnesses', suggesting that music can address emotional and psychological imbalances (Li, 2025). Al-Farabi's classification of the psychological impact of music, especially its ability to evoke and balance emotions, aligns with principles seen in contemporary music therapy.

Mathematical Dimension

In his work, *Iḥsāʾ al-Ulūm* (*The Enumeration of the Sciences*), Al-Farabi (1968), who recognized the significant role of music, classified it as a branch of mathematics, placing it fifth in the hierarchy of sciences (Tercan, 2020). Al-Farabi applied mathematical principles to analyze musical intervals and scales. He developed precise methods for tuning instruments and understanding the relationships between notes. His contributions to the theory of intervals were rooted in Pythagorean traditions but extended to accommodate new cultural contexts within the Islamic world (Maarif et al., 2018). For example, his work detailed the construction of the *maqamat*, demonstrating his synthesis of mathematical precision and artistic sensibility. His understanding of harmonics also provided a theoretical basis that later influenced Western musical developments.

Al-Farabi described the nature of musical sounds as a combination of quantitative and qualitative properties, emphasizing that pitch (frequency) and timbre (harmonics) are inseparable in producing meaningful musical experiences. He argued that different musical modes and rhythms could evoke distinct emotions, showing an early understanding of the relationship between mathematical structure and human affect (Al-Farabi, 1998). He further explained the relationships between musical sounds could be expressed mathematically through ratios of frequencies, which determined intervals and tuning systems and ensured harmony in performance. This mathematical approach not only reinforced the logical structure of music but also offered educators a framework to support students' cognitive development in both musical and mathematical domains.

Pedagogical Dimension

In music education, Al-Farabi stressed the importance of integrating theoretical knowledge with practical skills. He advocated for a balanced curriculum that nurtures creativity and critical thinking through music. He emphasized the ability to discriminate, reason deductively, and understand the relationships between different pieces of information (Al-Farabi, 1987). Al-Farabi insisted that the study of music should not only focus on performance but also include its philosophical and ethical dimensions, ensuring that learners develop a holistic understanding of the art (Rauf et al., 2013). His pedagogical insights are particularly relevant today, as modern education strives to bridge the gap between academic theory and practical application.

DISCUSSION

Relevance of Al-Farabi's Theory of Music in Interdisciplinary Approach

Al Farabi's music theory has influenced cultures and eras throughout history (Al-Farabi, 1987). His seminal work, *Kitāb al-Mūsīqā al-Kabīr* (The Great Book of Music), was translated into Hebrew around the 12th century, and ideas from it were rendered into Latin and circulated in medieval European scholarly writings, enabling European thinkers to engage with and adapt his concepts on musical theory, intervals, and classification (Naroditskaya, 2009). Central to his approach is the understanding of music as a causal system, where the human mind naturally seeks to comprehend the effects of auditory stimuli on cognition and behavior (Nurysheva & Tercan, 2022). Al-Farabi emphasized that human cognition acquires information through three forces: the senses, imagination, and thought, which together mediate the psychological and emotional impact of music (Nurysheva & Tercan, 2022).

Al-Farabi's work exemplifies an interdisciplinary approach, defined as the integration of knowledge, methods, and perspectives from multiple disciplines to address complex issues (Repko & Szostak, 2025). His synthesis of philosophy, mathematics, psychology, and cultural insights demonstrates this approach, highlighting how music theory can simultaneously inform cognitive, emotional, and cultural understanding (Al-Farabi, 1987). Al-Farabi's emphasis on the universality of music aligns with contemporary efforts to use music as a bridge between cultures. His insights into the psychological effects of music have also found relevance in music therapy and cognitive studies. For instance, his works have inspired modern scholars to explore the relationship between music and neural pathways, highlighting its impact on memory, emotions, and behavior (Nurysheva & Tercan, 2021). Additionally, Al-Farabi's interdisciplinary approach has influenced modern fields such as ethnomusicology, where the study of music is deeply connected to cultural anthropology and sociology, as it has adopted anthropological aims, presumptions, and practices (Reyes, 2012). Despite this rich legacy, little attention has been given to the systematic integration of these insights into music curricula that combine cognitive, emotional, and cultural learning outcomes.

Al-Farabi's focus on the interdisciplinary nature of music corresponds closely with educational goals that aim to create well-rounded learners. In Western academia, music education has increasingly recognized the importance of integrating theoretical knowledge with practical skills, a principle that Al-Farabi advocated over a millennium ago (Schippers, 2010). However, few studies have explored how his interdisciplinary perspectives could be systematically applied in contemporary curricula. In the Malaysian context, Sun and Wong (2024) noted that Malaysian primary school teachers demonstrated a solid understanding of music education and popular music, and they asserted that music education could contribute to students' overall development. However, there has been limited focus on connecting Al-Farabi's theoretical insights, including his detailed analysis of musical scales, intervals, and mathematical principles, with practical teaching approaches that enhance both cognitive and creative skills (Nicholson, 2021).

In addition, Al-Farabi's insights into the psychological effects of music connect to modern pedagogical strategies using music to enhance cognitive and emotional development. This connection is evident because Al-Farabi theorized that different melodies and musical modes influence the emotions and mental states of listeners, providing a framework for understanding how music can shape cognition and emotion (Al-Farabi, 1987). Aligned with this view, studies have shown that music can improve memory retention, encourage emotional intelligence, and stimulate creativity (Bokiev et al., 2018; Boustani & Al Abdwani, 2023; Waterhouse, 2006). Al-Farabi's categorization of melodies based on their emotional impacts offers a structured way to use music as a tool for psychological well-being and effective learning. For instance, in classrooms where music is integrated into lessons, students often show improved focus and reduced anxiety (Jiang, 2024), outcomes that align with Al-Farabi's views on the therapeutic potential of music.

In higher education, particularly in music conservatories and universities, Al-Farabi's theories provide a historical and philosophical context that deepens students' understanding of music as both an art and a science (Rauf et al., 2013). His works are studied alongside Western theorists such as Pythagoras and Boethius, highlighting the global connection of musical traditions (Farmer & George, 1925). While his integration of philosophical, mathematical, and psychological dimensions of music is intellectually impressive, it can be argued that some of his theoretical constructs remain abstract and may be challenging to translate directly into contemporary pedagogical practice (Korthagen, 2010). Furthermore, the balance between artistic expression and scientific rigor in his approach requires careful interpretation, as the emphasis on rational order may risk underestimating the experiential and improvisational aspects of music (Rujiter, 2023). Through his integration of philosophy, mathematics, psychology, and cultural insights, Al-Farabi's ideas encourage students to approach music from an interdisciplinary framework that promotes critical thinking and cultural appreciation (Yuldashev, 2026). Educators must critically navigate between preserving the philosophical depth of his work and adapting it to practical classroom realities (Syafitri & Mu'minin, 2024).

Application of Al-Farabi's Theory of Music in Malaysian Educational Context

Philosophical Foundation

According to Abdullah (2007), the Malaysian Ministry of Education implemented music education in primary schools in 1983, while a new secondary school music curriculum was completely developed in 1996. Malaysia, with its rich multicultural heritage, provides a conducive ground for applying Al-Farabi's music theories. Traditional Malaysian music, such as *gamelan* and *dikir barat*, embodies the integration of mathematical precision and emotional expression, principles echoed in Al-Farabi's universal principles of music that transcend cultural boundaries (Matusky & Beng, 2017). In the Malaysian context, this perspective supports a multicultural approach to music education, where diverse musical traditions can be explored and appreciated while emphasizing shared principles such as rhythm, melody, and emotional expression. As mentioned by Meddegoda (2015), the *maqam* system, which Al-Farabi elaborated upon, shares similarities with certain modal structures in traditional Malaysian music, suggesting a historical and conceptual connection. However, previous research has not addressed the systematic incorporation of Al-Farabi's music theory into Malaysian school curricula.

Application Strategies in Malaysian Schools

The study of these intricate rhythms, harmonic structures, musical tuning and scales can be incorporated into Malaysia's school curricula to reinforce students' understanding of fractions, ratios, and proportions. Research on Al-Farabi's work demonstrates that arithmetic operations such as addition, multiplication, and division can be applied to his interval ratios, providing students with practical, hands-on opportunities to connect mathematical concepts with real musical relationships (Oshanova, 2020). Malaysian teachers can design interdisciplinary lessons in which students not only learn musical modes and *maqamat* but also develop essential mathematical skills, enhancing numeracy through the inherent structure and patterns of sound by integrating Al-Farabi's theory into music education (Nurysheva & Tercan, 2021).

The use of music therapy, informed by Al-Farabi's insights, is another area where his theories could be effectively applied in Malaysia. Programs designed for students with special needs or those dealing with stress and anxiety could benefit from his detailed exploration of music's psychological effects. According to Lonsdale and Kuan Boon (2016), music therapy techniques can incorporate exercises and movement that promote relaxation, improve posture, and enhance physical well-being, thereby mitigating the risk of musculoskeletal disorders. Music therapists can employ techniques like imagery, relaxation exercises, and cognitive-behavioral therapy to help musicians manage performance anxiety and build resilience. Collaboration between educators, psychologists, and musicians could lead to innovative applications of his ideas in both mainstream and special education settings.

Additionally, Al-Farabi's ideas on the shared mathematical and emotional foundations of music across cultures could serve as a foundation for cross-cultural music programs that highlight Malaysia's multicultural identity. This approach would provide students with a deeper appreciation of their cultural heritage while also connecting them to universal principles of music (Dockan et al., 2025). Recognizing Malaysia's multicultural landscape, a main feature of the Malaysian music education system is the emphasis on developing culturally diverse music programs (Kwan Yie & Chiu, 2017). One of the four standards outlined in the Integrated Curriculum for Primary Schools mandates that students appreciate the various forms of Malaysian music and culture (Wong et al., 2016). This standard focuses on multicultural music education, while the remaining standards concentrate on other aspects of music, primarily rooted in Western classical traditions. Existing studies rarely examine the integration of Al-Farabi's interdisciplinary music principles into multicultural music education programs. The goal of incorporating multicultural music is to expose children to the diverse musical and cultural expressions of Malaysia's various ethnic groups, facilitating an understanding of their unique characteristics and promoting mutual respect and tolerance among these cultures.

In the Malaysian educational setting, music is increasingly recognized as a tool for enhancing unity and creativity among diverse communities (Jamaludin et al., 2024). Al-Farabi's emphasis on the scientific and emotional aspects of music could enrich the national curriculum, promoting a deeper appreciation of both traditional and contemporary forms of music. Furthermore, his philosophical approach to music education aligns with Malaysia's aspirations to cultivate holistic and culturally rooted learners (Tan & Li, 2005). Wong et al. (2016) affirmed that music classes that emphasize these dimensions could help students develop empathy and mutual respect, key values in Malaysia's multicultural society. For instance, integrating Al-Farabi's theories into the teaching of Malaysian instruments such as the sape and rebab could deepen students' understanding of their cultural significance and theoretical foundations (Dawe, 2001).

Furthermore, Al-Farabi's pedagogical emphasis on integrating theory and practice aligns with Malaysia's efforts to modernize its educational curriculum. For example, music programs in Malaysian schools often include both traditional and contemporary elements, but the theoretical aspects are sometimes overlooked. According to Bokiev and Ismail (2021), nearly all Malaysian ESL teachers reported that one of the main challenges faced when using music and songs in their instruction was identifying the songs that would serve the purpose of the lesson, match the proficiency level of their students and be appropriate for classroom use. Al-Farabi's structured approach to scales, modes, and the psychological effects of music can help educators to create more comprehensive programs that cater to diverse learning needs.

Overall, mandatory music education for Malaysian school students can be justified as a component of holistic education grounded in both philosophy and empirical research. From Al-Farabi's perspective, music functions as a disciplined science that cultivates intellectual reasoning, emotional balance, and ethical refinement (Meddegoda, 2015; Syafitri & Mu'minin, 2024). Aligned with this view, contemporary studies indicate that structured music education enhances cognitive development, including memory retention and creativity, while supporting emotional intelligence and self-regulation (Bokiev et al., 2018; Boustani & Al Abdwani, 2023; Waterhouse, 2006). Within Malaysia's multicultural context, research on culturally relevant music pedagogy further shows that music education promotes social interaction and intercultural understanding among diverse student groups (Dockan et al., 2025; Wong & Chiu, 2017). Collectively, these findings support the integration of Al-Farabi's interdisciplinary music philosophy into Malaysia's curriculum to enhance academic, emotional and social value while supporting educational harmony in a plural society such as Malaysia.

Challenges and Opportunities

While the potential benefits of applying Al-Farabi's music theory in education are immense, challenges remain. One significant obstacle is the limited availability of resources and expertise related to his works. Yie and Ying (2017) highlighted that the problem occurs when teachers' approaches are inadequate and unreliable, leaving students with little comprehension of the context, function, and significance of the musical examples. Translating his complex ideas into practical teaching methods requires dedicated research and training for educators. Moreover, it takes a sophisticated strategy for achieving a balance between his theories' traditional elements and the demands of modern education.

The challenges presented by implementing Al-Farabi's music theories also offer exciting opportunities for innovation. Collaboration between academic institutions, cultural organizations, and policymakers can drive the development of new curricula and teaching materials grounded in Al-Farabi's principles. In today's digital age, music education is undergoing a transformation. Online pedagogy is revolutionizing how students learn to sing, with new approaches significantly impacting vocal music instruction. These advancements not only enhance students' singing skills but also open new possibilities for the future of music education (Chang, 2022; Schiavio et al., 2021). Key trends in online pedagogy include virtual choirs and ensembles, online interactive masterclasses, digital voice analysis, online music theory training tools, and virtual reality (VR) and augmented reality (AR) experiences (Longlong & Luen, 2023). In addition, digital platforms and online courses have the potential to democratize access to Al-Farabi's theories, enabling educators and students worldwide to benefit from his insights.

In conclusion, while implementing Al-Farabi's music theory in education presents challenges, its potential benefits are significant. As we address the need for resources and expertise, and by embracing innovative approaches like online pedagogy and digital platforms, educators can unlock the transformative power of Al-Farabi's ideas. This will not only enrich music education but also enhance a deeper understanding of music's role in personal and societal development.

CONCLUSION

Al-Farabi's works in music theory and education demonstrate that music is far more than the notes we hear. It reflects life, thought, emotion, and even the universe itself. Although articulated centuries ago, his ideas remain relevant, showing how deeply music is woven into human understanding. Across cultures, Al-Farabi's theories inspire musicians, thinkers, and educators. In Malaysia, his principles offer a rich foundation for nurturing a deeper appreciation of local musical traditions, encouraging both preservation and creative growth. This philosophical inquiry affirms that education becomes more meaningful when it reflects culture, history, and human values.

Al-Farabi's influence extends well beyond music. His cosmological view, for example, presents music as a mirror of the harmony found in the universe. In Islamic thought, this aligns with the belief that creation reflects divine order: the cosmos operates according to God's laws, and its harmony points to His perfection. This idea also reflects that music not only as sound, but as something that connects human to the wider order of creation. It gives music a sense of purpose, beauty, and unity that modern educators and musicians can still appreciate. Psychologically, Al-Farabi understood that music shapes emotions and behavior. Today, his insights are being utilized in areas including music therapy, emotional development, and mental well-being. He recognized that different musical modes could influence a person's mood and character, an idea that continues to guide educators who want to support students not only academically but emotionally.

His work in mathematics also shows how carefully he studied music. Al-Farabi highlighted the deep relationship between sound and numbers by analyzing intervals, ratios, and musical structures. This mathematical foundation offers a powerful means of connecting music with logical thinking and problem-solving, an approach that aligns well with the interdisciplinary learning employed in many modern classrooms. As a teacher, Al-Farabi believed that music could build good character and sharpen the intellect. He saw music education as something that should be guided with care and purpose, combining both technical skills and moral development. His ideas suggest that education should aim to develop well rounded individuals, not just performers or exam takers.

In Malaysia, his ideas offer meaningful possibilities. They can inspire music curricula that honor both Islamic heritage and local musical traditions such as gamelan and dikir barat (Abdul Rahman, 2025; Fitriah et al., 2025; Wong & Augustine, 2017). His psychological insights can support school programs that use music to help students manage emotions and build confidence. His mathematical approach can help teachers design lessons that connect rhythm and pattern with numeracy skills. Most importantly, his holistic educational philosophy aligns with Malaysia's goal of nurturing balanced, ethical, and creative learners.

To conclude, the lasting relevance of Al-Farabi's ideas shows that ancient knowledge still has much to offer to the modern world. His works continue to inspire scholars and teachers everywhere, emphasizing that music is not only an art, but a means to cultivate the mind, nurture ethical values, and connect with cultural heritage. Integrating music into education shapes character, promotes social harmony, and deepen understanding of the world.

RECOMMENDATION

Based on the conclusion, it is proposed that Malaysia's current education system could adopt Al-Farabi's holistic educational approach to enhance interdisciplinary learning and intellectual engagement across various fields. His philosophical ideas on harmony, balance, and the integration of intellect and emotion could guide pedagogical techniques that combine multiple disciplines in meaningful ways. For instance, in subjects like philosophy, ethics, or social sciences, teachers could use case studies, debates, and reflective exercises to illustrate how the principles governing the natural world can be applied to human relationships, societies, and personal development. Incorporating Al-Farabi's ideas into mathematics and science education is another possible approach. His exploration of mathematical ratios in the context of music could be included in lessons on algebra, geometry, or physics, providing students with real-world applications of abstract concepts. His idea of knowledge as universal and interconnected supports collaborative and cross-cultural learning techniques, including international workshops, joint research projects, and global exchange programs, which represent an effective means of shared intellectual traditions. Finally, public awareness campaigns could play a significant role in promoting Al-Farabi's intellectual legacy to a wider audience. These campaigns might include academic conferences, exhibitions, documentaries, and publications that highlight the historical connection between Islamic and Southeast Asian intellectual traditions. Integrating Al-Farabi's ideas into the broader educational framework and public discourse would not only preserve his contributions but also ensure that his teachings continue to inspire future generations.

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Exploring the Role of Generative Artificial Intelligence in Transforming Mathematics Teaching and Learning: A Systematic Mapping Review

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ABSTRACT

Recent advances in generative artificial intelligence (GenAI), in particular, large language models (ChatGPT, Gemini, Claude, etc.) have reshaped digital innovation in education. While prior studies have examined specific classroom applications, few studies to date have provided a comprehensive mapping of the empirical research landscape across tools, educational levels, mathematical domains, research designs, and geographical distribution, leaving structural patterns and research gaps insufficiently synthesized. This paper presents a systematic mapping review on the integration of GenAI in mathematics education. Using the PRISMA framework, studies published between 2022 and 2025 (final search conducted in December 2025) were retrieved from Web of Science and Scopus, complemented by a full-text search in ScienceDirect. After screening and eligibility procedure, 30 peer-reviewed empirical articles were included for analysis. The mapping results indicate that ChatGPT is the most frequently examined tool, with research predominantly concentrated at the tertiary education level and focused largely on algebra and calculus topics. Most studies employed qualitative or mixed-method designs, and the majority were conducted in Asia and Europe, reflecting emerging but uneven global research distribution. Thematic analysis was employed to identify commonly reported pedagogical applications, including problem-solving support, content generation, scaffolding, lesson planning, and differentiated instruction, as well as frequently reported challenges such as conceptual errors, limitations in abstract and spatial reasoning, and variability in output quality across platforms. Rather than evaluating effectiveness, this review provides an overview of research trends, identifies concentrations and gaps in the literature, and highlights directions for future empirical and theoretical work on GenAI-supported mathematics education.

Keywords
Generative artificial intelligence; Large language models; Mathematics education; Systematic mapping review; Educational technology

Introduction

The recent advancement of generative artificial intelligence (GenAI) in the current digital age has generated significant discussion within mathematics education, particularly regarding its implications for teaching, learning, and assessment (Seebut et al., 2024; Yunianto et al., 2024). In mathematics classrooms, large language models such as ChatGPT, Gemini, and Claude are increasingly explored as tools for problem-solving support, step-by-step explanation generation, and adaptive feedback (Marco & Stylianides, 2025; McGalliard & Otten, 2025; Wardat et al., 2023). Unlike earlier educational technologies that primarily automated practice, GenAI systems can generate context-sensitive explanations and multiple solution pathways, positioning them as potential cognitive partners in mathematical reasoning.

Existing empirical studies report that GenAI is used as a problem-solving assistant, content generator, and scaffolding tool, particularly in self-regulated and personalized learning contexts (Contel & Cusi, 2025; Segal & Klemer, 2025; Yunianto et al., 2024). These models operate by finding patterns in large datasets to generate human-like outputs as the textual explanations, step-by step solutions, and computational code. When guided through iterative prompting, students may refine queries, compare alternative strategies, and reflect on procedural reasoning (Seebut et al., 2024;

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Yunianto et al., 2024). However, evidence regarding these pedagogical roles remains context-dependent and fragmented across educational levels and mathematical domains (Kock et al., 2025).

Despite such possible benefits, significant limitations have been documented. GenAI outputs may include significant cognitive error in tasks, fail in abstract reasoning and have poor performance in spatial geometry, higher-order calculus, and conceptual understanding (Parra et al., 2024; Wardat et al., 2023; Marco & Stylianides, 2025). The accuracy and reliability of outputs are highly dependent on prompt quality and platform-specific characteristics, as it may affect the curriculum alignment and credibility of the knowledge generated (Stamenkova, 2025; Mani & Zargeh, 2025). Moreover, while GenAI may improve procedural fluency or provide a variety of solution strategies, this method still cannot identify misconceptions independently and instil them in reasoning, which highlights the critical role of teacher mediation, guidance, and verification (Segal & Klemer, 2025; Pavlova, 2024).

Although individual empirical studies have examined specific classroom applications of GenAI, few studies to date have systematically mapped the empirical research landscape across tools, educational levels, mathematical domains, research designs, and geographical distribution. As a result, structural patterns, research concentrations, and underexplored areas remain insufficiently synthesized. Given the rapid expansion of GenAI research since 2022, a systematic mapping review is timely to provide a structured overview of emerging trends and gaps.

Accordingly, this study presents a systematic mapping review of empirical research on GenAI in mathematics education. Rather than evaluating instructional effectiveness, this review synthesizes how the reviewed studies are distributed across GenAI platforms (e.g., ChatGPT 3.5/4.0, Gemini, Claude), educational contexts (primary to tertiary), mathematical topics, research methodologies, and geographical regions. Essentially, this study clarifies the current state of the field and outlines directions for future pedagogical and theoretical development, by identifying dominant research clusters and underrepresented areas.

Literature Review

Generative Artificial Intelligence in Mathematics Education

The literature indicates that GenAI assists students in their engagement, motivation, self-regulated learning, problem-solving processes, and conceptual understanding, while also highlighting challenges such as errors in complex tasks, variability of outputs, ethical concerns and the need for teacher mediation (McGalliard & Otten, 2025; Parra et al., 2024; Delima et al., 2024; Contel & Cusi, 2025; Walkington, 2025).

To provide a conceptual synthesis, the reviewed studies reveal four main thematic patterns in the use of GenAI in mathematics education. First, regarding cognitive and learning outcomes, studies consistently report improvements in procedural fluency, problem-solving support, and self-efficacy (Seebut et al., 2024; Wahba et al., 2024; Yunianto et al., 2024). However, methodological limitations such as small sample sizes, short-term interventions, and reliance on self-report measures constrain the generalizability of these findings (Daher & Anabousy, 2025; Sutrisno et al., 2025).

Second, teacher mediation and professional development emerge as critical factors, as GenAI cannot independently detect student misconceptions or ensure conceptual fidelity (Segal & Klemer, 2025; Pavlova, 2024; Busuttil & Calleja, 2025). Effective integration therefore requires targeted professional development, scaffolding strategies, and continuous teacher oversight.

Third, ethical and epistemic considerations are frequently highlighted, with studies noting biases, inaccuracies, and misalignment with curricula as main challenges (Walkington et al., 2025; Marco & Stylianides, 2025). Maintaining content reliability and fairness necessitates critical reflection on the ethical use of AI and structured prompt design.

Finally, tool-specific patterns and pedagogical applications indicate that ChatGPT is the most frequently investigated platform, followed by Gemini and Claude (Seebut et al., 2024; Marco & Stylianides, 2025). Pedagogical applications include scaffolding, iterative problem-solving, differentiated instruction, and adaptive feedback. While GenAI demonstrates potential as a cognitive co-agent, performance varies across mathematical domains, with weaknesses most pronounced in abstract reasoning, spatial geometry, and higher-order calculus (Parra et al., 2024; Wardat et al., 2023).

The evidence suggests a fragmented landscape: studies are concentrated in higher education and specific topics like algebra and calculus, with limited longitudinal or cross-cultural investigations. Methodological robustness is uneven, and early-stage research often emphasizes practicality over efficacy. Therefore, a systematic mapping review is necessary to synthesize patterns, identify gaps, and provide a structured overview of GenAI research in mathematics education. Table 1 provides a summary of the 30 reviewed empirical studies, including aims, design, key findings, and recommendations, illustrating both recurring patterns and critical challenges in practice.

Table 1
Summary of the Studies

No.	Studies	Aims and Design	Key Findings	Recommendations
1	McGalliard & Otten (2025)	Investigate GenAI engagement in complex mathematical reasoning through a qualitative analysis of ChatGPT and Gemini responses to three cognitively demanding secondary tasks.	GenAI can respond to demanding tasks but makes substantial errors; it demonstrates the ability to refine work through iterative prompting.	Educators should stay updated with current GenAI trends and encourage student interaction to explore concepts beyond answer-getting.
2	Marco & Stylianides (2025)	Investigate ChatGPT-4's mathematical knowledge using Plato's slave-boy experiment and interactive chat guidelines.	Defined the "Chat's ZPD" for problems solvable with user prompting; GenAI knowledge reflects both recollection and generation patterns.	Use designated prompts to help GenAI make cross-contextual connections and specify the type of knowledge required.
3	Parra et al. (2024)	Analyse the abilities of ChatGPT, Bing Chat, and Bard to provide solutions to a Spanish-language geometry competition problem.	Performance was disappointing; errors were categorized into Construction, Conceptual, and Contradiction due to lack of symbolic structure.	Use errors as educational tools to promote critical thinking and reflection on alternative solutions.
4	Wardat et al. (2023)	Examine stakeholder perspectives and user experiences through interviews and three educational scenarios.	GenAI improves task performance but lacks deep understanding of geometry and cannot correct misconceptions effectively.	Ensure secure and accountable integration of GenAI into mathematics curricula.
5	Busuttil & Calleja (2025)	Investigate secondary teacher beliefs and practices in Malta using a case study with pre- and post-PD surveys.	Teachers with discovery and connectionist philosophies view GenAI positively as a tool for active learning and exploration.	Provide ongoing professional development to help teachers integrate GenAI effectively into pedagogy.
6	Seebut et al. (2024)	Evaluate student self-efficacy after a three-phase activity combining GPT-3.5 and Google Colab to solve difference equations.	Integration significantly enhanced self-efficacy and shifted students' roles from programmers to work directors/prompt engineers.	Students must develop conceptual foundations and procedural knowledge before relying on GenAI.
7	Schorcht et al. (2025)	Explore a network of customized GPT agents functioning as a multi-professional team to modify mathematical tasks.	Balancing text generation and precision is crucial; the network enriched tasks with solution hints and actions.	Refine inter-agent communication protocols and reduce information overload in AI-modified tasks.

8	Segal & Klemer (2025)	Observe teachers interacting with Claude 2.1 to plan primary lessons using mixed-methods.	Teacher-GenAI dialogue improved all TPACK components; iterative dialogue and critical evaluation of GenAI gaps are required.	Maintain a balance between GenAI innovation and human expertise; tailor professional development to individual teacher contexts.
9	Delima et al. (2024)	Investigate the impact of ChatGPT and music on MSRL and Math Anxiety using correlational descriptive research.	GenAI use significantly enhanced MSRL; neither GenAI nor music had a significant effect on anxiety.	Use GenAI to support independent exploration; integrate music with GenAI to influence learners' dispositions and habits of mind.
10	Kock et al. (2025)	Analyse three interviews with engineering students using the Instrumental Approach to identify initial utilization schemes.	GenAI acts as a co-agent for conceptual explanation and code optimization; students developed critical attitudes toward hallucinations.	Institutions should monitor and guide students in developing sophisticated GenAI utilization schemes over time.
11	Davis (2025)	Use an instrumental approach to analyse prompt logs and synopses of four prospective teachers.	Identified three instrumentalization and five instrumentation schemes; GenAI limitations forced a shift from graphical to algebraic content.	Share iterative refinement and specificity schemes with future teachers to reduce out-of-class lesson preparation time.
12	Pavlova (2024)	Present a case study flipping the classical dialogic method using ChatGPT to stimulate student activity.	The model promotes active roles and research qualities; students initially accept results without critical reformulation.	Teach students to ask "the right questions" and detect GenAI gaps to reduce stress and enhance learning.
13	Susilawati et al. (2025)	Investigate the synergy between GenAI, RME, and gamification using a sequential explanatory mixed-methods design.	Integrated model significantly improves problem-solving (β=0.40) and motivation (β=0.35); motivation acts as a structural mediator.	Align gamification with deep thinking; implement adaptive scaffolding that preserves productive struggle.
14	Contel & Cusi (2025)	Investigate GPT-4 scaffolding of metacognition using micro/macro analysis based on the MAEAB construct.	Identified replacement vs. diagnostic schemes; GenAI tends to bypass planning and exhibits semantic limitations.	Design interventions to support critical, reflective mathematical thinking beyond replacement schemes.
15	Yunianto et al. (2024)	Use educational design research (EDR) to investigate ChatGPT assisting with GeoGebra code generation for area of circle tasks.	GenAI supported programming and debugging; its varied responses allow differentiated instruction.	Provide professional development to help students develop effective prompts and critically evaluate GenAI responses.
16	Stamenkova (2025)	Evaluate 11 LLM models solving problems from the Bulgarian National External Assessment (NEA).	Models like DeepSeek and Mistral achieved perfect accuracy but often deviated from national curricular standards.	Ensure success metrics include mathematical accuracy, methodological alignment, and culturally relevant terminology.
17	Borys et al. (2025)	Assess the effectiveness of GenAI-driven exercise generation using student	Pass rates improved; GenAI accelerates exercise creation but content requires human validation.	Prioritize process-supervised reward models to improve accuracy and

		performance data on the Compass platform.		reduce hallucinations in human-GenAI alignment.
18	Walkington et al. (2025)	Case study of 36 girls using GenAI for game design pitches involving story problems and DALL-E2 visuals.	Students identified racial and gender bias in GenAI images; ChatGPT problems often had low authenticity and mathematical errors.	Provide guidance on prompting strategies to sound like students and minimize biased or inappropriate outputs.
19	Zhuang & Zhang (2025)	Track PSMTs' perceptions of ChatGPT 4.0 and Student GPT over a semester using surveys and interviews.	Perceptions became more positive with familiarity; Student GPT was valued as a practice-based training tool.	Teacher education programs should offer structured guidance and formative feedback on prompt writing and GenAI evaluation.
20	Noster et al. (2024)	Analyse 11 teachers solving four tasks using qualitative content analysis and the KTMT model.	Teachers lacked prompting knowledge and frequently accepted erroneous GenAI outputs.	Explicitly address LLMs and prompting techniques in teacher training to ensure teachers can judge mathematical fidelity.
21	Horrocks & Shearman (2025)	Use thematic analysis of 33 educator interviews to identify core goals in the age of GenAI.	Four primary themes emerged: content mastery, mathematical thinking, communication, and appreciation.	Reframe mathematics and statistics as experimental sciences; prioritize conceptual depth over algorithms.
22	Kim et al. (2025)	Investigate PT capacities for error recognition and correction using AIM activities and AIS strategies.	PTs excelled at verifying correct problems but struggled (53.5% failure rate) to identify errors.	Provide multiple opportunities for PTs to evaluate GenAI outputs.
23	Sutrisno et al. (2025)	Investigate justification abilities of 13 students using a descriptive qualitative study on linear equations.	61.5% understood instructions; students struggled to identify GenAI reasoning errors due to weak conceptual mastery.	Strengthen conceptual understanding and critical thinking to evaluate GenAI outputs independently.
24	Yoon et al. (2024)	Develop the SIPE-AI framework through task-based interviews observing engagement with proving tasks.	Proving with GenAI involves a cyclic process shaped by students' and AI's conceptions and ethical considerations.	Encourage students to take authorship over final proofs and establish class norms for ethical GenAI use.
25	Milenković et al. (2025)	Rank o1 and o3-mini solutions against student results from the 2024 Serbian National Competition.	Both tools qualified for medals in seven of eight cases; o3-mini slightly outperformed o1-mini.	Use GenAI for strategic guidance and inspiration; maintain critical analysis of reasoning processes.
26	Xuan et al. (2025)	Comparative study examining the impact of GenAI on mathematics learning in Vietnamese private and public high schools.	GenAI improved understanding in private schools but was less effective than traditional teaching in resource-limited public schools.	Ensure contextual readiness before implementation; improve infrastructure and AI literacy; conduct longer-term studies.
27	Gurl et al. (2025)	Qualitative study examining PST reactions to mathematical and pedagogical outputs during microteaching.	PSTs were accurate on pedagogy but often accepted incorrect solutions as "different approaches."	Develop a framework to examine GenAI-generated mathematical outputs.

28	Daher & Anabousy (2025)	Study four bots in writing lessons based on Kolb's model using content analysis.	Bots succeeded in lesson writing but differed in defining teaching strategies; Perplexity used authoritative citations.	Use GenAI for co-design workshops; emphasize referencing accurate sources.
29	Wahba et al. (2024)	Evaluate the influence of ChatGPT-based learning on undergraduates using quasi-experimental pre- and post-tests.	ChatGPT-based learning significantly enhanced statistical reasoning and positive attitudes.	Motivate students to use GenAI in learning statistics and incorporate it into teaching methods.
30	Etcuban (2025)	Investigate ChatGPT's use in addressing anxiety and promoting confidence among 320 freshmen using a descriptive correlational method.	Students reported reduced algebra anxiety and increased confidence, leading to "Very Good" performance scores.	Integrate ChatGPT into algebra courses to promote practical and diverse learning settings.

Research Objectives

This study aims to map and describe existing empirical research on the integration of generative artificial intelligence (GenAI) in mathematics teaching and learning. The research objectives of this study are as follows:

1. To identify how GenAI tools are used in mathematics teaching and learning across different educational levels and mathematical topics.
2. To examine the pedagogical roles attributed to GenAI tools in mathematics education.
3. To analyse the types of research designs employed in empirical studies on GenAI in mathematics education.
4. To synthesize the benefits, challenges, and limitations of GenAI integration in mathematics teaching and learning as reported in the literature.

Research Questions

This study is guided by the following research questions:

1. How are generative artificial intelligence (GenAI) tools used in mathematics teaching and learning across different educational levels and mathematical topics?
2. What pedagogical roles are attributed to GenAI tools in mathematics education?
3. What types of research designs are employed in empirical studies on the use of GenAI in mathematics education?
4. What benefits, challenges, and limitations of GenAI integration in mathematics teaching and learning are reported in the existing literature?

Methods

The current study adopted a systematic mapping review approach to examine existing empirical research on the use of GenAI in mathematics teaching and learning. Systematic mapping reviews provide a structured overview of an emerging research field by identifying patterns, trends, and gaps in the literature, rather than synthesizing evidence of effectiveness. The analysis was conducted in accordance with the PRISMA (Preferred Reporting Items to Systematic Reviews and Meta-Analyses) framework, according to which the high-quality, transparent, and reproducible reviews should be conducted (Moher et al., 2009; Page et al., 2021). PRISMA involves four steps, including identification, screening, provision of eligibility, and inclusion. The initial step identifies potentially relevant studies through systematic database searches, followed screening for duplicates and relevance, assessing eligibility, and including studies meeting the criteria. This approach was selected as it allows for a consistent, transparent, methodologically rigor synthesis of research trends, pedagogical applications, and limitations of GenAI tools, including ChatGPT, Gemini and Claude across different educational levels. Figure 1 presents an adapted PRISMA framework depicting the study selection process.

A comprehensive literature search was conducted using two major citation indexing databases (Web of Science and Scopus) and the full-text publisher platform Science Direct. Keywords and phrases were applied to article titles, abstracts, and author-generated keywords to identify studies on GenAI in mathematics education. This includes search terms like "generative AI," "generative artificial intelligence," "ChatGPT,", "large language model,", as well as domain-specific terms like problem-solving, algebra, calculus, geometry, and STEM mathematics. To ensure comprehensiveness, the reference lists of retrieved articles were manually screened to identify additional studies not captured in the initial searches. Mendeley Reference Management software was used to remove the duplicates, and only studies published in English were considered. Using the PRISMA framework, the search was limited to studies published between 2022 and 2025, and the final database search was conducted on 31 January 2025. This timeframe aligns with the emergence and rapid expansion of GenAI technologies within mainstream academic and educational discourse, especially after the introduction of GPT-3 and GPT-4. Table 2 provides the detailed search strings.

Following the identification stage, records were screened based on titles, abstracts, and keywords. Full-text screening was then conducted using predefined inclusion and exclusion criteria focusing on empirical studies that examined applications, opportunities, or challenges of GenAI in mathematics education across educational levels. The final set of included studies was analysed descriptively and thematically to map research characteristics, pedagogical uses, and reported limitations of GenAI in mathematics teaching and learning.

A systematic mapping review approach was selected for this study due to the emerging, rapidly evolving, and methodologically heterogeneous nature of research on generative artificial intelligence (GenAI) in mathematics education. Existing empirical studies vary widely in terms of research design, educational context, unit of analysis, and reported outcomes, making effectiveness synthesis or quality-weighted integration premature at this stage of the field's development. Systematic mapping reviews are particularly appropriate for providing an overview of research trends, identifying concentrations and gaps in the literature, and describing how a research area is being investigated, rather than evaluating the strength or effectiveness of interventions. Accordingly, this review focuses on mapping reported applications, pedagogical roles, and challenges of GenAI in mathematics teaching and learning, rather than drawing causal or effectiveness-based conclusions. As a systematic mapping review, this study does not evaluate the effectiveness of GenAI interventions or weight findings based on methodological quality, but instead aims to provide an overview of research trends, reported applications, and gaps in the existing literature

Figure 1
PRISMA Framework (Page et al., 2021)

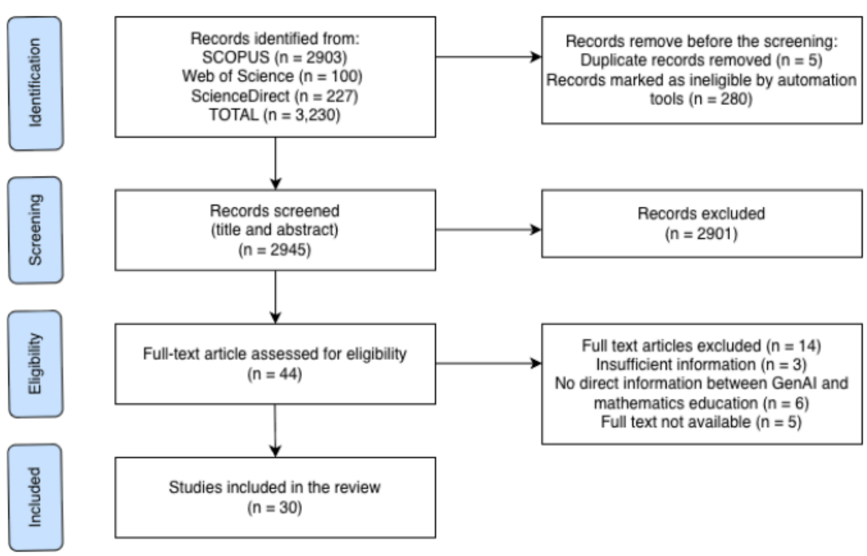


Table 2
The Search Strings

Database	Search Equation
Scopus	(("generative AI" OR "generative artificial intelligence" OR "ChatGPT" OR "large language model" OR "AI-powered" OR "artificial intelligence") AND TITLE-ABS-KEY("mathematics education" OR "math education" OR "algebra" OR "calculus" OR "geometry" OR "problem-solving" OR "STEM mathematics"))
Web of Science (WoS)	(TITLE-ABS-KEY("generative AI" OR "generative artificial intelligence" OR "ChatGPT" OR "large language model" OR "AI-powered" OR "artificial intelligence") AND TITLE-ABS-KEY("mathematics education" OR "math education" OR "algebra" OR "calculus" OR "geometry" OR "problem-solving" OR "STEM mathematics"))
ScienceDirect	(("generative AI" OR "generative artificial intelligence" OR "ChatGPT" OR "large language model" OR "AI-powered" OR "artificial intelligence") AND TITLE-ABS-KEY("mathematics education" OR "math education" OR "algebra" OR "calculus" OR "geometry" OR "problem-solving" OR "STEM mathematics"))

Data Analysis

The systematic mapping review focused exclusively on peer-reviewed literature articles that examine the use of generative artificial intelligence (GenAI) in mathematics education. Studies were included if they explored the applications, challenges, or pedagogical implications of GenAI in mathematics teaching and learning, provided empirical evidence regarding student learning, involvement, motivation, or conceptual understanding, or addressed teachers' perspectives on integrating GenAI. To ensure methodological rigor and relevance, non-empirical sources such as editorials, review papers, book chapters, conference proceedings, dissertations, and other non-peer-reviewed articles were excluded. Studies published in languages other than English were also omitted to guarantee accurate interpretation. Studies in all levels of education, such as primary, secondary, and tertiary studies, were considered to ensure a comprehensive overview of the GenAI practices in mathematics education.

These databases were selected due to their comprehensive coverage, academic rigor, and relevance to educational research. Web of Science and Scopus are widely recognized citation indexing databases that index high-quality, peer-reviewed journals across multiple disciplines, ensuring methodological rigor and credibility in the studies retrieved. ScienceDirect, as a full-text publisher platform, provides direct access to current and relevant articles, particularly in education, computer science, and STEM-related fields, allowing for efficient retrieval of empirical studies on GenAI applications in mathematics education. The combination of these databases maximizes coverage of high-impact journals, reduces the risk of missing main studies, and ensures that the review captures a representative sample of research trends and pedagogical practices across different educational levels and geographical regions. Table 3 summarizes the inclusion and exclusion criteria applied in this study.

Table 3
The Selection Criterion in Searching

Inclusion Criteria (IC)	Exclusion Criteria (EC)
IC1. Peer-reviewed articles published in indexed journals (Web of Science, Scopus, ScienceDirect)	EC1. Non-indexed journals, book chapters, review papers, conference proceedings, dissertations, prefaces, or opinion pieces
IC2. Studies covering all educational levels in mathematics (primary, secondary, tertiary)	EC2. Studies unrelated to mathematics education
IC3. Focus on the application of generative AI in mathematics education	EC3. Studies mentioning AI but not focusing on generative AI in mathematics education
IC4. Reports findings on opportunities, challenges, or practical applications of generative AI in teaching and learning mathematics	EC4. Studies lacking discussion of outcomes, applications, or challenges of generative AI
IC5. Published in English	EC5. Published in languages other than English
IC6. Specifically applied to mathematics or mathematics education	EC6. General application in other professional fields (e.g., medicine, public health, environmental science, engineering)

To extract data for mapping, each study was coded for key characteristics, including GenAI tool type (e.g., ChatGPT, Gemini, Claude, Copilot, Khanmigo, Compass), education level (K-12, undergraduate, teacher education), mathematics topic (algebra, geometry, calculus, statistics, number theory, mixed/problem-solving), research design (qualitative, quantitative, mixed-methods), and geographical location. These variables guided both descriptive reporting and thematic analysis, ensuring alignment with the study objectives of mapping trends, gaps, and pedagogical applications.

The systematic evaluation of each study followed a multi-stage process based on PRISMA framework, that involved identifying, screening, eligibility, and inclusion. This strategy ensured that only the studies that fit the predefined criteria were retained to qualitative thematic analysis and offered reliable information about the pedagogical functions, capabilities, limitations, and educational implications of GenAI. During the identification step, 3,230 records were initially retrieved from multiple databases. Five duplicates were removed in the process of screening with the help of Mendeley, resulting in 2,945 records for further evaluation. These were screened based on the titles, abstracts, and keywords. This leads to the exclusion of 2,901 studies because it was irrelevant to mathematics education, non-peer-reviewed, lack of focus on GenAI, or was not written in English. During the eligibility phase, the full texts of the rest of the 44 articles were assessed against inclusion criteria, whereby a focus on GenAI in mathematics education, empirical results, and a participation of learners at any level of education were considered. Fourteen articles were excluded due to insufficient relevance, missing information, or entire text was not available. Lastly, 30 studies that met all the criteria were included for qualitative thematic analysis. These studies were reviewed to identify pedagogical applications, research trends, and the capabilities and limitations of GenAI tools.

The thematic analysis followed a systematic coding process. An inductive approach was adopted to identify recurring pedagogical applications, reported challenges, and trends in GenAI usage. Two independent coders reviewed all 30 studies, with discrepancies resolved through discussion to ensure reliability. NVivo software was used to organize codes and track themes. Themes were then cross-checked against extracted variables to confirm consistency with descriptive results, including tool usage, educational level, mathematics topic, and geographical distribution.

This approach ensures that the review provides a structured and reproducible overview of GenAI research in mathematics education, highlighting patterns, gaps, and emerging trends rather than evaluating effectiveness or weighting findings based on methodological quality.

Results

GenAI Tool Usage

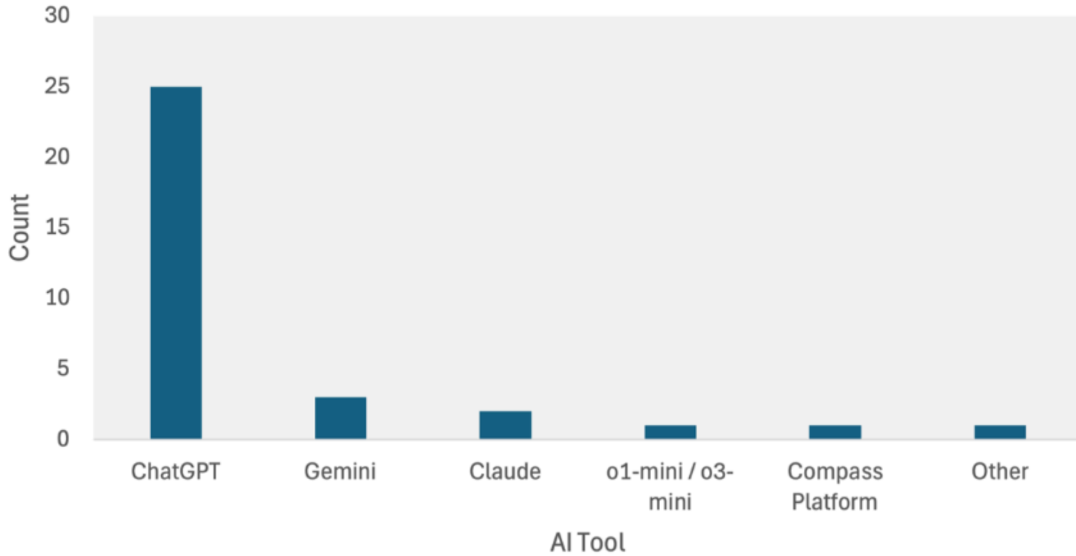
In relation to RQ (i), which examines how GenAI tools are used in mathematics teaching and learning across educational levels and mathematical topics, Figure 2 represents the distribution of GenAI tools across the 30 reviewed studies. ChatGPT (all versions) was the most frequently used tool with 25 studies (83%), showing it was widely used in mathematics education research. Other tools were considerably less represented: Gemini (3 studies; 10%), Claude (2 studies; 7%), OpenAI o1-mini and o3-mini (1 study each; 3%), Compass Platform (1 study; 3%), and emerging platforms such as Student GPT, Copilot and Khanmigo (1 study each; 3%).

The strong concentration on ChatGPT suggests that empirical evidence regarding GenAI in mathematics education is largely shaped by a single dominant platform. This dominance may reflect factors such as early public release, ease of access, widespread institutional adoption, and strong media visibility (Seebut et al., 2024; Walkington et al., 2025; Zhuang & Zhang, 2025; Xuan et al., 2025). Methodologically, this concentration indicates a potential platform bias, where conclusions about "GenAI in mathematics education" are primarily derived from the affordances and limitations of one tool rather than representing the broader ecosystem of generative AI systems.

The limited representation of alternative platforms suggests that comparative research across different GenAI architectures remains underdeveloped. Consequently, current findings may reflect tool maturity and accessibility rather than systematic evaluation of diverse GenAI technologies. This pattern indicates that while research activity is expanding, diversification of investigated platforms is still emerging.

Figure 2

AI Tool Usage Frequency in the Reviewed Studies



Education Level

In response to RQ (i), which examines how GenAI tools are used across different educational levels, Figure 3 presents the distribution of studies by educational context. Of the 30 included studies, 13 (43%) were conducted in undergraduate or higher education settings, 12 (40%) in K–12 contexts (middle and high school), and 8 (27%) in teacher education or pre-service teacher programs.

For classification purposes, undergraduate or higher education refers to studies involving university-level students, including postgraduate participants where specified. Teacher education was treated as a distinct category to capture research specifically focused on the professional preparation of future educators, even though such programs are institutionally situated within higher education. These categories were coded based on the primary participant group identified in each study to minimize overlap.

The relatively balanced distribution between K–12 (40%) and higher education (43%) suggests that GenAI integration is not confined to a single educational stage but is being explored across developmental levels (McGalliard & Otten, 2025; Delima et al., 2024; Xuan et al., 2025). The slightly higher concentration in higher education may reflect fewer institutional restrictions, greater digital infrastructure, and increased academic freedom to experiment with emerging technologies (McGalliard & Otten, 2025; Xuan et al., 2025). In contrast, the strong representation in K–12 contexts indicates growing interest in early curricular integration and classroom-level experimentation (Segal & Klemer, 2025; Parra et al., 2024).

The presence of teacher education studies (27%) is particularly significant, as it signals recognition that effective GenAI integration depends not only on student use but also on preparing educators to critically and pedagogically engage with these tools. This suggests that the field is moving beyond exploratory student-focused applications toward broader professional and systemic considerations. Overall, the distribution indicates that research on GenAI in mathematics education is expanding across educational levels, though institutional context may influence the pace and nature of adoption.

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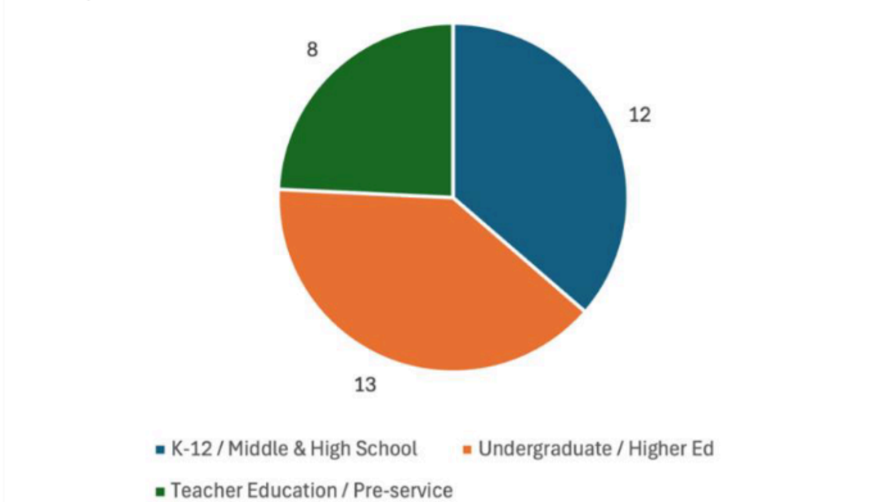
Figure 3
Distribution of Studies by Educational Level



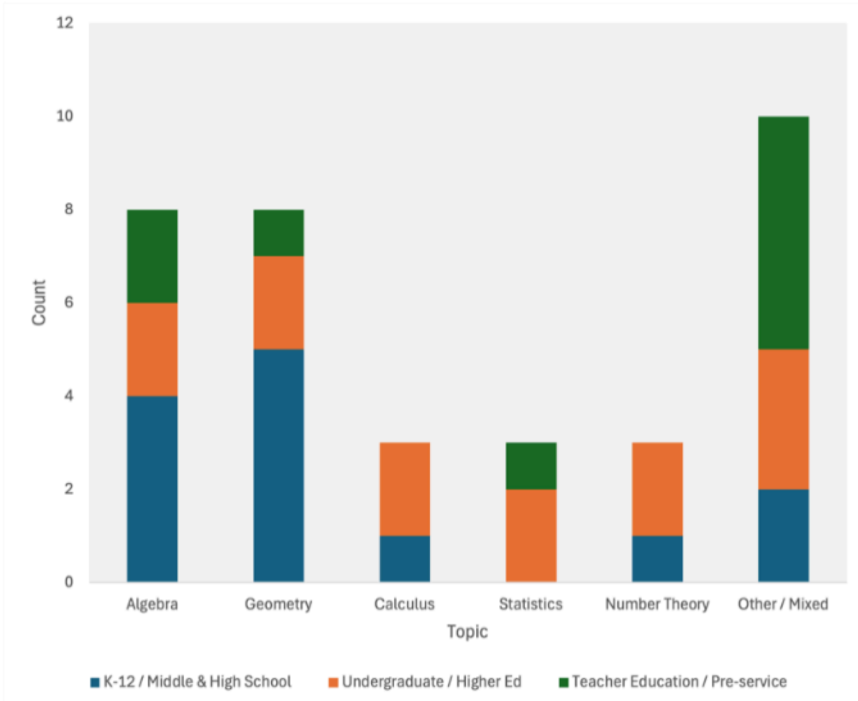
Mathematics Topics

Figure 4 presents the distribution of studies by topic. Across the 30 included studies, Algebra was the most frequently investigated topic, appearing in 14 studies (47%), followed by Geometry in 9 studies (30%). Calculus was addressed in 2 studies (7%), Statistics in 3 studies (10%), Number Theory in 3 studies (10%), and Other/Mixed topics in 7 studies (23%).

For classification, each study was coded based on the mathematics topic(s) primarily addressed. Studies covering multiple topics were counted in all relevant categories. The "Other / Mixed" category includes problem-solving, mathematical literacy, and RME-based activities, often spanning multiple educational levels, particularly in teacher education or pre-service contexts.

The distribution indicates that research on GenAI in mathematics education focuses predominantly on foundational and visual-spatial reasoning topics, such as Algebra and Geometry, across K–12 and undergraduate contexts. Higher-order topics like Calculus, Statistics, and Number Theory are less frequently studied and are primarily explored in undergraduate or higher education settings. The presence of Other/Mixed topics highlights attention to integrative, cross-topic applications, especially in professional preparation for future educators. Overall, these patterns suggest that GenAI research in mathematics education prioritizes core foundational topics, while also exploring broader, integrative applications to support diverse pedagogical and curriculum needs.

Figure 4
Mathematics Topics Addressed in Studies across Educational Contexts



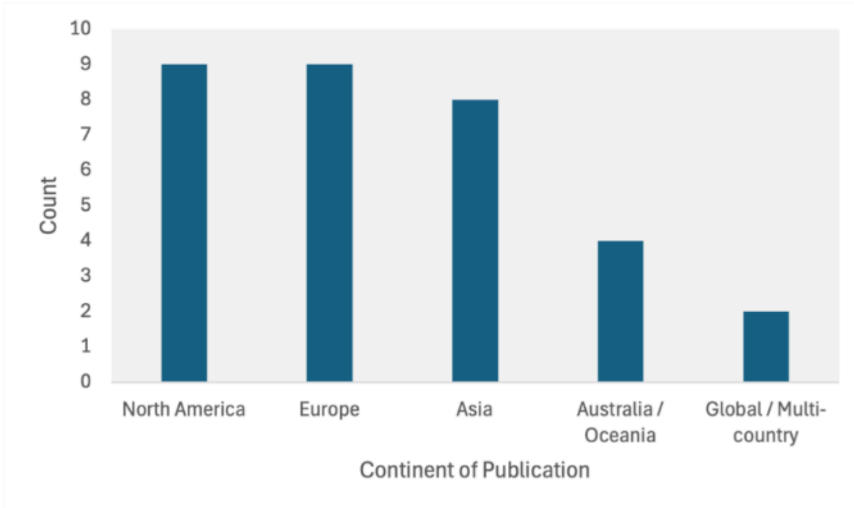
Geographical Distribution

Figure 5 shows the distribution of the reviewed studies according to continent, based on the country where the research was conducted. Of the 30 included studies, 9 (30%) were conducted in North America, 9 (30%) in Europe, 8 (27%) in Asia, 4 (13%) in Australia/Oceania, and 2 (7%) involved multiple countries or global collaborations. In Asia, studies were conducted in countries such as Indonesia, Israel, Thailand, South Korea, Jordan, and the Philippines. Studies conducted across multiple countries were categorized under Global / Multi-country to avoid duplication.

This distribution implies that research in the field of GenAI in mathematics education is concentrated in North America, Europe, and part of Asia, with other regions underrepresented. The findings highlight potential geographical gaps in the literature, suggesting the need for broader international exploration to understand contextual differences in GenAI implementation and adoption.

Figure 5

Continent of Publication



Discussion

Capabilities and Limitations of Generative AI in Mathematics

Across the reviewed studies, GenAI is described as flexible across mathematics education contexts, serving as a problem-solving assistant, content generator, and scaffolding tool across multiple levels (McGalliard & Otten, 2025; Seebut et al., 2024; Segal & Klemer, 2025). However, the effectiveness reported varies considerably depending on study design and methodological rigor; for example, in-depth qualitative analyses (McGalliard & Otten, 2025) provide richer insights into AI reasoning limitations compared to simple pre-post quantitative surveys (Delima et al., 2024). Eighteen of the thirty studies (60%) reported the use of AI for procedural problem-solving, while twelve studies (40%) highlighted its role in content generation and scaffolding. For example, McGalliard and Otten (2025) evaluated ChatGPT and Gemini 1.0 on cognitively demanding secondary tasks and discovered that AI could solve complex problems, such as rates, quadratics, and geometry proofs. Critically, these findings intersect with Marco and Stylianides (2025) who showed that AI's performance is tightly bound to human guidance. This findings emphasize that procedural success does not equate to conceptual understanding. Initial outputs usually had a lot of errors, which require iterative prompting and refinement. Based on the Technological Pedagogical Content Knowledge (TPACK) framework, the findings highlight the importance of integrating technological knowledge with pedagogical strategies to ensure that AI-mediated solutions are conceptually accurate and educationally meaningful (Mimoudi & Mokhtari, 2025; Tan et al., 2025).

Marco and Stylianides (2025) then introduced the concept of a "Chat's Zone of Proximal Development," emphasizing that AI can assist in solving the tasks that can be solved with human guidance, which is a combination of recollection and generative reasoning. Synthesizing this with McGalliard and Otten (2025) and Segal and Klemer (2025), it becomes clear that AI's pedagogical value emerges primarily at the intersection of task design, user input, and iterative scaffolding, rather than as a standalone tool. Although this analogy to Vygotskian scaffolding is insightful, inappropriate use of AI may overstate its role as a cognitively adaptive agent; since AI cannot truly diagnose errors or adapt responsively beyond surface-level patterns, which constrains its transformative pedagogical potential.

At the higher education levels, GenAI supports computational and programming tasks. Seebut et al. (2024) reported that integrating GPT-3.5 with Google Colab to solve difference equations improved students' self-efficacy and encouraged roles such as prompt engineers instead of passive consumers of content. Likewise, Yunianto et al. (2024) demonstrated that GenAI could generate GeoGebra code to solve geometry problems, enabling differentiated learning that catered to diverse student paces. However, these apparent benefits are double-edged; students may become more efficient, but also might lose the ability to think conceptually, since AI can mask procedural fluency with automated outputs, a concern that Seebut et al. (2024), briefly acknowledge, but do not fully explore. These findings illustrate

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GenAI's dual roles as a virtual peer and procedural guide, which makes mathematical computation more engaging, but at the same time it supports the idea that GenAI's contributions remain fundamentally instrumental rather than intellectually generative. From a socio-didactical perspective, this highlights the necessity of teacher mediation in co-constructing mathematical understanding, ensuring that AI serves as a scaffold rather than a substitute for conceptual engagement (Tan et al., 2025).

GenAI exhibits significant limitations, especially in abstract reasoning. Parra et al. (2024) analysed large language models (LLMs) solving geometry competition problems in Spanish and identified errors primarily in three categories: Construction, Conceptual, and Contradiction. Eight studies reported similar domain-specific reasoning challenges, and it shows that AI reasoning is fragile and domain-specific. Intersections with Wardat et al. (2023) indicate that repeated limitations in conceptual reasoning are consistent across studies, suggesting a systemic challenge rather than isolated incidents. Moreover, ChatGPT struggles to rectify errors in geometry, which reinforces the view that GenAI cannot yet replace human conceptual mediation. This limitation challenges overly optimistic narratives about GenAI democratizing high-level mathematical tasks, showing that human expertise is still required in the process of guiding abstraction and reasoning.

Contextual weaknesses are evident as well. High-level spatial problems (Marco & Stylianides, 2025) and advanced calculus tasks (Parra et al., 2024) are among the problems that models like ChatGPT fail to solve successfully. Reports of differing accuracy and national curricular standards across the studies highlight that such differences are not merely technical but epistemologically significant (Stamenkova, 2025). In effect, educators must critically evaluate AI-generated solutions, before introducing them to students. This approach emphasizes the teacher's dual role in facilitation and verification. Learning theories, such as Vygotsky's socio-cultural theory, further support the need for guided interaction, where AI outputs are interpreted, critiqued, and integrated within students' evolving cognitive structures (Boulhrir & Hamash, 2025).

The pedagogical implication is clear: AI should function as a complementary tool rather than a replacement. Teachers must guide students on how to interpret, verify, refine GenAI outputs, and encourage students to focus on prompt engineering and critical evaluation (Mani & Zargeh, 2025; Borys et al., 2025). Integration across K–12 and higher education studies suggests that effective AI use requires teacher competency, digital literacy, and curricular awareness. This findings indicate that the potential benefits of GenAI may be unevenly distributed and could further deepen educational disparities.

GenAI Enhancing Conceptual Understanding, Engagement, and Motivation

GenAI has significant potential for enhancing conceptual learning in mathematics, though its scaffolding is limited. Across the reviewed studies, three cross-cutting themes emerge: metacognitive support, motivation and engagement, and multiple solution strategies. As evidenced by Contel and Cusi (2025), GPT-4 can support metacognitive strategies when solving problems, but it tends to bypass planning stages, and create diagnostic instead of replacement learning opportunities. This implies that AI scaffolding may reinforce fragmented reasoning, as students receive solutions without fully internalizing procedural logic, a risk often underemphasized in the literature. Flipped-dialogue models, as presented by Pavlova (2024), exemplify how structured AI-student interaction can stimulate critical thinking and research skills. Evidence from eight other studies similarly indicates that AI cannot independently diagnose or adapt beyond surface-level patterns, emphasizing the role of human orchestration and instrumental genesis (Wardat et al., 2023; Kock et al., 2025).

GenAI appears most effective in terms of motivation and engagement when integrated into interactive or gamified settings. According to Susilawati et al. (2025), methods such as AI combined with Realistic Mathematics Education (RME) and gamification significantly improved problem-solving and engagement, with motivation acting as a structural mediator. Walkington et al. (2025) showed that middle school girls using ChatGPT and DALL-E2 attempted to pose mathematical problems, though outputs required careful human supervision to counter bias and inaccuracies. While promising, gains in engagement are conditional: self-reported motivation increased (Delima et al., 2024; Susilawati et al., 2025), yet few studies triangulated these outcomes with performance data. Critical evaluation of these studies shows that strong methodological designs, such as sequential explanatory or mixed-method studies, offer richer insights on how motivation interacts with teacher support and task complexity, while weaker designs risk overgeneralizing benefits.

AI also supports multiple solution strategies, contributing to deeper understanding. Wardat et al. (2023) discovered that ChatGPT could generate alternative explanations for algebraic manipulations or statistical reasoning, benefiting students who struggle with traditional teaching approaches. Similarly, Kock et al. (2025) described students treating AI as a co-agent to conceptualize problems and optimize solutions, at the same time, developing critical evaluation skills. However, the co-agent framing can be exaggerated when it comes to the capacity of AI to think independently. The model lacks intentionality and adaptive cognition, i.e. the students need to constantly filter outputs for accuracy. In this context, deterministic reasoning refers to the tendency of students to accept AI-generated outputs as fixed, authoritative solutions without interrogating underlying assumptions or alternative pathways (Kruijssen & Emmons, 2025). Theoretically, this aligns with concerns in metacognitive and self-regulated learning research, where reduced monitoring and evaluation can constrain deeper conceptual processing (Panadero et al., 2025; Shekh-Abed, 2025). This introduces a potential cognitive load, which is rarely measured but could constrain learning, consistent with Sweller's (2011) cognitive load theory.

The gains of engagement are, however, not uniform. Parra et al. (2024) reported that GenAI struggles with complex geometrical problems, which may reduce the confidence of students if errors are misinterpreted as correct. Ethical concerns are present as well, including students relying on AI to generate proofs without fully understanding underlying the concepts (Yoon et al., 2024). This indicates a larger conflict, in which AI can motivate students superficially but fail to develop deep comprehension, thus posing a paradox that requires extensive pedagogical guidance. Effective integration thus requires active reflection, iterative prompting, and teacher-mediated dialogue (Segal & Klemer, 2025; Mani & Zargeh, 2025).

From a TPACK perspective, these findings highlight the importance of integrating technological knowledge with pedagogical and content knowledge to ensure AI-mediated solutions are conceptually accurate and educationally meaningful. Similarly, socio-didactical frameworks emphasize the teacher's role in shaping AI outputs into coherent learning experiences, while instrumental genesis underscores the necessity of students internalizing AI-mediated reasoning rather than passively consuming solutions.

In summary, GenAI has clear potential to enhance conceptual understanding, engagement, and motivation, but these benefits are contingent on teacher guidance, structured mediation, and student prior competence. Gains are more pronounced when AI is integrated with reflective, interactive, or gamified activities, yet uneven across learners and educational levels. Effective implementation requires active reflection, critical evaluation, and theoretically informed scaffolding to prevent superficial engagement and maximize conceptual learning.

Pedagogical Integration of GenAI in Mathematics Education

When it comes to teaching mathematics, GenAI implementation must be mediated by the teacher. Across the reviewed literature, pedagogical integration consistently follows a teacher-regulated orchestration model, in which AI operates within established instructional structures rather than as an autonomous agent. Mani and Zargeh (2025) proposed a socio-didactical tetrahedron positioning the student at the center with AI as a new vertex, emphasizing that teacher oversight is essential to prevent over-reliance. Segal and Klemer (2025) reported that teacher-AI conversation improved the TPACK components but required iterative evaluation to ensure pedagogical integrity. Synthesizing these perspectives suggests a unified pedagogical model: AI integration is less about innovation and more about restructuring current teacher-led practices, challenging claims that AI inherently transforms pedagogy. This teacher-mediated and context-sensitive model is reinforced by Xuan et al. (2025), who found that GenAI demonstrated marginal benefits in well-resourced private schools characterized by strong digital literacy and self-regulated learning, whereas traditional teacher-centered instruction remained more effective in resource-constrained public schools. Their findings highlight that AI effectiveness is contingent upon contextual readiness, infrastructure, and pedagogical scaffolding rather than technological capability alone.

Professional development should focus on prompt engineering, critical evaluation, and ethical use. A cross-study synthesis reveals three emerging professional development orientations: (1) technical-operational training (prompt construction and tool navigation), (2) pedagogical-design training (embedding AI into task design and lesson sequencing), and (3) critical-ethical training (bias detection, epistemic evaluation, and responsible authorship). Relying on the guided practice of AI prompts, Zhuang and Zhang (2025) noted that the perceptions of pre-service teachers improved, which shows the significance of hands-on training. Noster et al. (2024) emphasized that without sufficient prompt knowledge, it leads to the uncritical acceptance of AI outputs. However, most empirical evidence is concentrated in higher education contexts and specific geographical regions, as identified in the mapping results, which limits systematic generalization across systems. This points to a structural constraint since teacher competence and digital literacy are crucial factors that determine the effectiveness of AI integration. While several studies imply that unequal access to structured professional development may widen existing gaps, comparative cross-level or cross-regional evidence remains limited, these findings imply that AI may worsen inequities rather than address them unless systematic support is provided.

GenAI also presents new pedagogical opportunities, such as lesson planning, simulation of problem-solving tasks, and rapid generation of differentiated teaching materials (Gurl et al., 2025; Daher and Anabousy, 2025). According to Borys et al. (2025), AI-generated exercises can accelerate learning process but require human validation to ensure accuracy. Across studies, this recurring need for validation positions AI primarily as an efficiency-enhancing augmentation tool rather than an independent mechanism of knowledge construction. It can act as a co-designer of the learning experience and help teachers to create learner-centered classrooms. However, it remains highly reliant on human expertise.

Ethical and practical considerations remain critical. Sawyer and Aga (2025) discovered that AI-generated content could be repetitive or shallow, particularly in elementary curricula. Educators need to instruct students in critical thinking, authorship responsibility, and ethical engagement with AI-generated materials (Yoon et al., 2024; Sutrisno AB et al., 2025). Synthesized across studies, these concerns converge on the need for explicit epistemic scaffolding to prevent deterministic acceptance of AI outputs. In the absence of explicit ethical scaffolding, AI may unintentionally promote superficial thinking, which reinforces surface-level engagement rather than meaningful mathematical reasoning.

Conclusion

This systematic mapping review investigated how GenAI tools are integrated into mathematics education across educational levels, mathematical topics, and geographical contexts. The review reveals that the integration of GenAI predominantly revolves around a single tool, ChatGPT, which appeared in 83% of the studies, while other platforms such as Gemini, Claude, and emerging tools are underrepresented. Research evidence (McGalliard & Otten, 2025; Contel & Cusi, 2025; Delima et al., 2024) shows that GenAI can enhance student engagement, motivation, self-regulated learning, and conceptual understanding, particularly in foundational topics such as algebra and geometry, with less frequent exploration in advanced topics like calculus, statistics, and number theory. The review also shows that studies are relatively balanced between K–12 (40%) and higher education contexts (43%), with 27% focusing on teacher education, and that research is concentrated in North America, Europe, and parts of Asia, revealing geographical gaps in the literature.

GenAI is most effectively applied when combined with interactive, gamified, or differentiated learning activities (Gurl et al., 2025; Susilawati et al., 2025; Yunianto et al., 2024), where it can scaffold procedural fluency, generate multiple solution strategies, and encourage new learner roles, such as prompt engineers and co-agents (Seebut et al., 2024; Kock et al., 2025). However, its contributions are limited by domain-specific reasoning errors, weak abstract thinking, and reliance on precise prompting, which underscores the necessity of teacher-mediated scaffolding to ensure conceptual depth, ethical engagement, and critical evaluation of AI outputs (Segal & Klemer, 2025; Pavlova, 2024; Yoon et al., 2024). These findings indicate that while GenAI has the potential to transform certain aspects of mathematics learning, its impact is conditional, unevenly distributed across learners, and influenced by task design, user input, and platform reliability.

Importantly, GenAI is capable of scaffolding procedural fluency and generating multiple solutions to parallel problems. However, it lacks actual adaptive understanding, intentionality, and the ability to independently identify errors within its outputs, meaning that teacher mediation remains fundamental to ensure conceptual depth, ethical engagement, and critical evaluation of AI outputs (Pavlova, 2024; Segal & Klemer, 2025; Yoon et al., 2024). The outcomes of these studies emphasize the need for thoughtful integration, in which teachers are trained in prompt engineering, ethical use of AI, and iterative validation to maximize learning outcomes while reducing risks of over-reliance, surface-level reasoning, and inequitable access (Noster et al., 2024; Zhuang & Zhang, 2025).

Systematic mapping of the current literature provides insight into patterns of tool dominance, topic concentration, educational level distribution, and geographical imbalances, offering a synthesis that has been limited in prior reviews. Overall, the findings also reveal emerging professional development needs, including prompt engineering, ethical use, and iterative validation of AI outputs, emphasizing that GenAI's transformative potential is achievable only through purposeful pedagogical design, structured teacher mediation, and continuous evaluation, rather than being inherent to the technology.

Limitations and Future Studies

While providing valuable insights, the systematic mapping literature review has several limitations. To begin with, only studies in English were considered in the review, which may have excluded relevant research in other languages and limited the understanding of GenAI applications in diverse linguistic and cultural contexts. Second, the review focused exclusively on peer-reviewed empirical studies, excluding theoretical, conceptual, or non-peer-reviewed research, such as conference proceedings, which may provide complementary perspectives on the pedagogical roles and instructional design of GenAI in mathematics education; this exclusion is particularly relevant given the rapidly evolving nature of the field. Third, the search strategy was limited to selected databases (e.g., ScienceDirect), which may introduce database bias, and potential inconsistencies in search strings, duplicate counts, or the absence of inter-rater reliability checks could further constrain the comprehensiveness and reproducibility of the review. Fourth, no formal quality appraisal or risk-of-bias assessment was conducted, which limits the ability to evaluate the methodological robustness of the included studies. Finally, the rapid evolution of GenAI tools means that findings may quickly become outdated as new versions with enhanced capabilities are introduced. This highlights the need for ongoing evaluation of emerging platforms.

The gaps to be addressed in future research include the longitudinal effects of GenAI integration, in terms of whether it leads to sustained learning outcomes, conceptual mastery, and problem-solving abilities across various areas of mathematics. Cross-cultural studies are also essential to evaluate the adaptability of GenAI-supported instruction in diverse educational systems and cultural settings, particularly given the geographic imbalances highlighted in this mapping. Ethical and pedagogical concerns, including bias, over-reliance, and inequitable access, should also be addressed, as these remain underexplored (Qian, 2025; Tan et al., 2025). Moreover, future studies should explore the ethical and pedagogical aspects of AI implementation, especially the idea of bias, over-reliance, and equitable access. It is also important to balance the innovation of AI and conceptual depth so that AI can support learning and develop critical thinking, autonomy, and ethical reasoning. This balance may be quite difficult to achieve because, to date, GenAI is most effective in enhancing efficiency and motivation (Contel & Cusi, 2025; Delima et al., 2024; McGalliard & Otten, 2025), whereas its ability to improve true conceptual mastery remains uncertain. Lastly, comparative studies across different GenAI platforms such as ChatGPT, Gemini, Claude, and other emerging tools, are also recommended to identify platform-specific strengths, limitations, and best practices for instructional integration.

Conflict of Interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

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Generative AI Declaration

This manuscript was developed with limited assistance from generative artificial intelligence (GenAI) tools, including ChatGPT. The tool was used solely to support language refinement, grammar checking, and minor improvements in sentence clarity during the manuscript preparation process. All conceptualization of the study, literature selection, data interpretation, synthesis of findings, and academic arguments were conducted independently by the authors. The authors take full responsibility for the accuracy, integrity, and originality of the content presented in this paper. The use of GenAI did not influence the research design, data analysis, or conclusions of the study, and all sources cited were verified by the authors.

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"TAWHIDIC EPISTEMOLOGY AND THE PURSUIT OF HOLISTIC KNOWLEDGE"

AL-FARABI'S THEORY OF MUSIC: ITS RELEVANCE IN INTERDISCIPLINARY APPROACHES AND THE MALAYSIAN EDUCATIONAL CONTEXT

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ABSTRACT

This study investigates Al-Farabi's music theory and explores its relevance in interdisciplinary education, particularly within the Malaysian context. The objectives focus on analyzing his philosophical and scientific perspectives on music and proposing ways to incorporate these principles into modern educational practices. The methodology involves a qualitative review of historical texts, scholarly interpretations, and curriculum analyses, emphasizing Al-Farabi's integration of cosmological, psychological, mathematical and pedagogical aspects of music. Findings suggest that Al-Farabi's holistic approach underscores music's role in emotional regulation, cultural identity, and universal harmony, which can enhance Malaysia's multicultural education system. The discussion highlights the potential to adopt his principles to foster intercultural understanding and creative development through music pedagogies aligned with his systematic analysis of sound and emotion. The conclusion advocates for integrating Al-Farabi's theories into the Malaysian curriculum to promote interdisciplinary learning, cultural appreciation, and holistic development, emphasizing the timeless relevance of his ideas in contemporary education.

Keywords: al-Farabi; music theory; interdisciplinary approach; Malaysia; holistic development

INTRODUCTION

Al-Farabi was a prominent Muslim philosopher, scholar, and polymath whose intellectual contributions left a lasting impact on both the Islamic world and Western thought. Born in the region of Farab (in present-day Kazakhstan), he received extensive education in various disciplines, mastering Greek philosophy, logic, mathematics, and the natural science (Firdaus et al., 2020; Maarif et al., 2018; Tercan, 2020). Al-Farabi became renowned for his ability to synthesize and interpret the works of Aristotle and Plato, adapting their ideas to the Islamic intellectual tradition.

Widely recognized as one of the most influential Muslim thinkers, Al-Farabi earned the title of the "Second Master" after Aristotle for his profound contributions to the development of Islamic philosophy (Rauf et al., 2013).In particular, his intellectual engagement with Greek philosophical heritage helped create a stable foundation for rational inquiry in the Islamic Golden Age. He then played a major role in shaping the philosophical landscape of medieval Islamic civilization, by articulating complex ideas in a systematic and accessible manner.

Al-Farabi's Kitāb al-Mūsīqā al-Kabīr (The Great Book of Music) stands as a monumental work in the history of music theory, offering one of the most comprehensive analyses of musical principles from the medieval Islamic world (Firdaus et al., 2020). In this work, Al-Farabi systematically examined the mathematical foundations of music, including intervals, scales, and rhythm, linking them to philosophical and ethical concepts (Nicholson, 2021). He explored how music affects the human soul, shaping emotions, character, and intellect, reflecting his belief in the transformative power of art when guided by reason (Rauf et al., 2013). The relevance of Al-Farabi's theories extends well into the modern educational context, particularly in Malaysia, where interdisciplinary approaches are increasingly valued. His ideas illustrate how music can serve as a bridge between cognitive, emotional, and cultural development, making it a versatile tool in teaching, therapy, and cultural preservation.

METHODOLOGY

A qualitative literature review was conducted, analyzing primary texts by Al-Farabi and modern scholarly interpretations. Curriculum policies and pedagogical practices within Malaysia's multicultural context were examined to identify opportunities for applying Al-Farabi's principles. The study also compared traditional Malaysian musical elements with Al-Farabi's maqam system, emphasizing their conceptual similarities (Jamaludin et al., 2023).

RESULTS AND DISCUSSION

The study found that Al-Farabi's integration of mathematical harmony and emotional impact can inform culturally relevant music education in Malaysia. His classification of music's psychological effects supports the development of therapeutic and creative pedagogies. Additionally, his cosmological views aligned with Malaysia's multicultural ethos, offering a framework for promoting unity through shared musical principles (Nurysheva & Tercan, 2021).

Discussion centers on how Al-Farabi's holistic approach encourages interdisciplinary links between music, philosophy, and education. In metaphysics and psychology, Al-Farabi proposed a cosmological hierarchy of intellects, which enables human understanding and shapes the development of the soul (Maarif et al., 2018). His work in music theory, especially Kitāb al-Mūsīqā al-Kabīr, applied mathematical ratios to musical structures, influencing later Islamic and European traditions (Firdaus et al., 2020). He also emphasized that education is important to enhancing virtuous individuals and achieving emotional and spiritual balance, highlighting the link between intellectual growth, moral development, and a well-ordered society.

The relevance of al-Farabi's work extends far beyond his era, as his theories provide meaningful insights into the interdisciplinary nature of music and its applications in the Malaysian educational context. Al-Farabi's emphasis on the mathematical foundation of musical structure aligns closely with Malaysia's curriculum goals in strengthening students' understanding of fractions, ratios, and patterns, allowing music to serve as a tool for reinforcing numeracy in an engaging manner. His view of music as a medium that shapes emotions and character also support current initiatives in holistic education, where learning is designed to nurture emotional intelligence, creativity, and student well-being.

Furthermore, his philosophical appreciation of music as a cultural expression complements Malaysia's multicultural environment, encouraging the preservation and appreciation of diverse musical traditions. When teachers integrate al-Farabi's perspectives into their pedagogy, they can create learning activities that connect different subject areas, enhance cognitive skills, promote cultural literacy, and support a more integrated educational framework.

CONCLUSION

The study concludes that adopting Al-Farabi's music theories can enrich Malaysia's educational approach by enhancing interdisciplinary learning and cultural appreciation. Focusing on the mathematical and structural elements of music, including scales, intervals, and rhythm, allows teachers to design lessons that integrate music with subjects such as mathematics, physics, and language (Nicholson, 2021). This integration not only reinforces cognitive skills but also encourages students to see connections across different fields of knowledge, promoting a more holistic and engaging approach to education (Maarif et al., 2018). Al-Farabi's systematic and analytical perspective on music offers educators a model for designing lessons that stimulate critical thinking, problem-solving, and creativity.

Beyond cognitive development, Al-Farabi's work highlights the emotional and ethical dimensions of music, providing valuable insights for nurturing students' social and emotional growth (Rauf et al., 2013). Music, according to Al-Farabi, has the power to influence character and moral sensibilities, making it a tool for promoting empathy, self-discipline, and emotional intelligence. In the Malaysian educational context, where holistic education is increasingly emphasized, integrating these principles into classroom practice can support not only intellectual development but also the formation of well-rounded, ethically mindful individuals. This approach aligns with national educational goals that prioritize values education alongside academic achievement.

Finally, Al-Farabi's theories contribute to the preservation and appreciation of cultural heritage, which is particularly relevant in Malaysia's multicultural society (Nurysheva & Tercan, 2021). Through the application of his theories, educators can introduce students to traditional musical forms while fostering an understanding of their underlying structures and philosophical significance. This promotes cultural literacy and encourages respect for diverse artistic traditions. His philosophical insights into harmony and emotion remain vital for developing holistic curricula that integrate theory and practice across disciplines. The paper advocates for policies that embed his principles to cultivate culturally rooted, innovative learners, highlighting the enduring relevance of ancient wisdom in modern education (Farabi, 1940).

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