

A systematic review of technology-enhanced music learning models: Impacts on music education

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ABSTRACT

Technology-enhanced music education has grown globally, but understanding of its models, outcomes, and challenges remains fragmented. This systematic review synthesizes research on technology-enhanced music learning models (TEMLem) to identify key educational dimensions, technologies, learning outcomes, and implementation challenges. Analyzing 30 studies (2010–2024) from five databases, we identified patterns and gaps. The review highlights how technology influences music education across four dimensions: approaches, technologies, outcomes, and challenges. The findings reveal a dominance of constructivist approaches (83%) and generic educational technologies (90%) over specialized music tools, with a focus on adult beginners, while children and advanced learners are underrepresented. Music performance proficiency was the most common outcome (70%), but emotional expression (10%) and aesthetic sensitivity (7%) were less emphasized. Contrary to technology-centric narratives, pedagogical challenges (93%) were more significant than technological barriers (87%). The analysis shows a rapid technological diversification from 2022–2024, with 77% of studies published during this period. This review proposes a conceptual model integrating learning conditions, outcomes, design, and technology. It challenges assumptions about technology's democratizing potential, suggesting current implementations may reinforce traditional limitations. Future research should focus on music-specific frameworks, underserved populations, and balancing technical proficiency with aesthetic development.

1. Introduction

Technology-Enhanced Learning is one of the methods of education, with instructors employing diverse methods tailored to the cultural needs of each society [148]. A broad range of methods in music education can be observed globally, reflecting significant diversity in approaches to teaching musical knowledge and performance skills [57, 109]. Various methods of music instruction have evolved over time, each with distinct strengths and weaknesses depending on the context in which they are applied. The most widely adopted and traditional approach to music education across the globe is face-to-face instruction [6]. This method has historically formed the foundation of music learning and has developed alongside broader educational practices [57, 115]. One of the key advantages of in-person instruction is the ability of teachers to provide immediate physical guidance, such as correcting posture, hand placement, and technique [135]. Additionally, this

approach eliminates concerns about internet connectivity, bandwidth issues, or the quality of audio and video, ensuring that real-time feedback remains uninterrupted [48,57,135].

Despite these benefits, traditional face-to-face instruction has notable limitations. Scheduling flexibility is often restricted, and access is limited to instructors within a specific geographic area [49,137,147, 156]. Furthermore, the cost of in-person lessons tends to be higher compared to alternative methods. Geographic, financial, and time-related constraints can also hinder learners' ability to attend physical classes, making this method less accessible to all individuals [48,76].

In addition to the aforementioned limitations, the impact of the COVID-19 pandemic on music education presents a significant challenge that must be addressed. Since music education heavily relies on in-person instruction, the negative consequences of the pandemic have been particularly pronounced. Rosset et al. [119] investigated the effects

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of COVID-19 on music students' study routines, practice habits, and mental well-being. The findings revealed that, alongside heightened levels of stress and anxiety, students also reported a noticeable decline in their practice hours.

This study, along with similar research, underscores the profound disruption caused by the pandemic in music education. The adverse effects include diminished motivation among both students and instructors, increased stress levels, a decline in educational quality, inadequate adoption of alternative instructional methods, and weakened communication between teachers and learners [15,22,96,119].

Given the growing challenges faced by traditional face-to-face music instruction in the modern era, experts continuously seek innovative solutions to address these issues. Broadly, three primary approaches to music education have emerged: traditional instruction (face-to-face), blended instruction (a combination of in-person and remote learning supported by technology), and remote instruction (entirely technology-driven) ([26,39,91]). Research has highlighted the positive impact of the blended learning approach on music education, often demonstrating its superiority over traditional methods [29,62]. However, while blended learning leverages technology, it still requires some level of in-person interaction. This dependency poses a challenge in situations where physical attendance is not feasible, such as during pandemics [85] or in cases where geographic and time constraints limit access to instruction [105].

To address these limitations, technology-enhanced learning offers a promising alternative for overcoming the challenges associated with traditional music instruction [2,61,92]. Consequently, this study emphasizes blended and remote, technology-driven instruction, particularly through technology-enhanced learning, as a practical solution for music enthusiasts who, for various reasons, are unable to attend face-to-face or blended classes. The following sections will examine the potential impacts and advantages of implementing this approach in music education.

1.1. Technology-enhanced learning

Technology-enhanced learning (TEL) is broadly defined as "learning facilitated through digital technologies across various contexts, enabling interaction with content and peers through diverse electronic tools" [69]. TEL encompasses a wide range of learning experiences, including individual learning, collaborative learning, and context-based or situated learning. It offers numerous benefits, such as increased accessibility, interactivity, personalization, networking, collaboration, and cost-effectiveness [69,112].

In the context of music education, TEL can provide learners with access to an extensive range of digital resources, including audio and video content, musical scores, and instructional materials [72]. With the aid of digital tools and platforms, music students can conveniently access these resources anytime and from anywhere, enabling flexible, self-paced learning tailored to their individual needs and abilities [72, 98,151].

The key question now is whether integrating technology into music education-through various TEL strategies, including e-learning and digital platforms-has successfully addressed the limitations of traditional instruction and delivered significantly improved learning outcomes for music students.

Various and numerous studies have been conducted in the fields of TEL and music education [72]. Additionally, a wide variety of electronic music instruction courses are available. However, there is a notable scarcity of reliable research specifically examining the impact of TEL on the music education [72,151]. Furthermore, instructional software and courses developed based on principles of music learning and standard Models remain limited [76,90,91].

Several researchers have highlighted key factors contributing to the ineffective or limited use of technology in music education: (a) insufficient awareness of available music technology tools and their cost-effectiveness [95]; (b) the absence of well-defined conceptual frameworks to support the integration of technology in music education and assess its impact on teaching and learning outcomes [79,89]; (c) a lack of comprehensive research investigating both the short-term and long-term effects of technology integration in music instruction [144,145]; and (d) a shortage of advanced studies offering practical strategies, innovative ideas, and guiding principles for educators on effectively incorporating technology into music teaching [10,60].

1.2. Technology-enhanced music learning models

The use of instructional models in technology-enhanced learning (TEL) for music education is essential for improving the quality and effectiveness of the learning process [108,150]. These models offer a systematic and structured framework that enables teachers to present musical concepts in an engaging, activity-based manner using TEL tools, thereby facilitating a more efficient music education experience [67, 128,130]. The application of instructional models in this context is particularly important due to the unique demands of music education, the diverse learning styles of students, and the rapid evolution of TEL [44].

Music has a unique texture and nature compared to other learning domains, and therefore, instructional designers must consider various factors such as the nature of musical content (sound, rhythm, melody, harmony, etc.), the level of student engagement and interaction, cognitive, affective, and psychomotor domain objectives, and the degree of technology integration [1,110,118,136]. On the other hand, music technology is constantly evolving, and the latest advancements include virtual reality, augmented reality, mixed reality, artificial intelligence, and online platforms [16,32]. Furthermore, music education is continuously changing, with these changes occurring more with an emphasis on informal learning, creativity, and cultural diversity [17]. A music instructional model can respond to changes in music education by integrating contemporary pedagogical approaches and resources that are compatible with today's music learning [93,103,157].

The above considerations highlight the necessity of employing technology-enhanced learning (TEL) models in music education. An instructional model serves as a comprehensive blueprint, organizing and structuring teaching and learning activities [75]. It outlines all instructional tasks and decisions based on learners' needs and educational goals, specifies the sequence of these activities, and arranges meaningful learning experiences [46].

Conducting a systematic review of technology-enhanced learning (TEL) models for music instruction is of paramount importance. Notably, despite the growing body of TEL research, no prior systematic review has specifically examined TEMLeM as a distinct category - existing reviews either address general TEL practices or music education broadly, leaving the intersection uncharted [76,90,150]. This gap is consequential: without a dedicated synthesis, practitioners and researchers lack an evidence base for designing and evaluating music-specific TEL models. This significance can be understood from several perspectives. First, given the increasing prevalence of digital technologies and their deep integration into economic, cultural, and everyday life, music education must adapt to these changes. In this context, analyzing Technology-Enhanced Music Learning Models(TEMLeM) is crucial to harness their benefits and capabilities [4,69,99]. Additionally, the development and optimization of these models, grounded in scientific research and reliable data, is a key factor in enhancing the effectiveness of music education [89,104]. Therefore, a systematic review in this domain can provide valuable insights and

contribute to better strategic planning and decision-making for the advancement of music education.

1.3. Conceptualizing the review

This research aims to systematically identify TEL-based instructional models and frameworks in music education and evaluate the pivotal role of these models in improving teaching and learning outcomes. The systematic review was conducted with five objectives: 1- Identifying the educational dimensions of TEMLeM. 2- Identifying the technologies utilized in TEMLeM. 3- Identifying the learning outcomes associated with TEMLeM. 4- investigate the existing challenges and limitations in the design and implementation of TEMLeM. 5- developing a conceptual framework for utilizing learning strategies within TEMLeM. These objectives focus on formulating improvement strategies and approaches to increase the quality and efficiency of music instruction using technology. To achieve these objectives, the systematic review was conducted based on the following questions:

1. What are the educational dimensions of TEMLeM?
2. Which technologies are utilized in TEMLeM?
3. What are the Learning outcomes of TEMLeM?
4. What are the existing challenges and limitations in the design and implementation of TEMLeM?

Furthermore, To address a critical gap in the field, as no conceptual framework has been developed to date that synthesizes prior research in TEL models for music education into a cohesive structure of learning strategies [76,90,150]. This objective seeks to provide a foundation for advancing the theoretical and practical understanding of how TEL can effectively support diverse learning processes in music education. This framework guides the design and practice of future TEMLeM.

2. Method

This study utilized the PRISMA methodology for systematic reviews [94] to ensure a transparent approach in developing the search strategy, defining inclusion criteria, and identifying relevant literature. Subsequently, Theelen et al.'s [131] critical appraisal strategy was employed to evaluate the quality of the selected publications. Finally, a coding scheme, grounded in the proposed theoretical framework, was created and applied to analyze the identified studies.

2.1. Search strategy

Our systematic search strategy incorporated the most pertinent terms and synonyms aligning with the core concepts of this study, as identified through prior systematic reviews TEMLeM [49,63,72,76,103,110,128,136].

2.2. Criteria for inclusion

In the initial phase of literature screening, following criteria for inclusion and exclusion were employed. To achieve the systematic review objective, a publication year limit was applied by selecting articles from 2010 to 2024. The year limit ensures that the review focuses on recent advancements and trends in TEMLeM. Since technology evolves rapidly, articles before 2010 may not reflect current technological tools and approaches in music education. Additionally, setting a clear time range enhances the relevancy and reliability of the findings for contemporary educational contexts.

All research journal articles, peer-reviewed scientific journals, conferences, doctoral dissertations, book chapters, and Master thesis were included in the results. However, newspaper articles, general magazines, reports, and editorials were excluded from the search process. No other restrictions were applied during the search phase, such as the type of

research, publications, geographic location of the research, paper language, or the type of technology. We also selected empirical studies and conceptual studies too.

Given that technology-enhanced music learning model is a relatively new and developing research area, there are still notable research gaps [4,69,99]. Therefore, it is essential to adopt an open search strategy, ensuring the inclusion of most types of research. This approach maximizes the likelihood of identifying relevant studies and contributes to a more comprehensive analysis of existing knowledge. By avoiding strict restrictions on research type, the review can provide a broader perspective on the field, highlighting both well-established findings and emerging trends.

In the final phase of screening, we included only those publications that presented findings, implications, or evidence relevant to at least one of the research questions or contributed to the development of a conceptual framework for applying learning strategies within TEMLeM. Also, the exclusion of software, apps, or technologies that were not guided by specific models or frameworks ensures the focus remains on structured and intentional approaches to technology-enhanced music learning.

2.3. Identification of relevant publications

In the first phase of screening in selected databases, a total of 5003 papers were identified (Scopus (n=2246), ProQuest (n=1096), ERIC (n=390), Web of Science (n=907), IEEE (n=364)). The search strategy was based on Title, Abstract and Keywords. Despite the restrictions, some sources did not meet the source type criteria; therefore, 381 sources were removed due to non-compliance with the source types. Then, 1733 duplicate articles were identified and removed. The reason for duplicate articles was that a single article was indexed in multiple databases. A total of 2889 articles were identified for title and abstract screening. After reviewing the titles and abstracts of all identified articles, 2743 articles were excluded from the article review process due to their lack of relevance to the research questions. Consequently, 146 articles were selected for full-text review. For more accurate analysis and comparison of the final sources, more specific criteria, such as precise relevance to the research questions and the presence of a technology-enhanced music learning model, were considered. Based on these criteria, 106 articles were excluded during the full-text review. At this stage, there were 40 articles. Based on quality appraisal, 14 Studies with an average score below 2 points (good mention) were excluded. Also 4 articles were identified through manual citation searches and added to the final set. Ultimately, 30 articles were selected for data extraction. A summary of the article identification process is shown in Diagram 1. Table 1

2.4. Quality appraisal

We adopted the quality appraisal criteria proposed by Theelen et al. [131] as reflected in Table 2. These criteria were based on the work of Savin-Baden and Major [124] for critically evaluating qualitative studies and the NICE [100] checklist for appraising quantitative studies. The methodology quality was assessed using a scoring system ranging from no mention (0) to extensive mention (3). Studies with an average score below 2 points (good mention) were excluded. Therefore, 14 studies were excluded and other 30 studies met the minimum score requirement for methodological quality and were included in the final analysis.

2.5. Included publications

Our final pool of 30 selected publications for final analysis is detailed in Table A1 in the appendix. As shown in Table A1, most of the included papers have been published since 2020 (N = 23, 77 %) (Fig. 1). In terms of publication types, the majority of studies are journal articles (17 studies, 57 %). Additionally, doctoral dissertations (10 studies, 33 %)

Table 1
Search Strategy.

1
(music* OR piano OR guitar OR violin OR drums OR flute OR saxophone OR cello OR trumpet OR clarinet OR harp OR "musical instrument") AND (instruction* OR education* OR learning OR training OR teaching OR tutoring OR coaching OR pedagogy OR design OR curriculum OR knowledge OR "skill development" OR classroom OR "professional development" OR apprenticeship OR mentoring OR "lesson planning" OR "cognitive development" OR performance) AND (model OR framework) AND (TEL OR mobile OR "m-" OR technolog* OR distance OR online OR digital OR blended OR smartphone* OR tablet* OR app* OR "augmented reality" OR "virtual reality" OR "mixed reality" OR "cloud computing" OR "wearable technolog*" OR "assistive technolog*" OR "internet of things" OR iot OR "responsive design" OR intelligent* OR simulat*)

Table 2
Quality appraisal criteria.

Criteria	No mention (0)	Some mention (1)	Good mention (2)	Extensive mention (3)
Criteria for Qualitative Studies				
Study methodologically clear	1	12	12	5
Study theoretically substantiated	2	11	11	2
Ethical process transparent	4	4	20	2
Researcher(s) relation to participants clear	3	9	16	2
Researcher(s) relation to the data clear	3	5	19	3
Researcher(s) take a critical stance towards own research	6	8	15	1
Congruence between methodology and methods used for data collection, analysis, and interpretation	2	9	13	6
Participant involvement in data interpretation	5	6	15	4
Limitations voice	2	8	18	2
Criteria for Quantitative Studies				
Source population or source area well-described	1	5	19	1
Interventions and comparisons well-described	3	6	14	3
Outcome measures reliable	3	4	15	4
Outcomes relevant	3	11	11	1
Analytical methods appropriate	2	7	13	4
Study results internally valid (i.e., unbiased)	1	3	20	2
Findings generalizable to the source population	2	6	12	5

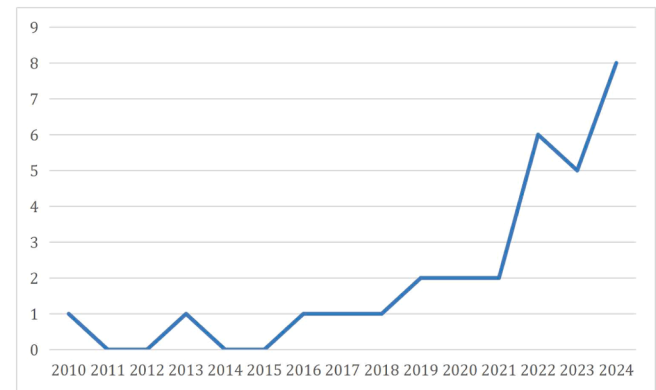


Fig. 1. Studies by Year.

contribute substantial empirical work, offering in-depth analysis. Other publication types include conference papers (1 study, 3.3 %), master's thesis (1 study, 3.3 %), and book chapters (1 study, 3.3 %), representing a smaller portion of the literature.

The language of publication is predominantly English (25 studies, 83 %), reflecting the global trend of academic publishing in English. However, a small number of studies were published in Persian (2 studies, 6.7 %), Turkish (2 studies, 6.7 %), and Spanish (1 study, 3.3 %), indicating contributions from non-English-speaking research communities.

Regarding geographic distribution, the included studies originate from 14 different countries, showcasing a diverse research landscape. The USA leads with 7 studies (23.3 %), followed by Turkey (5 studies, 16.7 %) and Iran (5 studies, 16.7 %). Other countries contributing to the research include Spain (2 studies, 6.7 %), Ukraine (2 studies, 6.7 %), and China, Finland, Australia, Malaysia, the Philippines, Sri Lanka, Romania, Luxembourg, and Hong Kong (each with 1 study, 3.3 %). This distribution highlights strong contributions from North America, Europe, and Asia, while research from Africa and Latin America remains underrepresented.

The research methods employed in these studies are varied, with mixed-methods approaches (12 studies, 40 %) being the most common. Additionally, qualitative studies (11 studies, 37 %) are widely used, while quantitative studies (7 studies, 23 %) emphasize statistical analysis and measurable outcomes.

The target populations in the included studies vary across different educational levels and professional groups. Music teachers represent the largest group, with 11 studies (37 %). High school students are also a significant group, featured in 10 studies (33 %). Higher education students and primary school students are each examined in 6 studies (20 %), while faculty members at universities are the focus of 4 studies (13.3 %). Secondary school students appear in only 2 studies (6.7 %) and students with disabilities (2 studies, 6.7 %) are investigated, highlighting an interest in professional development and inclusive education.

2.6. Analytic strategy

A coding scheme (including the info on Table A2) was developed based on the research questions to systematically analyze the included publications. The coding framework consists of four main categories corresponding to the research focus: educational dimensions of music education models (RQ1), technologies used (RQ2), learning outcomes (RQ3), and challenges/limitations (RQ4). There are 4 categories, 16 subcategories, and 54 labels for all subcategories.

All selected studies were entered into ATLAS.ti 9 for qualitative data analysis [45]. The studies were coded using the defined scheme, ensuring consistency in the classification of findings. To examine inter-rater reliability, two papers were randomly selected and coded by two independent coders. The Cohen's Kappa result showed 87 % agreement ($\kappa = 0.74$, $p < .001$), indicating substantial consistency and reliability in the coding process.

Descriptive statistics, including absolute frequencies (n) and percentages of the 30 included studies, were used to quantitatively summarize the characteristics of the included studies and the distribution of coded categories. These calculations were performed using Microsoft

Excel. Finally, this data was entered into the yEd Graph Editor, through which outputs related to graphs were obtained.

3. Results

3.1. RQ1: what are the educational dimensions of TEMLeM?

Tables 3 and 4 presents the distribution of educational key dimensions identified in TEMLeM across the 30 studies included in this systematic review. The educational dimensions are categorized into Five main components: Pedagogical Approach (A1), Instructional Design Level (A2), Learner Proficiency Level (A3), Stakeholders (A4), and Learning Theory and Strategies(A5). These dimensions were selected based on established frameworks in educational research literature. The pedagogical approach categories follow foundational learning theories that guide instructional design [42,127]. The distinction between macro and micro instructional design levels reflects standard educational planning hierarchies [19,114]. Learner proficiency classifications align with common developmental stages in music education [53,81]. The stakeholder categories correspond to age-based educational groupings typically used in educational research [70,107].

Table 3 displays the number of studies incorporating each dimension, the corresponding percentage of the total included studies, and the specific references to these studies. Many studies incorporated multiple approaches within each dimension, resulting in overlapping categorizations.

The analysis of the included studies revealed several notable patterns regarding the educational dimensions of music education models based on Technology-Enhanced Learning. Constructivism emerged as the dominant theoretical foundation, appearing in 25 studies (83 %). This substantial representation demonstrates a clear preference for learner-centered, experiential approaches in technology-enhanced music education. In contrast, behaviorism was identified in only 3 studies (10 %), and cognitivism in 3 studies (10 %), while connectivism appeared in 4 studies (13 %). Some studies incorporated multiple pedagogical approaches, as evidenced by Johnson [64], which integrated elements of behaviorism, cognitivism, and constructivism.

Regarding instructional design levels, a relatively balanced distribution was observed between macro-level designs (19 studies, 63 %) focusing on broad curriculum development, and micro-level approaches (17 studies, 57 %). Several studies, such as Mohammadian [90], Nijs and Behzadaval [101], and Castellano [24], incorporated both levels.

The learner proficiency levels addressed in the models showed a preference for beginner-level instruction (17 studies, 57 %), followed by intermediate-level approaches (11 studies, 37 %). Advanced proficiency received comparatively less attention, appearing in 10 studies (33 %). Notably, several studies (including [13,64,90]; and [147]) designed models applicable across multiple proficiency levels.

Analysis of stakeholder demographics revealed that adults (ages 19+) were the most frequently targeted group, appearing in 19 studies (63 %). Adolescents (ages 13–18) were represented in 13 studies (43 %), while children (ages 6–12) received the least attention, appearing in only 5 studies (17 %). Some studies (such as [59,130]) developed models applicable to multiple age groups, while others (like [13] and [90]) created frameworks relevant across all age groups.

The analysis of Learning Theories and Strategies revealed a diverse implementation of approaches across the included studies. Constructivist and Cognitive Theories (A52) and Personalized and Learner-Centered Approaches (A55) were the most frequently identified categories, each appearing in 10 studies (33 %). These were closely followed by Instructional Design Models (A53) and Blended and Flexible Learning Approaches (A54), each represented in 9 studies (30 %). Technological-Pedagogical Frameworks (A51) appeared in 8 studies (27 %), while Music-Specific Pedagogical Theories (A56) were identified in 7 studies (23 %). Several studies integrated multiple theoretical frameworks and strategies, with Imperio [60] and Mohammadian [90] notably

Table 3

Educational dimensions of TEMLeM.

Educational dimensions	Label	N of studies	Pct.	References
Pedagogical Approach (A1)	Behaviorism (A11)	3	10 %	Behzadaval and Vahedi [13], Johnson [64], Engizli and Uludag [41],
	Cognitivism (A12)	3	10 %	Mohammadyan and Pourroostaei Ardakani [91]; Mohammadyan and Purrustaei Ardakani [92], Johnson [64],
	Constructivism (A13)	25	83 %	Castellano [24], Bowman [18], C.N. Edward et al. [39], Imperio [60], Chen [25], Horton [59], Kuyumcu [71], Welch [147], Shcherbak et al. [126], Pavlenko et al. [108], Behzadaval [12], Cremata [28], Tuisku and Ruokonen [136], Johnson [64], Zhang and Zhang [154], Nedelcut and Pop [97], Tejada and Morel [128],
Instructional Design Level (A2)	Connectivism (A14)	4	13 %	Gértrudix Barrio [47], Nijs and Behzadaval [101], Mohammadian [90], Kibici [67], Teke and Sever [130], Dorfman [38], Häberlin [52], Tejada and Morel [128], Häberlin [52], Cremata [28], Shcherbak et al. [126],
	Macro Level (A21)	19	63 %	Gértrudix Barrio [47], Mohammadyan and Pourroostaei Ardakani [91]; Mohammadyan and Purrustaei Ardakani [92], Castellano [24], Häberlin [52], Welch [147], Shcherbak et al. [126], Pavlenko et al. [108], Dorfman [38], Behzadaval and Vahedi [13], Johnson [64], Zhang and Zhang [154], Nedelcut and Pop [97], Gértrudix Barrio [47], Nijs and Behzadaval [101], Mohammadian [90],
	Micro Level (A22)	17	57 %	Tuisku and Ruokonen [136], Horton [59], Kuyumcu [71], Imperio [60], Loo et al. [77], Imperio [60], Chen [25], Horton [59], Behzadaval [12], Engizli and Uludag [41], Nijs and Behzadaval [101], Mohammadian [90], Aksoy [4], Kibici [67], Teke and Sever [130], Castellano [24], Häberlin [52], Bowman [18], C.N.

(continued on next page)

Table 3 (continued)

Educational dimensions	Label	N of studies	Pct.	References
Learner Proficiency Level (A3)	Beginner (A31)	17	57 %	Edward et al. [39], Tejada and Morel [128], Gértrudix Barrio [47], Mohammadyan and Pourroostaei Ardakani [91]; Mohammadyan and Purrustaei Ardakani [92], Imperio [60], Chen [25], Horton [59], Welch [147], Behzadaval [12], Tuisku and Ruokonen [136], Behzadaval and Vahedi [13], Johnson [64], Gértrudix Barrio [47], Nijs and Behzadaval [101], Mohammadian [90], Aksoy [4], Kibici [67], Teke and Sever [130], Horton [59],
	Intermediate (A32)	11	37 %	Loo et al. [77], C.N. Edward et al. [39], Behzadaval and Vahedi [13], Johnson [64], Zhang and Zhang [154], Engizli and Uludag [41], Tejada and Morel [128], Nijs and Behzadaval [101], Mohammadian [90], Teke and Sever [130], Kuyumcu [71], Castellano [24], Häberlin [52], Shcherbak et al. [126], Pavlenko et al. [108], Dorfman [38], Behzadaval and Vahedi [13], Johnson [64], Zhang and Zhang [154], Mohammadian [90], Welch [147],
	Advanced (A33)	10	33 %	Chen [25], Behzadaval [12], Behzadaval and Vahedi [13], Teke and Sever [130], Horton [59],
Stakeholders (A4)	Children (A41)	5	17 %	Mohammadyan and Pourroostaei Ardakani [91]; Mohammadyan and Purrustaei Ardakani [92], Loo et al. [77], C.N. Edward et al. [39], Horton [59], Welch [147], Behzadaval and Vahedi [13], Engizli and Uludag [41], Mohammadian [90], Kibici [67], Teke and Sever [130], Imperio [60], Gértrudix Barrio [47],
	Adolescents(A42)	13	43 %	Castellano [24], Häberlin [52], Shcherbak et al. [126], Pavlenko et al. [108], Cremata [28], Tuisku and Ruokonen [136], Behzadaval and Vahedi [13], Johnson [64], Zhang and Zhang [154],
	Adults (A43)	19	63 %	

Table 3 (continued)

Educational dimensions	Label	N of studies	Pct.	References
Learning Theories and Strategies (A5)	Technological-Pedagogical Frameworks (A51)	8	27 %	[154], Nedelcut and Pop [97], Tejada and Morel [128], Mohammadian [90], Aksoy [4], Welch [147], Dorfman [38], Teke and Sever [130], Horton [59], Bowman [18], Kuyumcu [71], Welch [147], Dorfman [38], Tejada and Morel [128], Bowman [18], Horton [59], Castellano [24], Häberlin [52], Mohammadin (2024) Gértrudix Barrio [47], Cremata [28], Chen [25], Imperio [60], Mohammadian [90], Nijs and Behzadaval [101], Shcherbak et al. [126], Behzadaval [12], Pavlenko et al. [108], Zhang and Zhang [154]
	Constructivist and Cognitive Theories (A52)	10	33 %	Behzadaval and Vahedi [13], Engizli and Uludag [41], Castellano [24], Kibici [67], Mohammadyan and Pourroostaei Ardakani [91], Mohammadyan and Purrustaei Ardakani [92], Imperio [60], Mohammadian [90], Behzadaval [12]
	Instructional Design Models (A53)	9	30 %	Tuisku and Ruokonen [136], Chamila Nishanthi Edward et al. [39], Johnson [64], Kuyumcu [71], Nedelcut and Pop [97], Engizli and Uludag [41], Pavlenko et al. [108], Shcherbak et al. [126], Häberlin [52]
	Blended and Flexible Learning Approaches (A54)	9	30 %	Tuisku and Ruokonen [136], Chen [25], Loo et al. [77], Imperio [60], Mohammadian [90], Pavlenko et al. [108], Zhang and Zhang [154], Teke and Sever [130], Aksoy [4], Nedelcut and Pop [97]
	Personalized and Learner-Centered Approaches (A55)	10	33 %	Gértrudix Barrio [47], Imperio [60], Mohammadian [90], Häberlin [52], Tejada and Morel [128], Welch [147], Nijs and Behzadaval [101]
	Music-Specific Pedagogical Theories (A56)	7	23 %	

incorporating four different approaches. Other studies, such as Häberlin [52], demonstrated a comprehensive approach by combining Technological-Pedagogical Frameworks with Blended Learning and Music-Specific Pedagogical Theories. This distribution reflects the field's increasing recognition of the need for multifaceted theoretical foundations in technology-enhanced music education models, with particular

Table 4

Utilized technologies are in TEMLeM Based on Coding Scheme.

Technologies Used	Label	N of studies	Pct.	Mean Pct.	Overall Pct.	References
Digital Tools & Software	Digital content	10	33 %	43 %	27 studies 90 %	Loo et al. [77], Mohammadyan and Pourroostaei Ardakani [91]; Mohammadyan and Purrustaei Ardakani [92], Bowman [18], C.N. Edward et al. [39], Welch [147], Pavlenko et al. [108], Tuisku and Ruokonen [136], Zhang and Zhang [154], Aksoy [4],
	Music Software	17	57 %			Castellano [24], Bowman [18], Imperio [60], Chen [25], Horton [59], Kuyumcu [71], Welch [147], Shcherbak et al. [126], Pavlenko et al. [108], Cremata [28], Johnson [64], Engizli and Uludag [41], Nedelcut and Pop [97], Tejada and Morel [128], Gértrudix Barrio [47], Mohammadian [90], Teke and Sever [130],
	Interactive Music Learning Apps	12	40 %			Chen [25], Häberlin [52], Horton [59], Kuyumcu [71], Shcherbak et al. [126], Behzadaval [12], Behzadaval and Vahedi [13], Johnson [64], Zhang and Zhang [154], Engizli and Uludag [41], Nijs and Behzadaval [101], Mohammadian [90],
AI & Adaptive Technologies	AI-Based Tutoring Systems	3	10 %	10 %	6 studies 20 %	Shcherbak et al. [126], Zhang and Zhang [154], Mohammadian [90],
	Automated Music Assessment Tools	3	10 %			Zhang and Zhang [154], Engizli and Uludag [41], Mohammadian [90],
	Audio Analysis & Visualization	3	10 %			Horton [59], Nijs and Behzadaval [101], Mohammadian [90],
Simulation, Virtual & Augmented Reality	Virtual Reality (VR) Applications	1	3 %	5 %	5 studies 17 %	Shcherbak et al. [126],
	Augmented Reality (AR) Applications	2	7 %			Behzadaval [12], Nijs and Behzadaval [101],
	Game-Based Learning	2	7 %			Engizli and Uludag [41], Teke and Sever [130],
	Motion Tracking Devices	1	3 %			Nijs and Behzadaval [101],
Online Learning & Communication Platforms	LMS and Online Courses	16	53 %	50 %	24 studies 80 %	Castellano [24], Mohammadyan and Pourroostaei Ardakani [91]; Mohammadyan and Purrustaei Ardakani [92], Bowman [18], C.N. Edward et al. [39], Häberlin [52], Kuyumcu [71], Cremata [28], Dorfman [38], Tuisku and Ruokonen [136], Behzadaval and Vahedi [13], Johnson [64], Nedelcut and Pop [97], Tejada and Morel [128], Mohammadian [90], Kibici [67],
	Video Conferencing Tools	16	53 %			Castellano [24], Mohammadyan and Pourroostaei Ardakani [91]; Mohammadyan and Purrustaei Ardakani [92], Bowman [18], Imperio [60], Häberlin [52], Kuyumcu [71], Pavlenko et al. [108], Cremata [28], Johnson [64], Zhang and Zhang [154], Nedelcut and Pop [97], Mohammadian [90], Aksoy [4], Kibici [67], Teke and Sever [130],
	Collaborative Platforms	13	43 %			Castellano [24], Häberlin [52], Kuyumcu [71], Pavlenko et al. [108], Cremata [28], Dorfman [38], Johnson [64], Engizli and Uludag [41], Nedelcut and Pop [97], Gértrudix Barrio [47], Aksoy [4], Kibici [67], Teke and Sever [130],
Music Performance & Practice Technologies	Digital Instruments & MIDI Controllers	6	20 %	14 %	6 studies 20 %	Imperio [60], Horton [59], Tejada and Morel [128], Gértrudix Barrio [47], Nijs and Behzadaval [101], Mohammadian [90],
	Smart Wearables	2	7 %			Imperio [60], Horton [59],

emphasis on constructivist principles and personalized learning pathways.¹ The following section provides a detailed analysis of the learning theories and strategies employed across the selected studies, offering further insights into their theoretical foundations.

3.1.1. Learning theories and strategies

The Table A3 presents an analysis of learning theories and strategies utilized in each study in detail. The Learning Theory and Strategy dimension provides critical insights into the theoretical foundations guiding technology integration in music education. The analysis reveals a rich tapestry of learning theories and instructional strategies employed in technology-enhanced music education. Constructivist approaches emerged as the dominant theoretical foundation, with 10 studies (33 %) explicitly incorporating constructivist or social constructivist principles.

The TPack (Technological Pedagogical Content Knowledge) framework was the most frequently cited specific model, appearing in 7 studies (23 %). This framework's popularity reflects its utility in conceptualizing the complex relationships between technological,

pedagogical, and content knowledge required for effective technology integration in music education. Studies by Welch [147], Dorfman [37], Tejada and Morel [128], Bowman [18], Horton [59], Häberlin [52], and Castellano [24] all employed this framework to guide their instructional design.

Blended learning approaches represented another significant theoretical strand, appearing in 5 studies (17 %). These models integrate face-to-face and online learning components, reflecting the growing importance of flexible delivery methods in music education. Studies by Tuisku and Ruokonen [136], Chamila Nishanthi Edward et al. [39], Johnson [64], and Engizli and Uludag [41].

Notably, 12 studies (40 %) incorporated multiple complementary learning theories, suggesting a trend toward theoretical integration. For example, Imperio [60] combined social constructivism with comprehensive musicianship, spiral curriculum, and informal learning approaches, while Mohammadian [90] integrated constructivism, learner-centered approaches, self-regulation, and motivation theories.

The data also reveals the emergence of specialized theoretical frameworks tailored to technology-enhanced music education. Embodied approaches, represented in studies by Nijs and Behzadaval [101], emphasize the role of physical interaction in musical learning through technology. Similarly, the neuropedagogical approach in Shcherbak et al. [126] examines how understanding brain function can

¹ For further details and visual representation of the data, refer to the graphs in Appendix Graph 1 and Graph 2, which provide additional insights into the findings.

inform technology-enhanced music instruction.

Motivational frameworks appeared in 2 studies (7 %). Keller's ARCS model identified in studies by Teke and Sever [130] and Mohammadian [90]. Instructional design models provided structured approaches to implementing technology in music education, with models such as ADDIE [13,24], 5E [67], ASSURE [41], and Bruner's Spiral Curriculum [60,90–92] appearing across multiple studies.

Based on Fig. 2 the temporal distribution² of educational dimensions reveals distinct patterns across categories, with Constructivism dominating throughout the period (25 total studies, 83 %), showing steady presence from 2010–2023 before surging to 11 studies (37 %) in 2024. Behaviorism and Cognitivism emerged only after 2019, each appearing in just 3 studies total (10 %), while Connectivism remained sporadic with 4 studies (13 %) across the timeframe. Instructional design levels showed balanced development, with Macro Level (19 studies, 63 %) and Micro Level (17 studies, 57 %) both peaking in 2024 at 8 and 9 studies (30 %) respectively. Among learner proficiency levels, Beginner-focused studies (17 total, 57 %) maintained the most consistent presence, while Intermediate (11 studies, 37 %) and Advanced (10 studies, 33 %) categories showed later emergence and concentration in 2022–2024. Stakeholder demographics revealed Adults as the most studied group (19 studies, 63 %), followed by Adolescents (13 studies, 43 %), with Children receiving minimal attention (5 studies, 17 %). Learning theories demonstrated varied temporal patterns: Constructivist and Cognitive Theories concentrated heavily in 2024 (7 of 10 total studies), while Instructional Design Models emerged primarily after 2019, and Music-Specific Pedagogical Theories appeared sporadically throughout the period (7 studies, 23 %).³

3.2. RQ2: which technologies are utilized in TEMLeM?

Based on Table A4 and Table 4, the analysis of included studies revealed a diverse range of technologies utilized in TEMLeM. Table A4 lists all the technologies used in each individual study, while Table 4 organizes these technologies into distinct categories and subcategories based on a pre-designed classification scheme.

Based on Table A4 the most prevalent technology category was Learning Management Systems (LMS), appearing in 14 studies (47 %). These platforms, including Moodle, Canvas, and MusicFirst, provided structured environments for course delivery, content organization, and student assessment. Videoconferencing and synchronous communication tools represented the second most common category, implemented in 13 studies (43 %). Platforms such as Zoom, Skype, and Google Meet became particularly important for supporting real-time instruction and feedback in remote learning contexts.

Mobile learning technologies emerged as a significant trend, appearing in 10 studies (33 %). These included specialized music applications, smartphone-based tools, and tablet implementations like GarageBand. Digital Audio Workstations (DAWs) and music production software were utilized in 8 studies (27 %), facilitating composition, recording, and performance activities.

The data also reveals the emergence of innovative technologies, including augmented reality (AR) systems in Nijs and Behzadaval [101], artificial intelligence applications in Cremata [28] and Zhang and Zhang [154], and specialized music education software like EarToner and GNU Solfege in Shcherbak et al. [126].

² To enhance visual clarity in this chart, small vertical offsets (0.05 intervals) have been applied to data points where multiple categories share identical values in the same year. For example, if three categories each had a value of 1 in 2019, they are displayed as 1.00, 1.05, and 1.10. This minor adjustment prevents line overlap while preserving the data's integrity and trend patterns.

³ For further details and visual representation of the data, refer to the graphs in Appendix Graph 3 and Diagram 3, which provide additional insights into the findings.

Notably, 28 studies (93 %) employed technology combinations rather than single tools. For example, Imperio [60] integrated videoconferencing, notation software, collaboration tools, and mobile applications into a comprehensive technological ecosystem. Similarly, Mohammadian [90] combined LMS, mobile learning, audio signal processing, and e-assessment technologies to support multiple aspects of the music learning process.

The chronological analysis reveals an evolution from basic digital content delivery systems and multimedia presentations in earlier studies (2010–2017) toward more sophisticated, interactive, and specialized technologies in recent research (2018–2024).⁴

3.2.1. Technology classification

In the following Table 4, utilized technologies based on a coding scheme is provided. This revised classification system offers a structured framework for analyzing technology usage patterns across studies. By categorizing technologies into major functional groups and specific subcategories, we can more precisely identify prevalent and emerging tools in technology-enhanced music education.

Based on Table 4, the technologies were classified into five main categories: Digital Tools & Software, AI & Adaptive Technologies, Simulation, Virtual & Augmented Reality, Online Learning & Communication Platforms, and Music Performance & Practice Technologies. Each category was further divided into specific subcategories to provide a more nuanced understanding of technology utilization.

The most prevalent technology categories were Digital Tools & Software, appearing in 27 studies (90 %), and Online Learning & Communication Platforms, in 24 studies (80 %). These categories encompass a variety of specific technologies, including music software, interactive apps, learning management systems, and video conferencing tools. In contrast, more specialized technologies such as AI & Adaptive Technologies and Simulation, Virtual & Augmented Reality were less frequently represented, each appearing in 6 studies (20 %) and 5 studies (17 %), respectively. Music Performance & Practice Technologies, including digital instruments and smart wearables, were also present in 6 studies (20 %).

Within the Digital Tools & Software category, Music Software was the most commonly mentioned, featured in 17 studies (57 %), followed by Interactive Music Learning Apps in 12 studies (40 %) and Digital Content in 10 studies (33 %). This highlights the central role of software in facilitating music creation, practice, and theory instruction. Similarly, in the Online Learning & Communication Platforms category, both Learning Management Systems (LMS) and Video Conferencing Tools were equally prevalent, each appearing in 16 studies (53 %), underscoring their importance in enabling remote instruction and collaboration. Collaborative Platforms were also notable, appearing in 13 studies (43 %).

The use of AI & Adaptive Technologies, though less widespread, included AI-Based Tutoring Systems, Automated Music Assessment Tools, and Audio Analysis & Visualization Tools, each mentioned in 3 studies (10 %). These technologies offer personalized learning experiences and automated feedback, indicating a growing interest in adaptive and intelligent systems for music education [41,90,126,155]. Simulation, Virtual & Augmented Reality technologies, such as Augmented Reality (AR) Applications [12,101] and Game-Based Learning [41,130], were featured in a smaller subset of studies, with each appearing in 2 studies (7 %), while Virtual Reality (VR) Applications [126] and Motion Tracking Devices [101] were mentioned in 1 study (3 %) each.

Music Performance & Practice Technologies, primarily Digital Instruments & MIDI Controllers, were utilized in 6 studies (20 %), with Smart Wearables [59,60] appearing in 2 studies (7 %). These technologies support hands-on practice and performance.

⁴ For further details and visual representation of the data, refer to the graphs in Appendix Diagram 4, which provide additional insights into the findings.

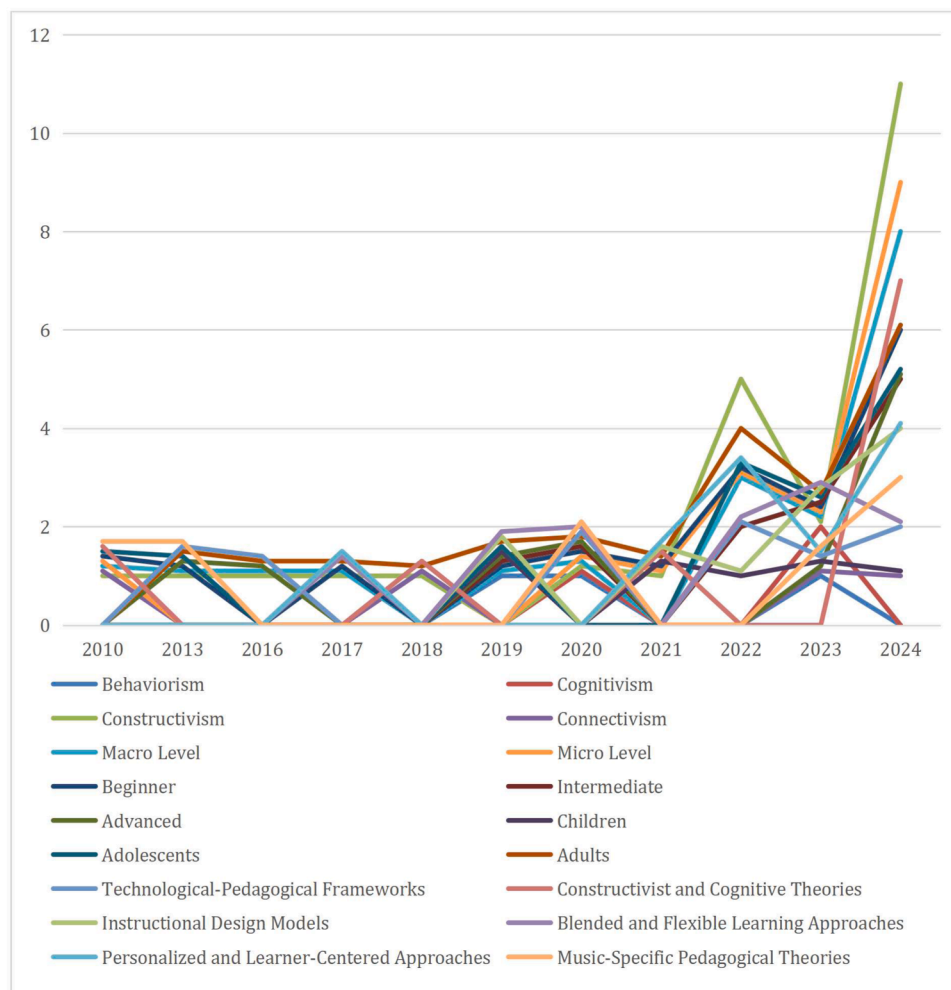


Fig. 2. Temporal Distribution of Educational Dimension.

Based on Fig. 3 The temporal analysis of technology utilization in music learning models reveals a stark transformation from minimal adoption (2010–2017) to rapid diversification and implementation (2022–2024). Music Software maintained the most consistent presence throughout the period, appearing sporadically until 2020, then surging to 6 implementations in 2024, reflecting its foundational role identified in 57 % of reviewed studies. The most dramatic shift occurred with AI and adaptive technologies, which emerged exclusively in 2024 with AI-Based Tutoring Systems (3 studies, 10 %), Automated Music Assessment Tools (2 studies, 7 %), and Audio Analysis & Visualization (2 studies, 7 %), suggesting a recent paradigm shift toward intelligent, personalized learning systems. Video Conferencing Tools showed steady growth from 2018 onwards, peaking at 5 studies (17 %) in 2024, likely accelerated by pandemic-driven remote learning needs. Digital communication platforms (LMS and Collaborative Platforms) demonstrated similar growth patterns, with LMS implementations jumping from 2 studies (7 %) in 2019–2020 to 4 studies (13 %) in 2022. Notably, immersive technologies (VR/AR) and specialized devices (Motion Tracking, Smart Wearables) appeared only in recent years (2021–2024), indicating an emerging trend toward more sophisticated, experiential learning environments.

3.3. RQ3: what are the learning outcomes of TEMLeM?

The systematic review of 30 studies identified four primary categories of learning outcomes associated with TEMLeM: Musical Knowledge, Music Performance Proficiency, Emotional & Aesthetic Learning,

and Pedagogical Music Teaching Skills. These categories emerged inductively from the analysis of the 30 selected studies, reflecting the educational objectives identified and reported within the reviewed literature. Table 5 below presents the distribution of these learning outcomes, detailing the number of studies (N), percentage of the total included studies (Pct.), mean percentage of sub-labels within each category (Mean Pct.), and overall percentage of studies addressing at least one sub-label per category (Overall Pct.). References to specific studies are included for each sub-label, where available.

Musical Knowledge emerged as a significant learning outcome category, with 18 studies (60 %) reporting at least one related sub-dimension. Within this category, three sub-dimensions were identified. Music Theory & Notation was the most frequently reported sub-dimension, appearing in 12 studies (40 %). This finding from studies by Shcherbak et al. [126], Behzadaval [12], Zhang and Zhang [154], Nedelcut and Pop [97], Gétrudix Barrio [47], Nijs and Behzadaval [101], Mohammadian [90], and Kibici [67], suggests that technology-enhanced approaches are particularly effective in facilitating the acquisition of foundational music literacy skills.

Music Analysis & Critical Thinking was addressed in 9 studies (30 %), indicating that technology also facilitates higher-order cognitive processes in music education. Mohammadyan and Pourroostaei Ardakani (2023a, 2023b) and Edward et al. [39] showed how digital tools enhanced students' analytical capabilities when examining musical compositions. Similarly, Chen [25], Tejada and Morel [128], and Gétrudix Barrio [47] found that technology-mediated environments promoted deeper analysis of musical structures. Additional research by

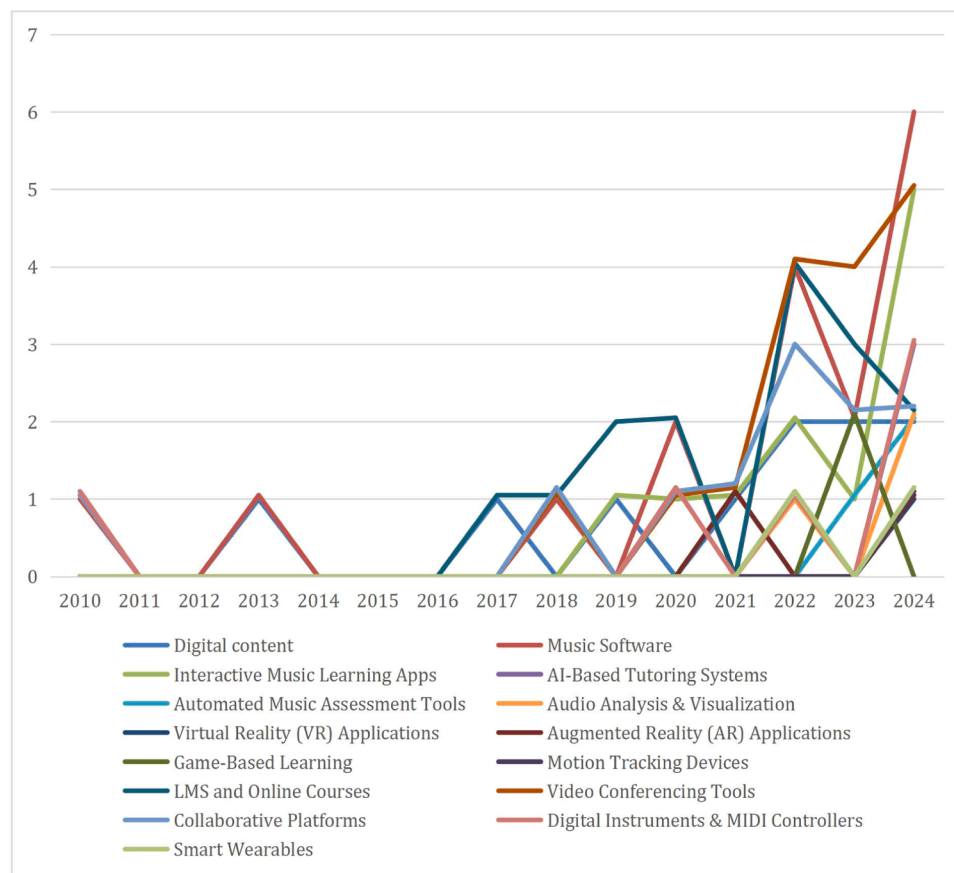


Fig. 3. Temporal Distribution of Technologies Utilized in TEMLeM (2010–2024).

Mohammadian [90], Kibici [67], and Teke and Sever [130] confirmed technology's potential to develop critical and cognitive thinking skills through music analysis tasks.

Music History, Cultural Awareness & Styles appeared in 7 studies (23 %). Loo et al. demonstrated that TEL improved students' understanding of diverse musical traditions. Edward et al. [39] found that digital resources expanded learners' cultural horizons, while Cremata [28] observed that technology facilitated cross-cultural music exploration and appreciation.

On the other hand, Music Performance Proficiency represented the most prevalent outcome category, with 21 studies (70 %) reporting at least one associated sub-dimension. Four distinct sub-dimensions emerged within this category. Technical and Instrumental Skills was the most frequently reported outcome overall, appearing in 16 studies (53 %). This finding underscores the significant role of technology in developing fundamental performance abilities. Loo et al. [77], found that digital feedback mechanisms enhanced precision in instrumental technique. Horton [59], Kuyumcu [71], and Shcherbak et al. [126] demonstrated how technology-supported practice improved motor skill development in instrumental performance. Additional studies by Pavlenko et al. [108], Tuisku and Ruokonen [136], Behzadaval and Vahedi [13], Nedelcut and Pop [97], Nijs and Behzadaval [101], Mohammadian [90], Aksoy [4], Kibici [67], and Teke and Sever [130] collectively confirmed technology's benefits for developing technical proficiency across various instruments.

Ensemble & Collaboration appeared in 9 studies (30 %), highlighting technology's capacity to support collective music-making. Bowman [18], Imperio [60], and Chen [25] found that digital platforms facilitated meaningful collaborative performance experiences. Horton [59] and Welch [147] demonstrated how technology-mediated environments enhanced ensemble coordination. Cremata [28], Behzadaval and Vahedi

[13], Engizli and Uludag [41], and Nijs and Behzadaval [101] observed improved collaborative skills through technology-enhanced group musical activities.

Composition & Creativity was identified in 5 studies (17 %), and Vocal & Listening Skills appeared in 4 studies (13 %). Edward et al. [39], Imperio [60], Shcherbak et al. [126], and Zhang and Zhang [154] found that technology-enhanced models improved aural perception, vocal production, and critical listening abilities.

Emotional & Aesthetic Learning emerged as a significant category, with 20 studies (67 %). Within this category, three sub-dimensions were identified. Motivation & Engagement was a prominently reported outcome, appearing in 15 studies (50 %). Loo et al. [77], Bowman [18], and Edward et al. [39] found that technology-enhanced models increased student interest and participation in music learning activities. Castellano [24], Chen [25], Horton [59], and Kuyumcu [71] demonstrated how digital tools captured and maintained learner attention. Additional research by Welch [147], Tuisku and Ruokonen [136], Zhang and Zhang [154], Engizli and Uludag [41], Nedelcut and Pop [97], G rtrudix Barrio [47], Aksoy [4], Kibici [67], and Teke and Sever [130] consistently showed that technology integration enhanced student motivation across various musical contexts.

Self-Regulated Learning was reported in 13 studies (43 %), indicating technology's role in fostering autonomous learning capabilities. Horton [59], Kuyumcu [71], and Shcherbak et al. [126] demonstrated how technology-enhanced models facilitated self-paced practice and reflection. Studies by Pavlenko et al. [108], Cremata [28], Dorfman [38], Tuisku and Ruokonen [136], Zhang and Zhang [154], Engizli and Uludag [41], and Teke and Sever [130] further confirmed technology's capacity to develop self-directed learning strategies in music education.

Emotional Expression in Performance appeared in 3 studies (10 %), and Music Appreciation & Aesthetic Sensitivity was reported in 2 studies

Table 5
Learning outcomes of TEMLeM.

Learning Outcomes	Label	N of studies	Pct.	Mean Pct.	Overall Pct.	References
Musical Knowledge	Music Theory & Notation	12	40 %	31 %	18 studies 60 %	Mohammadyan and Pourroostaei Ardakani [91]; Mohammadyan and Purrustaei Ardakani [92], Imperio [60], Chen [25], Shcherbak et al. [126], Behzadaval [12], Zhang and Zhang [154], Nedelcut and Pop [97], Gértrudix Barrio [47], Nijs and Behzadaval [101], Mohammadian [90], Kibici [67], Loo et al. [77], Mohammadyan and Pourroostaei Ardakani [91]; Mohammadyan and Purrustaei Ardakani [92], C.N. Edward et al. [39], Behzadaval [12], Cremata [28], Mohammadian [90], Mohammadyan and Pourroostaei Ardakani [91], Mohammadyan and Purrustaei Ardakani [92], C.N. Edward et al. [39], Chen [25], Tejada and Morel [128], Gértrudix Barrio [47], Mohammadian [90], Kibici [67], Teke and Sever [130],
	Music History, Cultural awareness & Styles	7	23 %			
	Music Analysis & Critical Thinking	9	30 %			
Music Performance Proficiency	Technical And Instrumental Skills	16	53 %	28 %	21 studies 70 %	Loo et al. [77], Mohammadyan and Pourroostaei Ardakani [91]; Mohammadyan and Purrustaei Ardakani [92], Imperio [60], Horton [59], Kuyumcu [71], Shcherbak et al. [126], Pavlenko et al. [108], Tuisku and Ruokonen [136], Behzadaval and Vahedi [13], Nedelcut and Pop [97], Nijs and Behzadaval [101], Mohammadian [90], Aksoy [4], Kibici [67], Teke and Sever [130],
	Vocal & Listening Skills	4	13 %			C.N. Edward et al. [39], Imperio [60], Shcherbak et al. [126], Zhang and Zhang [154],
	Composition & Creativity	5	17 %			Bowman [18], Imperio [60], Chen [25], Nedelcut and Pop [97], Nijs and Behzadaval [101],
	Ensemble & Collaboration	9	30 %			Bowman [18], Imperio [60], Chen [25], Horton [59], Welch [147], Cremata [28], Behzadaval and Vahedi [13], Engizli and Uludag [41], Nijs and Behzadaval [101],
Emotional & Aesthetic Learning	Emotional Expression in Performance	3	10 %	20 %	20 studies 67 %	Behzadaval [12], Behzadaval and Vahedi [13], Nedelcut and Pop [97],
	Music Appreciation & Aesthetic Sensitivity	2	7 %			Behzadaval [12], Behzadaval and Vahedi [13],
	Motivation & Engagement	15	50 %			Loo et al. [77], Bowman [18], C.N. Edward et al. [39], Castellano [24], Chen [25], Horton [59], Kuyumcu [71], Welch [147], Tuisku and Ruokonen [136], Zhang and Zhang [154], Engizli and Uludag [41], Nedelcut and Pop [97], Gértrudix Barrio [47], Aksoy [4], Kibici [67], Teke and Sever [130],
	Self-Regulated Learning	13	43 %			Loo et al. [77], Bowman [18], Häberlin [52], Horton [59], Kuyumcu [71], Shcherbak et al. [126], Pavlenko et al. [108], Cremata [28], Dorfman [38], Tuisku and Ruokonen [136], Zhang and Zhang [154], Engizli and Uludag [41], Teke and Sever [130],
Pedagogical Music Teaching Skills	Instructional Strategies	5	17 %	19 %	12 studies 40 %	Bowman [18], Häberlin [52], Shcherbak et al. [126], Dorfman [38], Tejada and Morel [128],
	Technology Integration in Teaching and Digital literacy	10	33 %			Castellano [24], Bowman [18], Häberlin [52], Horton [59], Welch [147], Shcherbak et al. [126], Pavlenko et al. [108], Dorfman [38], Tuisku and Ruokonen [136], Tejada and Morel [128],
	Accessibility & Equality	2	7 %			Aksoy [4], Welch [147]

(7 %). Some of these studies [12,13] demonstrated that technology-enhanced models deepened students' appreciation for musical aesthetics and heightened their sensitivity to expressive qualities in music..

Pedagogical Music Teaching Skills represented the fourth category, reported in 12 studies (40 %). Within this category, three sub-dimensions emerged. Technology Integration in Teaching and Digital Literacy was identified in 10 studies (33 %). Castellano [24], Bowman [18], and Häberlin [52] found that technology-enhanced models improved music educators' digital competencies. Horton [59], Welch [147], and Shcherbak et al. [126] demonstrated how digital integration enhanced instructional effectiveness. Studies by Pavlenko et al. [108], Dorfman [38], Tuisku and Ruokonen [136], and Tejada and Morel [128] further highlighted technology's role in expanding pedagogical approaches in music education.

Instructional Strategies appeared in 5 studies (17 %). Bowman [18], Häberlin [52], and Shcherbak et al. [126] found that technology-enhanced environments promoted the development of innovative teaching methods. Dorfman [38] and Tejada and Morel [128] demonstrated how digital tools expanded educators' instructional repertoires. Additionally, Accessibility & Equality was reported in 2 studies (7 %). Aksoy [4] and Welch [147] found that technology-enhanced models improved educational access and equality in music learning.

Based on Fig. 4 the temporal distribution of learning outcomes in TEMLeM demonstrates a marked shift from sporadic reporting (2010–2020) to comprehensive documentation of diverse outcomes (2021–2024). Technical and Instrumental Skills, the most frequently reported outcome (16 studies, 53 %), showed minimal presence until 2021, then dramatically increased to 5 studies each (17 %) in 2022 and 2024. Music Theory & Notation similarly surged from isolated appearances to 6 studies (20 %) in 2024. Motivation & Engagement maintained the most consistent presence across the timeline (15 studies, 50 %), with notable peaks in 2022 (5 studies, 17 %). Self-Regulated Learning emerged primarily after 2016, concentrating heavily in 2022–2024 (10 of 13 total studies). Notably, higher-order outcomes like Composition & Creativity and Vocal & Listening Skills appeared exclusively in recent years (2022–2024), while emotional outcomes (Emotional Expression, Music Appreciation) remained minimally reported throughout.

3.4. RQ4: what are the existing challenges and limitations in the design and implementation of TEMLeM?

Based on Table 6 The analysis of the 30 included studies revealed significant challenges and limitations affecting the design and implementation of TEMLeM. These challenges were categorized into three primary domains: Technological Challenges, Pedagogical Challenges, and Institutional & Cultural Barriers.

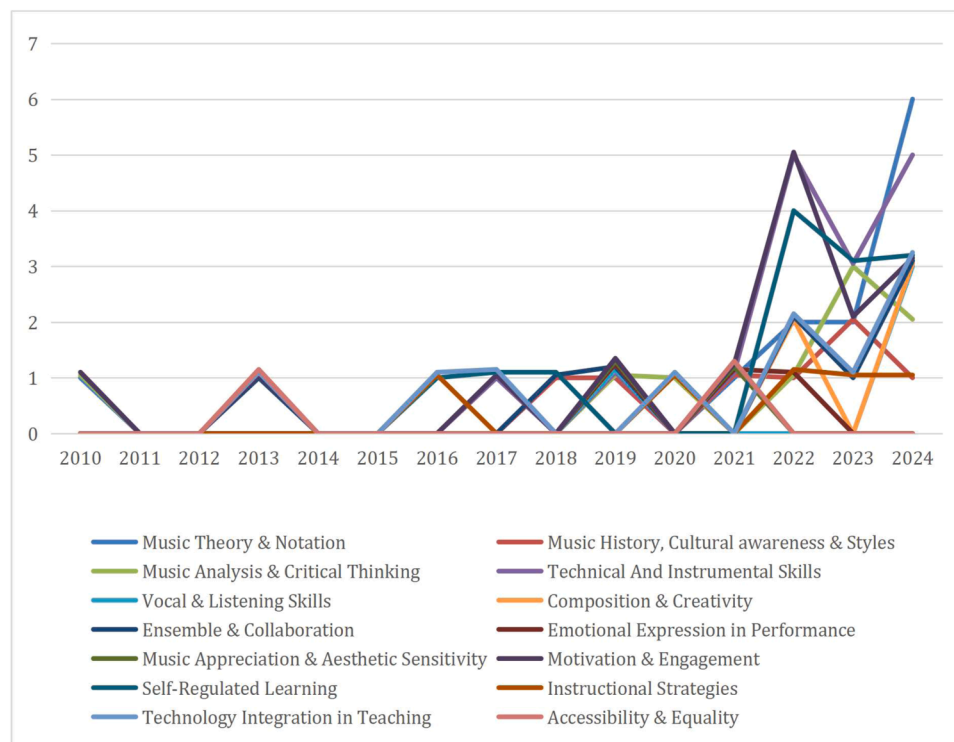


Fig. 4. Temporal Distribution of Learning Outcomes in TEMLeM (2010–2024).

Technological challenges were identified in 26 studies (87 %), constituting the most prevalent category of limitations. Technical Issues & Reliability emerged as the most significant subcategory, reported in 19 studies (63 %). Research by Loo et al. [77], Imperio [60], Häberlin [52], and Aksoy [4] highlighted various technical impediments including internet connectivity problems, latency issues during synchronous activities, audio quality limitations, and software compatibility concerns. These technical difficulties directly impacted the effectiveness of instruction and often interrupted learning processes.

Accessibility & Cost represented another substantial barrier, appearing in 16 studies (53 %). Studies by Castellano [24], Edward et al. [39], and Chen [25] documented disparities in access to required technologies, with socioeconomic factors contributing to a "digital divide" among students. Horton [59] specifically addressed how these barriers disproportionately affected students with disabilities and those from lower socioeconomic backgrounds.

Compatibility & Integration issues were noted in 7 studies (23 %), focusing on difficulties in incorporating technology-enhanced approaches with traditional music education methodologies and existing curriculum structures. Tuisku and Ruokonen [136] and Nijs and Behzadaval [101] emphasized challenges in seamlessly integrating digital tools with established pedagogical frameworks.

The Lack of Immediate Feedback was identified in 5 studies (17 %), with Johnson [64] and Nedelcut and Pop [97] highlighting the challenges in providing timely, personalized feedback in asynchronous learning environments, particularly for technical performance aspects requiring precise correction.

Pedagogical challenges were the most widespread category, appearing in 28 studies (93 %). Lack of Teacher Training emerged as a significant concern, mentioned in 12 studies (40 %). Research by Castellano [24], Bowman [18], and Chen [25] emphasized insufficient preparation of music educators for technology integration.

Similar prevalence was observed for Lack of Digital Literacy & Limited Adaptability, also appearing in 12 studies (40 %). Shcherbak et al. [126], Welch [147], and Kuyumcu [71] highlighted how limited technological proficiency among both teachers and students inhibited

effective engagement with digital learning environments. Additionally, several studies noted insufficient adaptability of existing technology tools to accommodate diverse learning needs and proficiency levels.

The absence of fundamental and experimental research was identified in 9 studies (30 %), with Mohammadyan and Pourroostaei Ardakani [91] and Mohammadian [90] emphasizing the need for more robust empirical evidence to guide the development of TEMLeM.

Issues related to Self-Regulation, Engagement & Motivation appeared in 7 studies (23 %), with Imperio [60] and Zhang and Zhang [154] documenting challenges in maintaining student motivation in digital learning environments, particularly when self-directed learning was required. Häberlin [52] noted the additional cognitive load imposed by navigating both musical content and technological interfaces.

Lack of Human Interaction was reported in 6 studies (20 %), with Loo et al. [77] and Kuyumcu [71] highlighting the diminished interpersonal dynamics and nonverbal communication essential to traditional music instruction. Johnson [64] specifically noted the challenges in fostering mentor-apprentice relationships in digital contexts.

Less frequently reported but still notable were Limitations in Expressiveness & Aesthetic Depth (4 studies, 13 %), Assessment Challenges (3 studies, 10 %), Anxiety & Stress (2 studies, 7 %), and Struggle with Motor Skills (1 study, 3 %), the latter specifically identified by Tuisku and Ruokonen [136].

Institutional and cultural barriers were reported in 16 studies (53 %), representing significant systemic challenges to implementation. Institutional Constraints and Curriculum Gaps were identified in 7 studies (23 %), with Castellano [24], Pavlenko et al. [108], and Tejada and Morel [128] highlighting rigidity in educational structures, inadequate curricular frameworks, and insufficient institutional support for technology integration.

Cultural Perceptions were also mentioned in 7 studies (23 %), with Mohammadyan and Purrustaei Ardakani [92] and Dorfman [38] documenting how cultural attitudes toward technology in music education varied across contexts and sometimes presented barriers to adoption. Cremata [28] specifically addressed how cultural traditions in music education could conflict with technological innovation.

Table 6
challenges and limitations in the design and implementation of TEMLeM.

Challenges/ Limitations	Label	N of studies	Pct.	Mean Pct.	Overall Pct.	References
Technological Challenges	Accessibility & Cost	16	53 %	39 %	26 studies 87 %	Castellano [24], Bowman [18], C.N. Edward et al. [39], Imperio [60], Chen [25], Häberlin [52], Horton [59], Welch [147], Pavlenko et al. [108], Cremata [28], Dorfman [38], Engizli and Uludag [41], Nedelcut and Pop [97], Nijs and Behzadaval [101], Aksoy [4], Kibici [67],
	Technical Issues & Reliability	19	63 %			Loo et al. [77], Imperio [60], Chen [25], Häberlin [52], Horton [59], Kuyumcu [71], Shcherbak et al. [126], Pavlenko et al. [108], Cremata [28], Johnson [64], Zhang and Zhang [154], Engizli and Uludag [41], Nedelcut and Pop [97],
	Compatibility & Integration	7	23 %			Tejada and Morel [128], Nijs and Behzadaval [101], Mohammadian [90], Aksoy [4], Kibici [67], Teke and Sever [130],
Pedagogical Challenges	Lack Of Immediate Feedback	5	17 %			C.N. Edward et al. [39], Cremata [28], Dorfman [38], Tuisku and Ruokonen [136], Gértrudix Barrio [47], Nijs and Behzadaval [101], Kibici [67],
	Lack of Human Interaction	6	20 %	20 %	28 studies 93 %	Johnson [64], Mohammadyan and Pourroostaei Ardakani [91], Mohammadyan and Purrustaei Ardakani [92], Nedelcut and Pop [97], Teke and Sever [130], Loo et al. [77], Häberlin [52], Kuyumcu [71], Johnson [64], Zhang and Zhang [154], Teke and Sever [130],
	Lack of Teacher Training	12	40 %			Castellano [24], Bowman [18], Chen [25], Welch [147], Pavlenko et al. [108], Cremata [28], Behzadaval and Vahedi [13], Johnson [64], Zhang and Zhang [154], Nedelcut and Pop [97], Gértrudix Barrio [47], Mohammadian [90],
	Lack of Digital Literacy & Limited Adaptability	12	40 %			Chen [25], Kuyumcu [71], Welch [147], Shcherbak et al. [126], Tuisku and Ruokonen [136], Engizli and Uludag [41], Nedelcut and Pop [97], Tejada and Morel [128], Gértrudix Barrio [47], Nijs and Behzadaval [101], Mohammadian [90], Kibici [67],
	Self-Regulation, Engagement & Motivation Issues	7	23 %			Castellano [24], Imperio [60], Häberlin [52], Tuisku and Ruokonen [136], Johnson [64], Zhang and Zhang [154], Engizli and Uludag [41],
	Limitations in Expressiveness & Aesthetic Depth	4	13 %			Bowman [18], Häberlin [52], Shcherbak et al. [126], Behzadaval and Vahedi [13],
	Lack of fundamental and experimental research	9	30 %			C.N. Edward et al. [39], Mohammadyan and Pourroostaei Ardakani [91]; Mohammadyan and Purrustaei Ardakani [92], Imperio [60], Chen [25], Shcherbak et al. [126], Behzadaval and Vahedi [13], Nijs and Behzadaval [101], Mohammadian [90],
	Struggle With Motor Skills	1	3 %			Tuisku and Ruokonen [136],
	Assessment Challenges	3	10 %			Johnson [64], Zhang and Zhang [154], Nedelcut and Pop [97],
	Anxiety & Stress	2	7 %			Engizli and Uludag [41], Teke and Sever [130],
Institutional & Cultural Barriers	Systemic limitations in education policies	4	13 %	16 %	16 studies 53 %	Mohammadyan and Pourroostaei Ardakani [91]; Mohammadyan and Purrustaei Ardakani [92], Behzadaval and Vahedi [13], Mohammadian [90],
	Resistance to Change	4	13 %			C.N. Edward et al. [39], Welch [147], Pavlenko et al. [108], Cremata [28],
	Institutional Constraints and Curriculum Gaps	7	23 %			Castellano [24], Horton [59], Kuyumcu [71], Pavlenko et al. [108], Behzadaval and Vahedi [13], Tejada and Morel [128], Mohammadian [90],
	Cultural Perceptions	7	23 %			Mohammadyan and Pourroostaei Ardakani [91]; Mohammadyan and Purrustaei Ardakani [92], Imperio [60], Cremata [28], Dorfman [38], Gértrudix Barrio [47], Mohammadian [90],
	Time Constraints	3	10 %			Tejada and Morel [128], Kuyumcu [71], Mohammadian [90],

Systemic limitations in education policies were reported in 4 studies (13 %), as were Resistance to Change (4 studies, 13 %), with Welch [147] and Pavlenko et al. [108] noting entrenched resistance among some educators and institutions. Time Constraints were mentioned in 3 studies (10 %), including Tejada and Morel [128] and Kuyumcu [71], highlighting the additional time required for technology integration beyond regular instructional hours.

Based on Fig. 5 the temporal analysis of challenges in TEMLeM reveals an escalation from minimal reporting (2010–2020) to comprehensive documentation of multifaceted barriers (2022–2024), with 86 of 128 total reported challenges (67 %) concentrated in the final three years. Technical Issues & Reliability emerged as the most frequently reported challenge (19 studies, 63 %), showing negligible presence until 2021, then surging to 7 studies (23 %) in 2024. Accessibility & Cost barriers similarly intensified, jumping from 1 study in 2021 to 5 studies (17 %) in 2024. Pedagogical challenges showed interesting temporal patterns: Lack of Teacher Training appeared consistently throughout the period but peaked in 2024 (5 studies, 17 %), while Lack of Digital

Literacy maintained steady presence before concentrating in 2022–2024 (7 of 12 studies). Notably, research-related challenges emerged predominantly in recent years, with Lack of Fundamental and Experimental Research appearing in 6 of 9 instances in 2024 alone. The minimal reporting during 2020–2021 (11 total challenges) seems paradoxical given pandemic disruptions, possibly indicating initial focus on rapid implementation over systematic challenge documentation. Institutional and cultural barriers showed consistent but modest presence throughout, while emerging challenges like Anxiety & Stress (2023) and specialized concerns like Motor Skills difficulties remained underreported.⁵

⁵ For further details and visual representation of the data, refer to the graphs in Appendix Graph 4, Graph 5 and Graph 6, which provide additional insights into the findings .

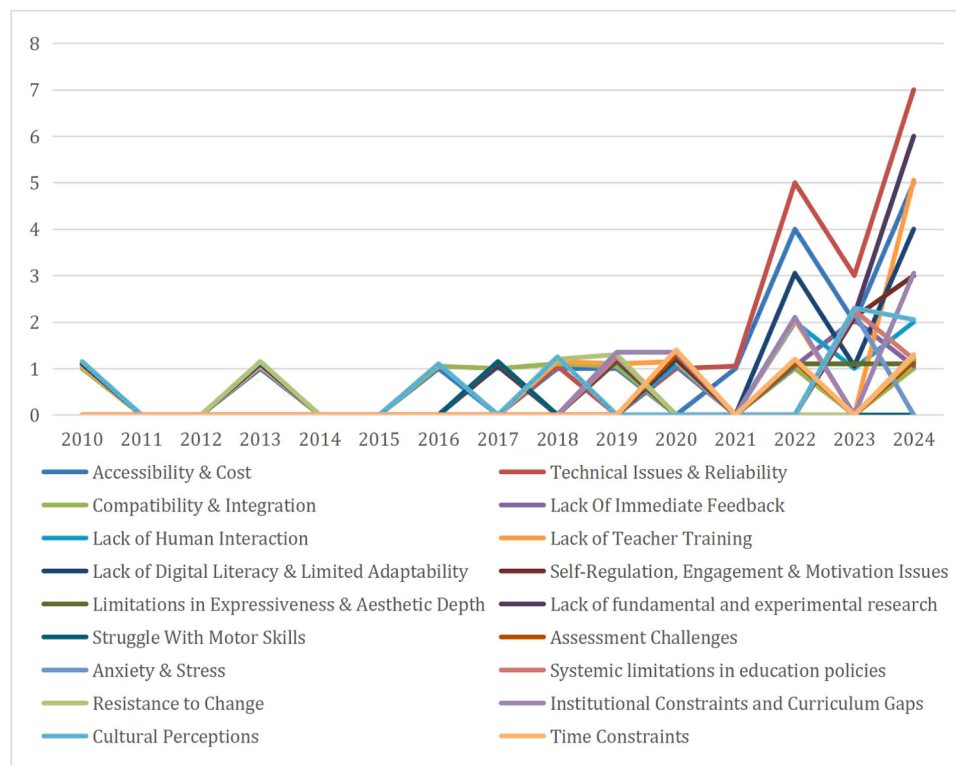


Fig. 5. Temporal Distribution of Challenges and Limitations in TEMLeM (2010–2024).

4. Discussion

4.1. Educational dimensions of TEMLeM

In addressing RQ1, the analysis of educational dimensions in TEMLeM reveals a pronounced dominance of constructivist pedagogical approaches (83 % of studies), with a strong emphasis on adult learners (63 %) and beginner proficiency levels (57 %). The temporal analysis demonstrates a significant paradigm shift from 2010–2024, with constructivist approaches intensifying dramatically in recent years, particularly in 2024. Learning theories show considerable diversity, with constructivist and cognitive theories alongside personalized and learner-centered approaches each appearing in 33 % of studies, while the TPACK framework emerged as the most frequently cited specific model (23 %).

The overwhelming prevalence of constructivism represents more than a methodological preference—it signals a fundamental reconceptualization of how musical knowledge is acquired in digital environments. This finding aligns with broader educational technology trends identified by Jonassen and Land [73], who argue that digital technologies inherently support constructivist principles through their capacity for interactivity, multimodal representation, and learner control. However, the near-absence of behaviorist (10 %) and cognitivist (10 %) approaches raises critical questions about the completeness of current pedagogical frameworks. The dominance of constructivism may inadvertently marginalize certain aspects of music learning that benefit from more structured, sequential approaches. As Hanna [54] demonstrated, certain foundational skills—particularly in music theory and technique—often require systematic drill and practice that aligns more closely with behaviorist principles. This finding contradicts the balanced pedagogical approach advocated by Ruthmann and Mantie [120], who argue for pedagogical pluralism in music education technology.

The relatively balanced distribution between macro-level (63 %) and micro-level (57 %) instructional design approaches, with several studies incorporating both, suggests an emerging holistic perspective. This

finding resonates with Reeves and Reeves' [113] authentic learning framework, which emphasizes the importance of connecting broader curricular goals with specific learning activities. The temporal concentration of both design levels in 2024 suggests a maturation of the field, where researchers increasingly recognize the necessity of addressing both curriculum-wide integration and classroom-level implementation. This aligns with Wang and Hannafin's (2005) design-based research paradigm, which advocates for iterative refinement across multiple levels of educational intervention.

The pronounced focus on beginner-level instruction (57 %) and adult learners (63 %) reveals significant disparities that challenge the assumption of democratized music learning through digital technologies. The underrepresentation of children (17 %) is particularly concerning given the documented benefits of early music education on cognitive development [53] and the digital nativity of younger generations. This adult-centric approach contradicts contemporary theories of differentiated instruction [133] and may inadvertently perpetuate educational inequities. The limited attention to advanced proficiency (33 %) suggests that current models may inadequately address the needs of developing musicians who require sophisticated feedback mechanisms and nuanced pedagogical approaches, contrasting sharply with the capabilities of modern music technology [153].

The diversity of learning theories employed indicates a field in theoretical flux, seeking appropriate frameworks for technology-mediated musical learning. The prominence of TPACK (23 %) reflects recognition of the unique knowledge domains required for effective technology integration, though its relatively low adoption rate suggests ongoing challenges in operationalizing this framework in music-specific contexts. The emergence of specialized frameworks—embodied music cognition and neuropedagogy—represents important theoretical innovations that acknowledge the unique characteristics of musical learning. These frameworks challenge the application of generic educational technology theories and support domain-specific theoretical development. The integration of multiple theoretical frameworks within individual studies suggests a move toward theoretical synthesis, aligning

with complexity theory in education [33], though this multiplicity also risks conceptual confusion.

The findings reveal significant practical implications, particularly regarding the implementation gap between theoretical frameworks and application. The concentration of studies in 2024 suggests growing awareness of implementation complexities as the field matures. While constructivism promises learner agency, collaborative meaning-making, and creative expression, the learning outcomes documented in 70 % of studies remain anchored in technical performance proficiency - suggesting that constructivist rhetoric has not yet been translated into constructivist practice. Educational institutions must recognize that the dominance of constructivist approaches requires fundamental shifts in assessment practices, teacher preparation, and resource allocation. The traditional conservatory model sits uneasily alongside constructivist principles, demanding innovative policy frameworks that can accommodate both traditional and technology-enhanced approaches. The diversity of theoretical frameworks highlights the urgent need for comprehensive professional development programs that treat technology as an integral component of music pedagogy rather than an add-on [10].

The demographic disparities demand immediate attention from researchers, educators, and policymakers. The focus on adult beginners neglects the transformative potential of technology for young learners and advancing musicians. The limited attention to children is particularly problematic given the critical period hypothesis in music learning [51] and technology's potential to provide multimodal, engaging experiences.

4.2. Technologies utilized in TEMLeM

In addressing RQ2, the systematic analysis of technologies employed in TEMLeM reveals a landscape dominated by foundational digital tools (90 %) and online platforms (80 %), yet characterized by significant gaps in specialized music technology adoption. The prevalence of generic educational technologies-particularly Learning Management Systems (53 %) and Video Conferencing Tools (53 %)-over music-specific innovations reveals a "technological conservatism paradox" that corroborates prior individual-context findings. Savage's [123] national survey found that ICT usage in music education reinforced traditional subject content rather than leveraging technology's broader potential, and Wise [143] observed that teachers remained fundamentally conservative in digital composition teaching. While Music Software represents the most common subcategory (57 %), its modest representation compared to generic platforms suggests superficial integration, aligning with Mroziak and Bowman's [95] critique that music educators use digital tools to replicate rather than reimagine practice. Waddell and Williamon (2019), surveying 338 international musicians, confirmed that the highest technology uses among teachers were administrative, while the lowest involved pedagogical functions such as giving feedback and tracking progress. The present study extends these observations by providing systematic quantitative evidence across 30 studies, demonstrating that technological conservatism constitutes a field-wide pattern rather than a context-specific phenomenon.

The temporal analysis reveals a striking acceleration in technological diversification from 2022-2024, with AI and adaptive technologies emerging exclusively in 2024. This sudden proliferation suggests reactive rather than pedagogically-motivated adoption, consistent with Daubney and Fautley's [34] documentation of the pandemic's sudden, unplanned shift to online music teaching and Pozo et al.'s [111] mixed evidence regarding whether forced technology adoption led to genuine transformation. The delayed emergence of AI-based tutoring systems (10 % of studies, all in 2024) is concerning given AI's decade-long development in education. Zhang et al. [155] confirmed that AI research in music education remains in its infancy compared to other educational sectors, and Merchán Sánchez-Jara et al. [84] identified intelligent tutoring systems as representing only 16 % of

AI-in-music-education literature.

The minimal adoption of immersive technologies (17 %) and motion tracking devices (3 %) is problematic given music's inherently embodied nature. Leman's [74] foundational framework established the body as a mediator between physical energy and musical engagement, and substantial empirical evidence supports embodied technology's effectiveness: Keebler et al. [66] found AR-based guitar instruction accelerated scale learning, Degli Innocenti et al. [35] reported statistically significant improvements with mobile VR for music genre identification, and Banquero et al. [8] demonstrated superior piano performance with mixed reality versus screen-based alternatives. The scarcity of smart wearables (7 %) is equally concerning, as van der Linden et al. [138] showed that wearable motion capture with vibrotactile feedback improved violin bowing with lasting retention, and Gonzalez-Sanchez et al. [50] demonstrated that motion-derived measures could distinguish musical skill levels. This gap contrasts with standard practices in sports science where motion analysis is commonplace [31]. Michalko et al. [86] found that instrumental teachers were largely unfamiliar with VR and wearable technologies, suggesting the gap reflects practitioner awareness rather than technology availability. This failure to leverage technologies that can capture and provide feedback on embodied aspects represents a significant missed opportunity, contrasting sharply with standard practices in sports science and physical rehabilitation where motion analysis is commonplace.

The modest representation of collaborative platforms (43 %) reveals a fundamental tension, as music-making is inherently social yet less than half of studies incorporated collaborative technologies. Rottondi et al. [121] identified an "Ensemble Performance Threshold" of approximately 25 milliseconds for synchronous musical performance, while Bartlette et al. [9] found musicians were strongly affected at delays of 100 milliseconds. The limited identification of specialized platforms (BandLab, Soundtrap) is significant given that Biasutti [14] demonstrated online settings can successfully support collaborative composition, and Rofo and Reuben [116] developed latency-control solutions enabling community musicians to perform without specialist networks. The present study reveals a translational gap between engineering-focused solutions and educational research adoption.

These patterns carry implications for theoretical development and practice. The dominance of generic technologies suggests a need to reconceptualize integration frameworks, as Macrides and Angeli [79] argued that TPACK is insufficient for music due to the missing affective domain, and Bauer [11] found technology knowledge to be the weakest TPACK component among music educators. Professionally, Haning [55] reported 43 % of pre-service music educators felt inadequately prepared for technology use, while Brudvik and Hebert [20] identified expense, accessibility, attitude, and complexity as key barriers. Doherty [36] found teachers predominantly learned technology on their own time, indicating systemic professional development failures. The temporal concentration of innovative technologies in 2024, echoing Camlin and Lisboa's [23] "digital turn," raises questions about whether institutional support structures can foster proactive innovation. The analysis contributes to existing literature by identifying critical areas requiring attention: music-specific AI systems [27,58], VR/AR applications for skill acquisition [5,125], and mainstream adoption of embodied technologies [140]. Future research must move beyond cataloging tools to evaluating pedagogical effectiveness through longitudinal studies.

4.3. Learning outcomes of TEMLeM

In addressing RQ3, the systematic analysis reveals multidimensional impacts across four domains: Music Performance Proficiency (70 % of studies), Emotional & Aesthetic Learning (67 %), Musical Knowledge (60 %), and Pedagogical Music Teaching Skills (40 %). Technical and Instrumental Skills (53 %) and Motivation & Engagement (50 %) emerged as the most frequently reported outcomes, while Emotional Expression in Performance (10 %), Music Appreciation & Aesthetic

Sensitivity (7 %), and Accessibility & Equality (7 %) received minimal attention. Temporal analysis shows a dramatic shift from sporadic reporting (2010–2020) to comprehensive documentation (2021–2024), with 67 % of outcomes concentrated in the final three years—a pattern consistent with recent reviews observing that digital tools most consistently target performance-related outcomes and engagement [72,152].

The predominance of Performance Proficiency over Musical Knowledge challenges assumptions that technology would primarily enhance theoretical understanding [10]. Instead, technology-enhanced models develop technical proficiencies through immediate feedback, aligning with Aquilino & Scavone [3] finding that most practice software is built around metronome and tuner paradigms, and Waddell et al.'s [141] observation that technology-mediated skill development is dominated by rhythmic accuracy. Critically, Composition & Creativity appeared in only 17 % of studies, corroborating Lam's [72] scoping review identifying only 17 empirical studies on technology-enhanced creativity in K-12 music across 35 years—confirming arguments by Webster [146] and Burnard [21] that creative dimensions remain marginalized. As Savage [123] observed, teachers continue traditionalist instruction after incorporating technology, and Tejada et al. [129] found student teachers surprised by creative potential beyond notation software, suggesting implementations perpetuate performance-oriented pedagogies.

A striking paradox emerges: Motivation & Engagement appeared in 50 % of studies, yet Emotional Expression in Performance in only 10 %. This extends evidence that technology boosts engagement without developing deeper capacities—Kim [68] demonstrated enhanced engagement and Nijs et al. [102] documented high flow states, yet neither found corresponding expressive gains. Meissner and Timmers [82,83] confirmed that dialogic teaching, not technology, improved expressiveness. The high Self-Regulated Learning prevalence (43 %) further suggests technology supports autonomous practice rather than interpretive dimensions, consistent with Karlsson and Juslin's [65] observation that technical instruction vastly outweighs expressive instruction.

Self-Regulated Learning's substantial representation extends the theoretical tradition of McPherson and Zimmerman [78] and corroborates Varela et al.'s [139] systematic review finding positive SRL-music learning relationships. Wan et al. [142] showed digital tools promoted independent problem-solving, though development depended on teacher facilitation. However, temporal concentration in 2022–2024 raises questions about pandemic-driven reactivity: Spahn et al. [122] found students developed more self-regulated methods during lockdown. Co-occurrence with Technical Skills suggests self-regulation primarily supports practice efficiency, echoing Miksza and Brenner's [87] finding that advanced violinists struggled with self-regulated strategies for broader musical objectives.

Minimal attention to Cultural Awareness & Styles (23 %) contrasts with calls for culturally responsive music education [56,80], suggesting implementations reinforce Western paradigms—substantiated by Yamaguchi's [149] analysis of AI tools' Euro-American training data bias, Allami's (2019) documentation of DAWs built for Western-mode music-making, and Ewell's [43] argument that Western-centric frames are structurally embedded in music technology. The near-absence of Accessibility & Equality outcomes (7 %) is troubling given technology's democratization claims, as Elpus and Abril [40] documented persistent enrollment disparities, and Park [106] and Merrick and Joseph [85] identified unequal digital music learning opportunities across regions.

Pedagogical Music Teaching Skills appeared in 40 % of studies, yet limited Instructional Strategies attention (17 %) reveals gaps between adoption and transformation—Bauer [11] found technology the weakest TPACK domain, Haning [55] reported 43 % of pre-service educators felt unprepared, and Bannerman and O'Leary [7] demonstrated personal technology use does not translate to pedagogical integration, a pattern Dorfman [38] documented in one-to-one environments.

These findings represent this study's central contribution to

theoretical debates. The theoretical dominance does not appear to translate into the holistic, creative, and aesthetic outcomes constructivism promises: 83 % of studies adopted constructivist frameworks, yet 70 % of reported outcomes centred on performance proficiency, with emotional expression (10 %) and aesthetic sensitivity (7 %) remaining largely absent—a theory-practice mismatch that runs through the field. The dominance of performance over aesthetic dimensions reflects the affective domain's underrepresentation identified by Macrides and Angeli (2020), necessitating reconceptualization through Burnard's [21] pluralist framework and Webster's [146] creative thinking model. Underrepresentation of collaborative outcomes (30 %) confirms Tobias's [132] argument that technology reinforces individual practice, despite evidence of collaborative music-making's value. Generic educational technology theories prove inadequate for music's embodied and cultural dimensions [79,102], demanding domain-specific frameworks [10].

Future research should investigate why expressive outcomes remain underrepresented, develop subjective assessment tools, examine SRL sustainability beyond pandemic conditions, and explore culturally responsive technology design addressing architectural biases. While technology effectively develops technical proficiency and learner autonomy, the systematic underrepresentation of aesthetic, cultural, and creative outcomes—consistent across multiple independent studies—suggests the field has yet to fully realize technology's transformative potential for music education.

4.4. Challenges and limitations in the design and implementation of TEMLeM

In addressing RQ4, the systematic analysis of 30 studies reveals a complex landscape of challenges affecting TEMLeM, with pedagogical challenges emerging as the most pervasive (93 % of studies), followed by technological challenges (87 %) and institutional & cultural barriers (53 %). The temporal concentration of reported challenges in 2022–2024 (67 % of all challenges) suggests not merely increased implementation but a maturation of the field's capacity to critically examine its own limitations.

The counterintuitive finding that pedagogical challenges exceed technological challenges contradicts prevailing assumptions about technology integration barriers. While conventional wisdom suggests technical infrastructure as the primary obstacle [69], our analysis reveals deeper pedagogical complexities. The equal prevalence of "Lack of Teacher Training" and "Lack of Digital Literacy & Limited Adaptability" (both 40 %) indicates a fundamental misalignment between technological possibilities and pedagogical preparedness. This finding aligns with Mishra and Koehler's [88] TPACK framework, yet our results suggest current implementations fail to achieve meaningful integration. As Bauer [10] argues, music educators often use technology to replicate traditional practices rather than transform them. The high prevalence of research gaps (30 % of studies) further indicates that evidence-based frameworks for technology-enhanced music pedagogy remain underdeveloped.

The prominence of "Technical Issues & Reliability" (63 %) reveals critical infrastructure gaps that undermine pedagogical innovation. Latency issues documented by Johnson [64] and audio quality limitations noted by Häberlin [52] are not merely technical inconveniences but fundamental barriers to musical communication. Music education's unique requirements for real-time synchronization, high-fidelity audio, and nuanced feedback mechanisms exceed the capabilities of generic educational technologies. This finding resonates with Dammers' [32] observation that music education requires specialized technological solutions. The temporal surge in technical challenge reporting suggests that as implementations scale, infrastructure limitations become increasingly apparent, indicating a critical mismatch between ambitious pedagogical goals and available technical capabilities.

The persistence of "Accessibility & Cost" barriers (53 %) despite

technological advancement reveals how the digital divide manifests uniquely in music education contexts. Unlike general educational technology, quality music education demands specialized software, high-quality audio equipment, and low-latency connections. Horton's [59] documentation of disproportionate impacts on students with disabilities and lower socioeconomic backgrounds highlights how technology may exacerbate existing inequalities rather than democratizing music education. This finding challenges the techno-optimistic narrative (Selwyn, 2011), as music-specific requirements create additional layers of exclusion. The minimal attention to accessibility in learning outcomes suggests the field has yet to seriously grapple with these equity implications.

The relatively low reporting of "Lack of Human Interaction" (20 %) presents an intriguing paradox given music education's historical emphasis on apprenticeship models and embodied learning [57]. This underreporting may indicate either successful mitigation strategies or a troubling normalization of reduced human interaction. The minimal attention to "Limitations in Expressiveness & Aesthetic Depth" (13 %) is particularly concerning, suggesting a potential shift toward technical proficiency at the expense of artistic development. This aligns with outcome analysis showing technical skills dominating over aesthetic sensitivity. The single study reporting "Struggle with Motor Skills" highlights a critical oversight, as musical performance inherently involves complex motor coordination that may be inadequately supported in digital environments.

The identification of institutional and cultural barriers in 53 % of studies reveals systemic challenges beyond individual or technical factors. The equal prevalence of "Institutional Constraints and Curriculum Gaps" and "Cultural Perceptions" (both 23 %) suggests dual challenges: rigid educational structures and cultural values conflicting with technological innovation. These findings align with Cuban's [30] analysis attributing technology integration failures to institutional cultures rather than technological limitations. The music education context adds complexity, as traditional conservatory models emphasize master-apprentice relationships seemingly antithetical to digital mediation. Cremata's [28] observations about conflicts between cultural traditions and technological innovation highlight deeply embedded pedagogical philosophies resisting transformation.

The minimal challenge reported during 2020–2021 despite pandemic-forced digital transitions presents a striking paradox, suggesting initial crisis-mode implementations prioritized continuity over critical evaluation. The subsequent surge in challenge identification indicates a shift from emergency response to systematic assessment. This temporal pattern aligns with the technology adoption lifecycle [117], where initial enthusiasm gives way to realistic appraisals. However, the concentration of research gap reports in 2024 suggests evidence-based understanding lags significantly behind implementation.

These findings challenge several theoretical assumptions underpinning technology-enhanced music education. The prevalence of pedagogical over technological challenges questions technology determinism, supporting instead a socio-technical systems perspective [134] where technological, pedagogical, and institutional factors interact dynamically. The minimal attention to aesthetic dimensions suggests a reductionist approach privileging measurable technical outcomes over holistic musical development.

The findings demand comprehensive interventions across multiple levels. The equal prevalence of teacher training and digital literacy gaps requires professional development integrating technological skills with pedagogical innovation through sustained, practice-based learning communities. Institutional barriers necessitate flexible curricular frameworks, music-specific funding mechanisms, and evaluation criteria valuing both technical proficiency and aesthetic development. Accessibility barriers demand targeted equity interventions addressing not only device access but specialized software and equipment need.

The substantial research gap indicates urgent need for longitudinal studies examining long-term impacts on musical development,

particularly regarding aesthetic sensitivity and creative expression. The underreporting of certain challenges suggests need for comprehensive assessment frameworks capturing embodied, emotional, and aesthetic dimensions. Future research must develop music-specific evaluation tools and investigate differential impacts across student populations.

The analysis reveals that challenges extend beyond technical issues to fundamental questions about musical learning in digital contexts. The predominance of pedagogical challenges, persistence of equity barriers, and underattention to aesthetic dimensions suggest current implementations may reproduce rather than transform traditional limitations. Addressing these challenges requires reconceptualizing music education for digital contexts while preserving essential human and aesthetic dimensions. The temporal concentration of challenge identification offers hope for developing critical awareness necessary for meaningful transformation, but substantial work remains to realize technology's potential for enhancing rather than diminishing musical learning.

4.5. A conceptual framework for utilizing learning strategies within TEMLeM

The systematic review revealed a gap in the field: the absence of a comprehensive conceptual framework that synthesizes prior research in TEMLeM into a cohesive structure of learning strategies [76,90,150]. While existing frameworks such as TPACK provide valuable theoretical foundations, they fail to address the unique multidimensional nature of music education that encompasses cognitive, psychomotor, affective, and aesthetic domains [95]. Based on our findings, we propose an evidence-based conceptual framework (Diagram 2). This conceptual framework addresses this gap by integrating the four categories identified in our analysis (Educational Dimensions, Technologies, Learning Outcomes, Challenges/Limitations) and transforming them into four key dimensions: Learning Conditions, Learning Outcomes, Learning Design, and Technology Integration.

The framework begins with Learning Conditions as the foundational layer, recognizing that effective technology-enhanced music education must be contextualized to learner characteristics. This component comprises two essential elements: stakeholders and learning proficiency levels. The stakeholder element acknowledges three primary age groups (Children, Adolescents, Adults). The proficiency structure acknowledges three tiers (Beginner, Intermediate, Advanced). This differentiation is crucial as each proficiency level demands distinct technological affordances and pedagogical approaches [136].

The Learning Outcome component represents the desired educational goals, synthesizing the four primary outcome categories identified in our analysis. Musical Knowledge encompasses theory, notation, history, and analytical skills. Music Performance Proficiency includes technical skills, ensemble collaboration, and creative expression. Emotional & Aesthetic Learning covers motivation, self-regulation, and aesthetic sensitivity. Finally, Pedagogical Music Teaching Skills focuses on technology integration and instructional strategies. This comprehensive outcome framework addresses the concerning imbalance identified in our analysis, where technical proficiency dominated over aesthetic and creative dimensions [13,101].

The Learning Design component serves as the pedagogical bridge between learner conditions and desired outcomes, incorporating three interconnected elements. The pedagogical approach element acknowledges four foundational learning theories including behaviorism, cognitivism, constructivism, and connectivism. The learning theory and strategies element synthesizes diverse theoretical frameworks, including Constructivist and Cognitive Theories, Instructional Design Models, Blended and Flexible Learning Approaches, and Personalized and Learner-Centered Approaches. The integration of multiple theoretical perspectives responds to the field's need for domain-specific frameworks that account for music education's unique characteristics [110]. The instructional design level element's balanced representation of macro-level and micro-level design approaches reflects the necessity of

addressing both curriculum-wide integration and classroom implementation [19,114].

The Technology Integration component addresses both opportunities and constraints in technology adoption. The framework categorizes diverse technologies identified across five main groups: Digital Tools & Software, AI & Adaptive Technologies, Simulation, Virtual & Augmented Reality, Online Learning & Communication Platforms, and Music Performance & Practice Technologies.

The framework operates through a cyclical, iterative process that begins with educators assessing learner conditions (age group and proficiency level) to establish the educational context. Based on these conditions, specific learning outcomes are selected from the four outcome categories, ensuring balanced attention to cognitive, performance, emotional, and pedagogical dimensions. Learning strategies are then selected and configured based on appropriate pedagogical approaches for the learner profile, relevant learning theories and strategies, and suitable instructional design levels. During implementation, technologies are selected and integrated while acknowledging potential challenges, with the bidirectional relationship between technologies and challenges emphasizing the need for continuous adaptation. The framework's cyclical nature supports continuous refinement based on outcomes achieved and challenges encountered. In Table A5 we provide some Key Insights for Framework Implementation.

5. Limitations and implications for future research

This systematic review presents several methodological and conceptual limitations. The temporal restriction (2010–2024) may exclude earlier foundational studies, while 77 % of the included research was published between 2022 and 2024, potentially overrepresenting implementations influenced by the COVID-19 period. Although the search strategy did not intentionally impose language or regional restrictions, the retrieved studies were predominantly published in English (83 %) and showed limited representation from Africa, Latin America, and several parts of Asia, which may restrict the generalizability of the findings across diverse educational contexts. In addition, as the search process concluded in 2025, more recent studies published in 2025 and 2026 were not included, which may limit the review's coverage of the latest developments in the field. While the sample of 30 studies reflects both the emerging nature of TEMLeM research and the rigorous quality appraisal applied, the findings should be interpreted cautiously given the relatively limited corpus of available studies.

Classification challenges arose from studies incorporating multiple overlapping pedagogical approaches, technologies, and outcomes. Quality appraisal revealed significant methodological variability, leading to 14 exclusions. The predominance of mixed-methods (40 %) and qualitative studies (37 %) over quantitative research (23 %) limits definitive conclusions about effectiveness. Also Including heterogeneous sources (e.g., dissertations, conference papers, and book chapters alongside journal articles) was necessary due to the emerging nature of the field. However, differences in peer-review processes and reporting standards may reduce methodological consistency and limit the comparability and reliability of the synthesized findings.

The demographic skew toward adult beginners (adults: 63 %, beginners: 57 %) while underrepresenting children (17 %) and advanced learners (33 %) contradicts evidence about critical periods for musical development and children's digital facility. This suggests current models inadequately support developmental progression toward professional musicianship.

The reliance on generic educational technologies (90 %) over specialized music tools, with AI emerging only in 2024 and minimal VR/AR adoption (17 %), indicates the field lags behind technological possibilities despite music's multimodal nature. Most critically, learning outcomes revealed fundamental imbalances: technical proficiency dominated while emotional expression (10 %), aesthetic sensitivity (7 %), and accessibility/equality (7 %) received minimal attention,

potentially producing technically proficient but artistically limited musicians.

Future research priorities include: developing integrated theoretical frameworks beyond constructivist dominance; establishing causal relationships through experimental designs and longitudinal studies; creating assessment instruments for aesthetic and creative dimensions; investigating emerging technologies (AI, VR/AR) for personalized learning and collaborative platforms; addressing underserved populations, particularly children and advanced learners; developing methodologies for holistic musical outcomes balancing technical proficiency with artistic development; examining conditions for sustainable technology integration including teacher preparation models and institutional support structures; conducting cross-cultural comparisons and cost-effectiveness analyses; and exploring innovative funding models to address persistent accessibility barriers.

These limitations highlight the need for comprehensive research addressing both methodological rigor and the full spectrum of musical learning in technology-enhanced contexts.

6. Conclusion

This systematic review of 30 studies (2010–2024) reveals both the potential and limitations of Technology-Enhanced Music Learning Models (TEMLeM). Our findings challenge prevailing assumptions about technology integration in music education and offer critical insights for advancing the field.

The prevalence of generic educational technologies (90 %) over specialized music tools indicates a failure to fully exploit domain-specific affordances. Most critically, the emphasis on technical proficiency came at the expense of aesthetic sensitivity (7 %) and emotional expression (10 %), potentially producing technically competent but artistically limited musicians.

The finding that pedagogical challenges (93 %) exceeded technological barriers (87 %) contradicts technology-centric narratives and highlights the need for fundamental reconceptualization of music pedagogy in digital contexts. The concentration of studies on adult beginners while neglecting children and advanced learners reveals significant gaps in addressing developmental trajectories and professional musicianship.

This review makes three key contributions. First, this study represents a focused systematic review of TEMLeM as a distinct research domain, providing empirical evidence of the current state of technology-enhanced music education and documenting both achievements and critical gaps. Second, unlike prior reviews addressing isolated dimensions, this study integrates pedagogy, technology, learning outcomes, and implementation challenges into a analytical discussion, offering a multi-dimensional portrait of the field. Third, the proposed conceptual framework constitutes an evidence-based structural model for TEMLeM, providing both theoretical grounding and practical design guidance for future implementations.

Technology-enhanced music education stands at a crossroads. The path forward requires moving beyond technological solutionism toward holistic models that balance technical proficiency with artistic expression, individual achievement with collaborative music-making, and digital innovation with human connection. Only through such integration can technology fulfill its promise of not merely replicating but transforming music education for the digital age.

CRedit authorship contribution statement

Rashed Mohammadian: Writing – original draft, Visualization, Validation, Software, Resources, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Saeid Pourroostaei Ardakani:** Writing – review & editing, Supervision, Project administration, Methodology, Data curation. **Esmail Zaraii Zavaraki:** Writing – review & editing, Validation, Supervision,

Resources, Project administration, Methodology, Investigation.

interests or personal relationships that could have appeared to influence the work reported in this paper.

Declaration of competing interest

The authors declare that they have no known competing financial

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at [doi:10.1016/j.caeo.2026.100354](https://doi.org/10.1016/j.caeo.2026.100354).

Appendix

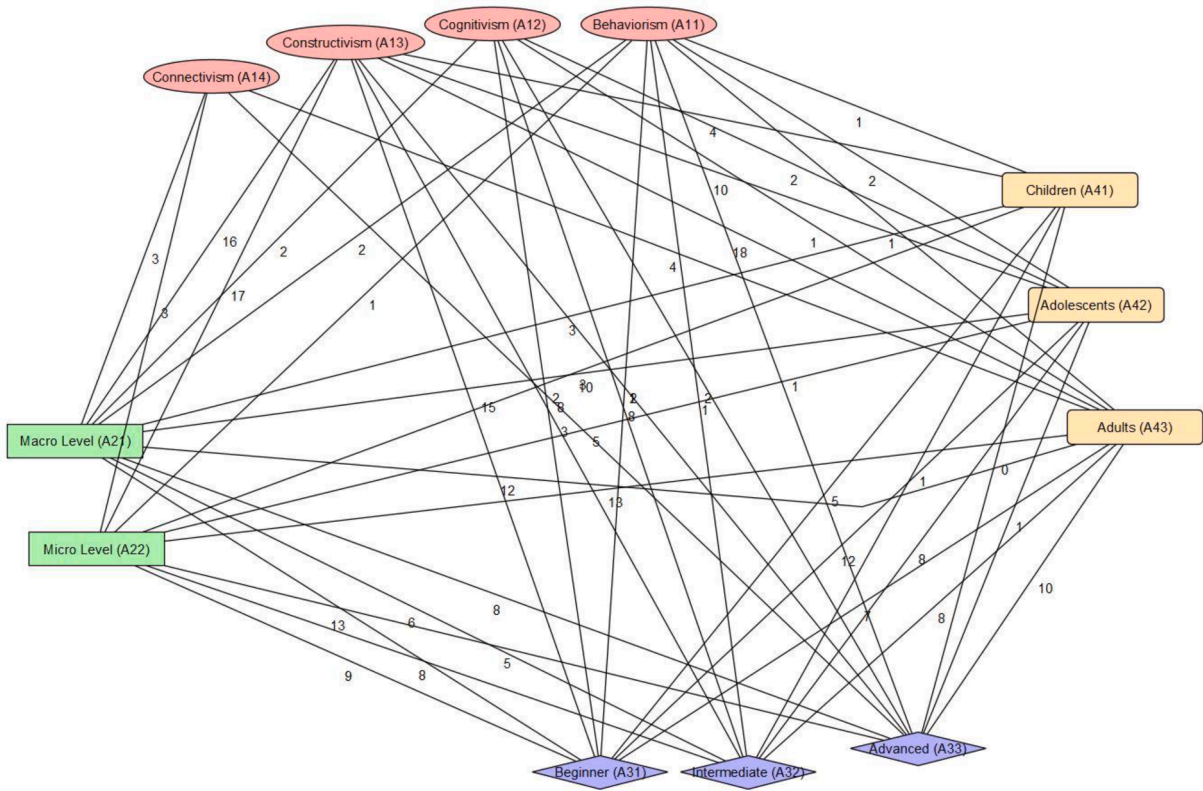
According to Graph 5 and Graph 6 the centrality of Digital Tools & Software (B1) as a dominant hub with the strongest connections to both Technological Challenges (D1, value=26) and Pedagogical Challenges (D2, value=25) reveals a fundamental paradox: while these tools are the most widely adopted (appearing in 90 % of studies), they simultaneously generate the most significant implementation barriers. This finding aligns with Mroziak and Bowman's [95] critique that technology integration often replicates traditional practices rather than transforming pedagogy. The robust connections between Constructivist and Cognitive Theories (A52) and Personalized and Learner-Centered Approaches (A55) with Digital Tools & Software (B1, both with value=10) suggest that theoretical frameworks are increasingly aligned with technological affordances, supporting the dominance of constructivism identified in 83 % of reviewed studies. Notably, the strong linkages between Music Performance Proficiency (C2) and both Digital Tools & Software (B1, value=22) and Online Learning & Communication Platforms (B4, value=17) validate the finding that technology-enhanced models have been most successful in developing technical skills (53 % of studies). However, the relatively weaker connections between emerging technologies like AI & Adaptive Technologies (B2) or Virtual Reality (B3) and learning outcomes indicate underutilization of transformative technologies, corroborating the temporal analysis showing AI adoption only in 2024. The network visualization ultimately reveals that while foundational technologies are deeply embedded in music education practice, their implementation is constrained by equally strong pedagogical and technological challenges, suggesting that the field requires not merely more technology adoption but fundamental reconceptualization of how technology, pedagogy, and musical learning intersect [10,69].

Based on Diagram 3, analysis of the learning theories network reveals that Constructivism emerges as the central theoretical hub in technology-enhanced music learning and education (TEMLem) research, demonstrating the highest connectivity with other approaches including collaborative learning, learner-centered pedagogy, personalized learning, and music-specific methodologies such as Gordon's Music Learning Theory and Comprehensive Musicianship. The TPACK framework forms another significant cluster, frequently paired with project-based learning, instructional design models (ADDIE, SAMR), and Community of Inquiry, indicating researchers' emphasis on integrating technological, pedagogical, and content knowledge in music education contexts. A notable pattern shows that personalized and learner-centered approaches create dense interconnections with technology integration, gamification, and various learning taxonomies (Bloom's, Marzano's), suggesting a trend toward individualized, technology-supported learning experiences. The network also reveals that blended learning approaches consistently connect with personalized learning and structured instructional design models (ASSURE), while music-specific pedagogies (Dalcroze/Willems/Orff, Gordon's MLT, Comprehensive Musicianship) tend to cluster together and maintain strong ties to constructivist theories, demonstrating how traditional music education methods are being reimaged through contemporary learning theories.

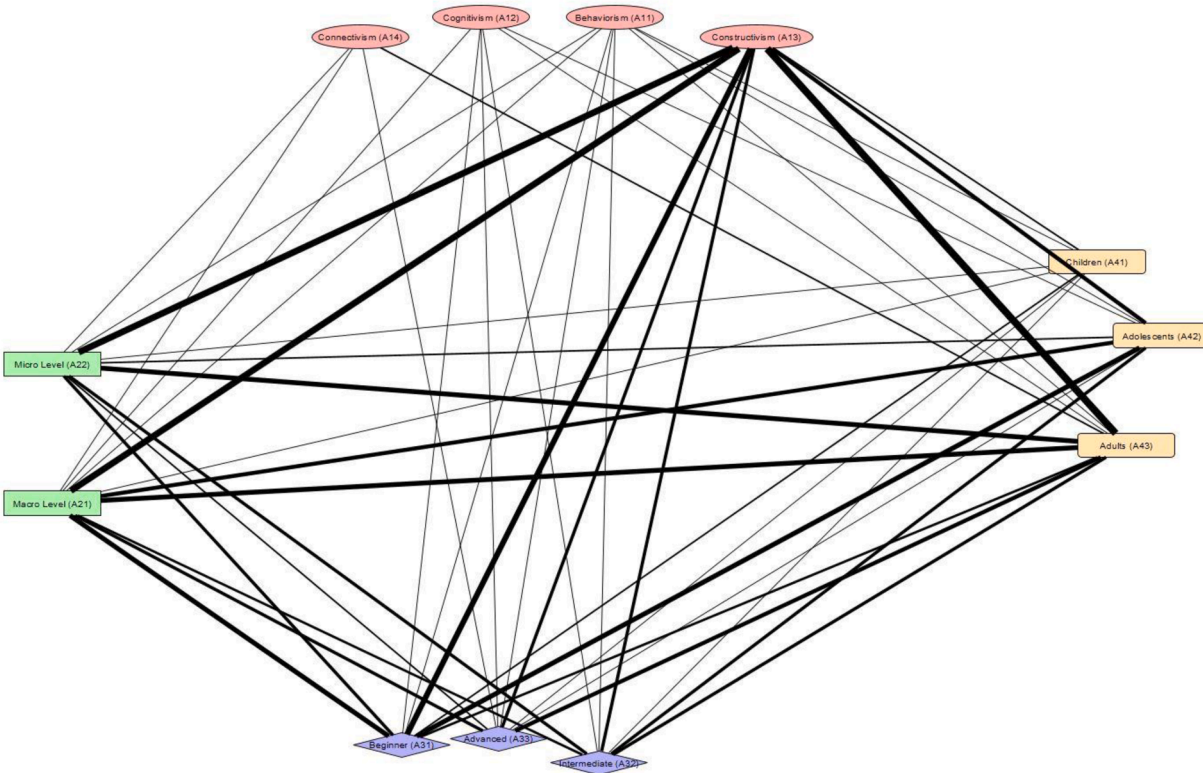
Based on Diagram 4, analysis of the technology network in TEMLeM research reveals that Learning Management Systems (LMS) serve as the central technological hub, with the strongest connections to video conferencing tools (particularly Zoom), specific LMS platforms (Moodle, Canvas, Blackboard), and mobile applications, indicating that most technology-enhanced music education implementations are built around comprehensive online learning environments. Video conferencing technologies form a highly interconnected cluster, with Zoom emerging as the dominant platform that bridges synchronous communication tools with asynchronous LMS environments, reflecting the critical role of real-time interaction in music education. The network demonstrates a clear pattern of integrated technology ecosystems where traditional music software (DAWs, notation software like Sibelius and MuseScore) consistently connects with collaborative tools and recording technologies, suggesting that researchers favor comprehensive technological solutions rather than isolated tools. Mobile applications and web platforms create important bridges between formal learning environments (LMS) and informal communication tools (WhatsApp, YouTube), indicating a trend toward ubiquitous learning that extends beyond traditional classroom boundaries. The emergence of newer technologies like AI tools and AR/VR technologies shows connections primarily to multimedia and mobile platforms, suggesting these are being integrated as enhancement layers rather than core infrastructure. Notably, the network reveals that successful TEMLeM implementations typically combine synchronous tools (video conferencing) with asynchronous platforms (LMS) and music-specific software (DAWs, notation tools), creating a triangulated approach that addresses the unique demands of music education-real-time performance, collaborative creation, and individual practice-within digitally mediated environments.

[Graph 1](#), [Graph 2](#), [Graph 3](#), [Graph 4](#), [Graph 5](#), [Graph 6](#), [Diagram 1](#), [Diagram 2](#), [Diagram 3](#), [Diagram 4](#)
[Table A1](#), [Table A2](#), [Table A3](#), [Table A4](#), [Table A5](#)

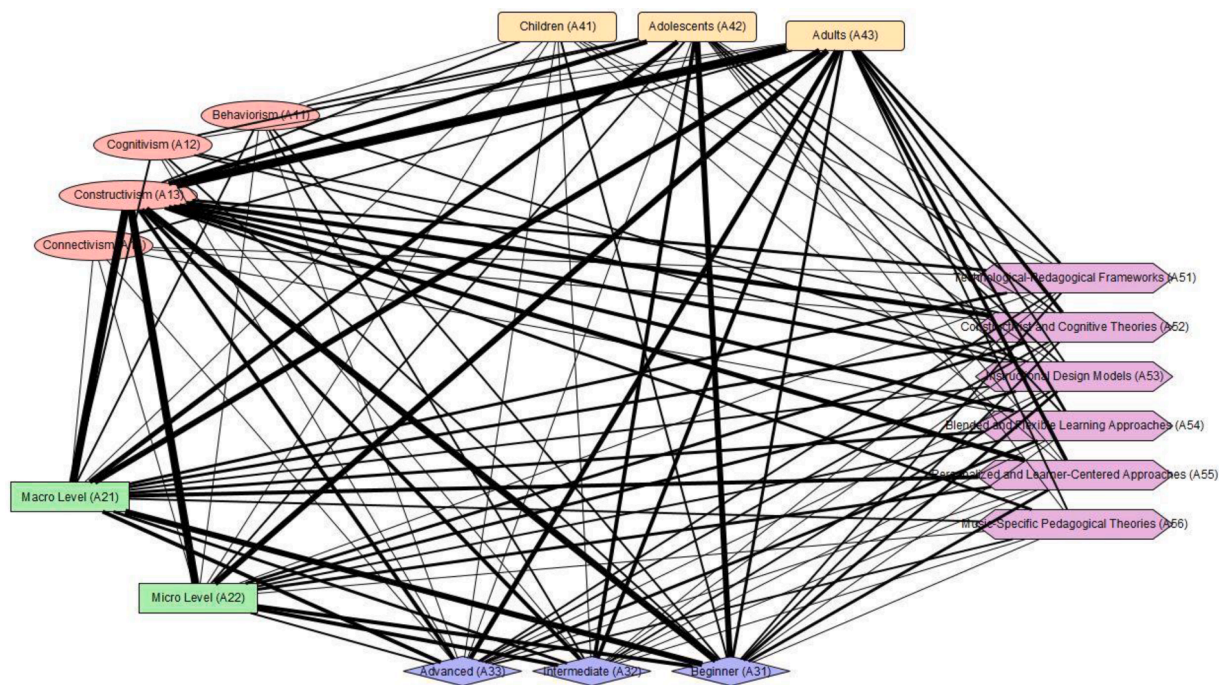
⁶ Numbers in each box represent the count of studies at each screening stage.



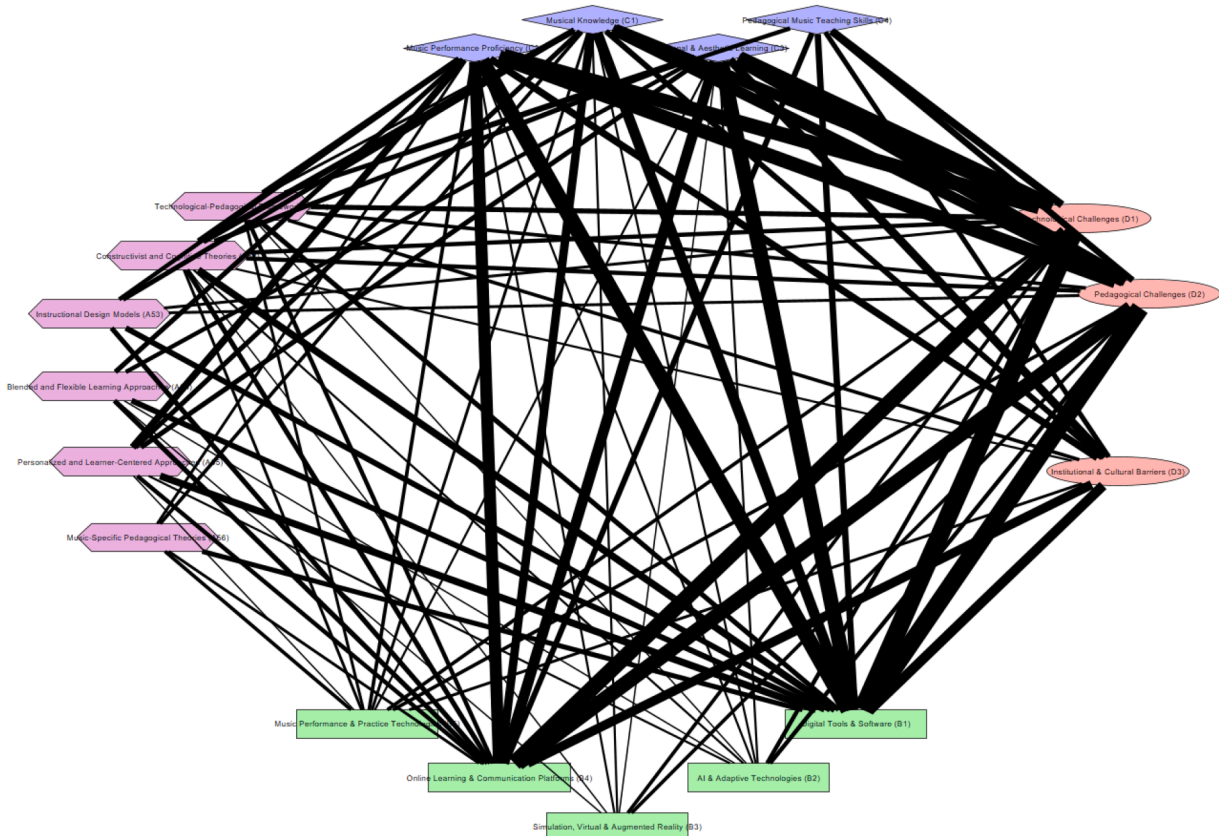
Graph 1. Network analysis of the educational dimensions of TEMLeM based on the interconnections among dimensions according to frequency counts.



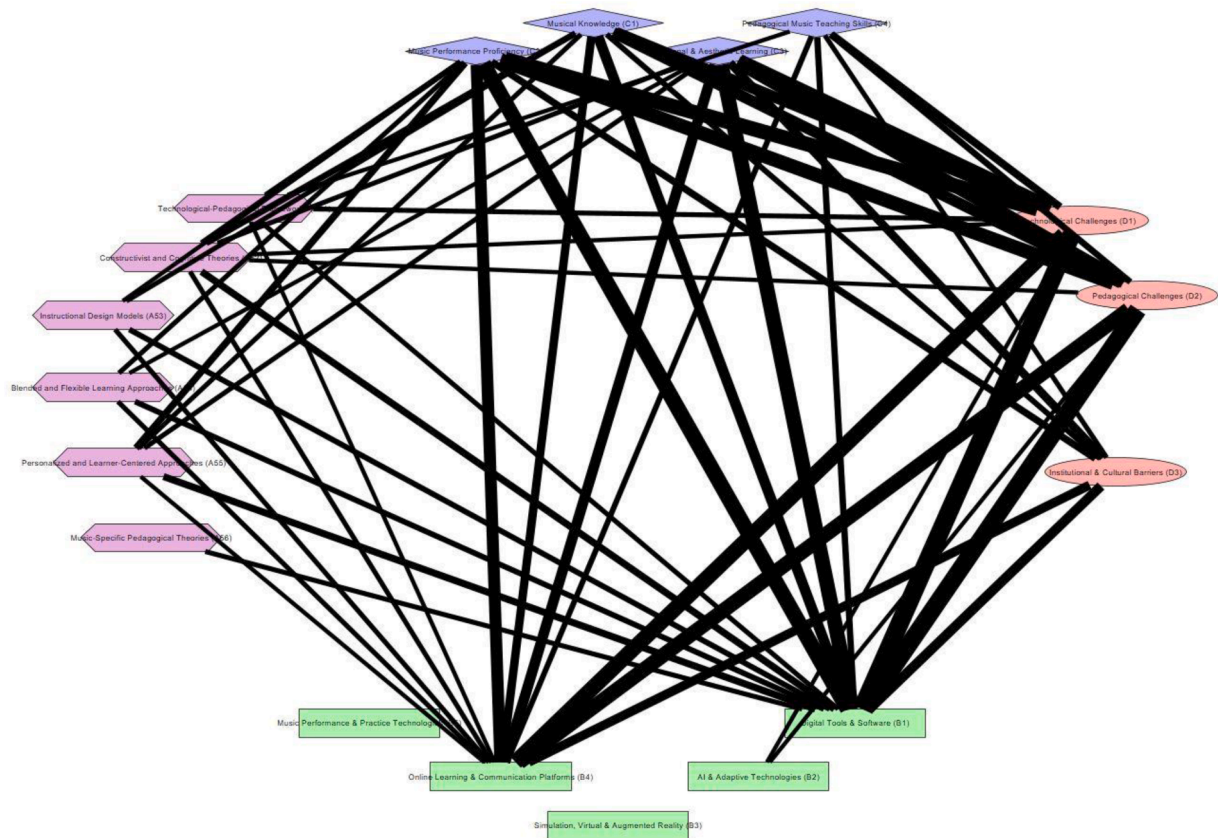
Graph 2. Network analysis of the educational dimensions of TEMLeM based on the interconnections among dimensions.



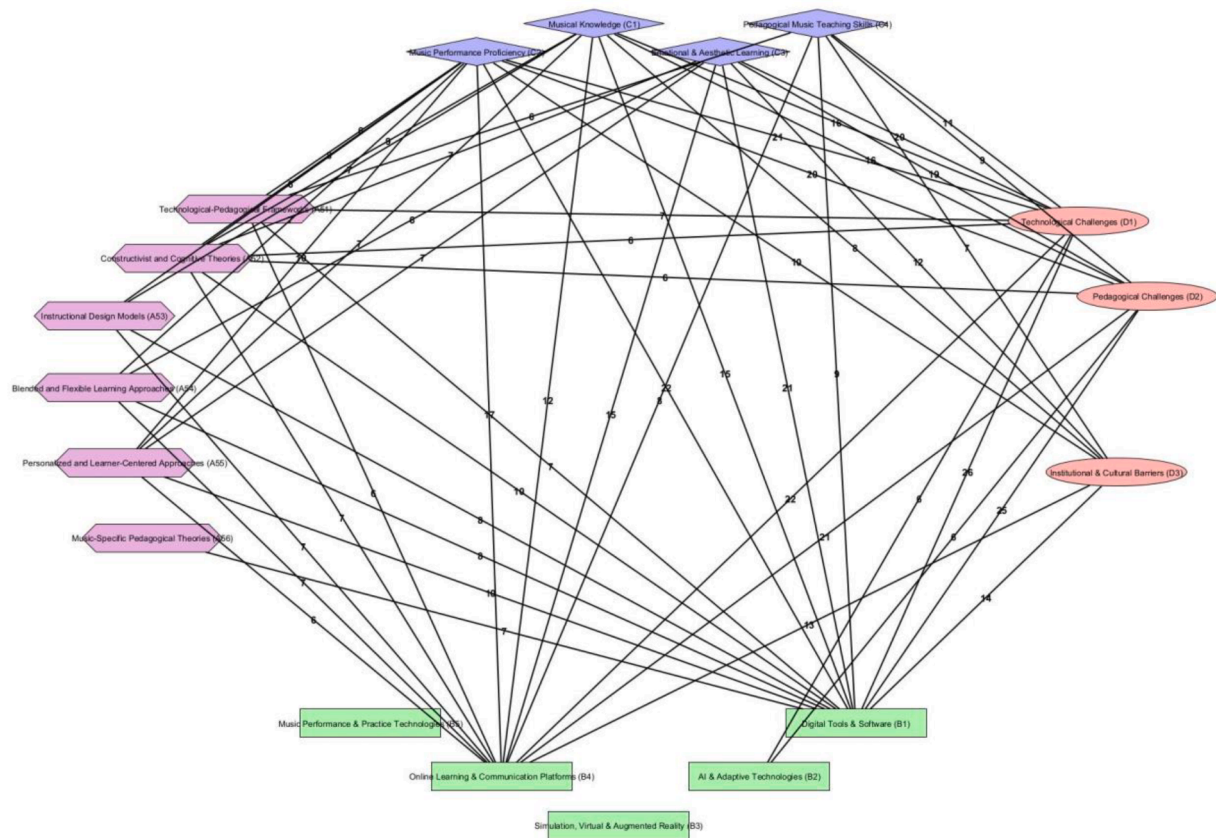
Graph 3. Network Analysis of TEMLeM: Relationships Between Pedagogical Approaches, Instructional Design, Learner Proficiency, Stakeholders, and Learning Theories.



Graph 4. Network Analysis of TEMLeM: Relationships Between Learning Theories and Strategies, Technologies, Learning outcomes, Challenges and Limitaitons.



Graph 5. Network Analysis of TEMLeM: Relationships Between Learning Theories and Strategies, Technologies, Learning outcomes, Challenges and Limitaitons (Weak edges with 5 or less connections have been removed).



Graph 6. Network Analysis of TEMLem: Relationships Between Learning Theories and Strategies, Technologies, Learning outcomes, Challenges and Limitaitons (Weak edges with 5 or less connections have been removed).

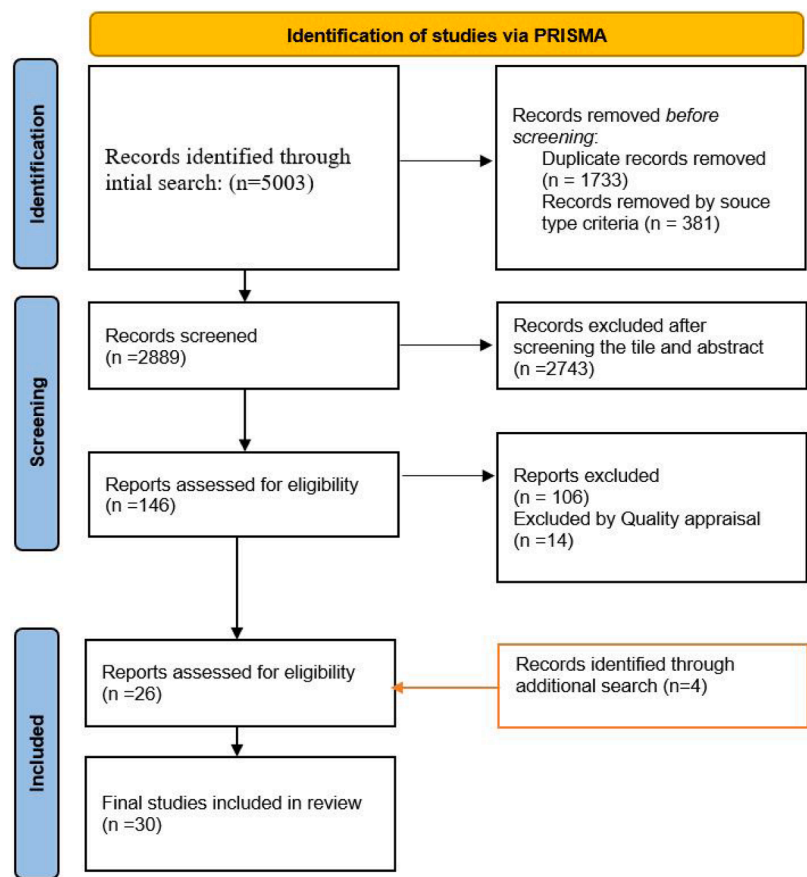


Diagram 1. The Process of Identification of Studies using the PRISMA Method⁶.

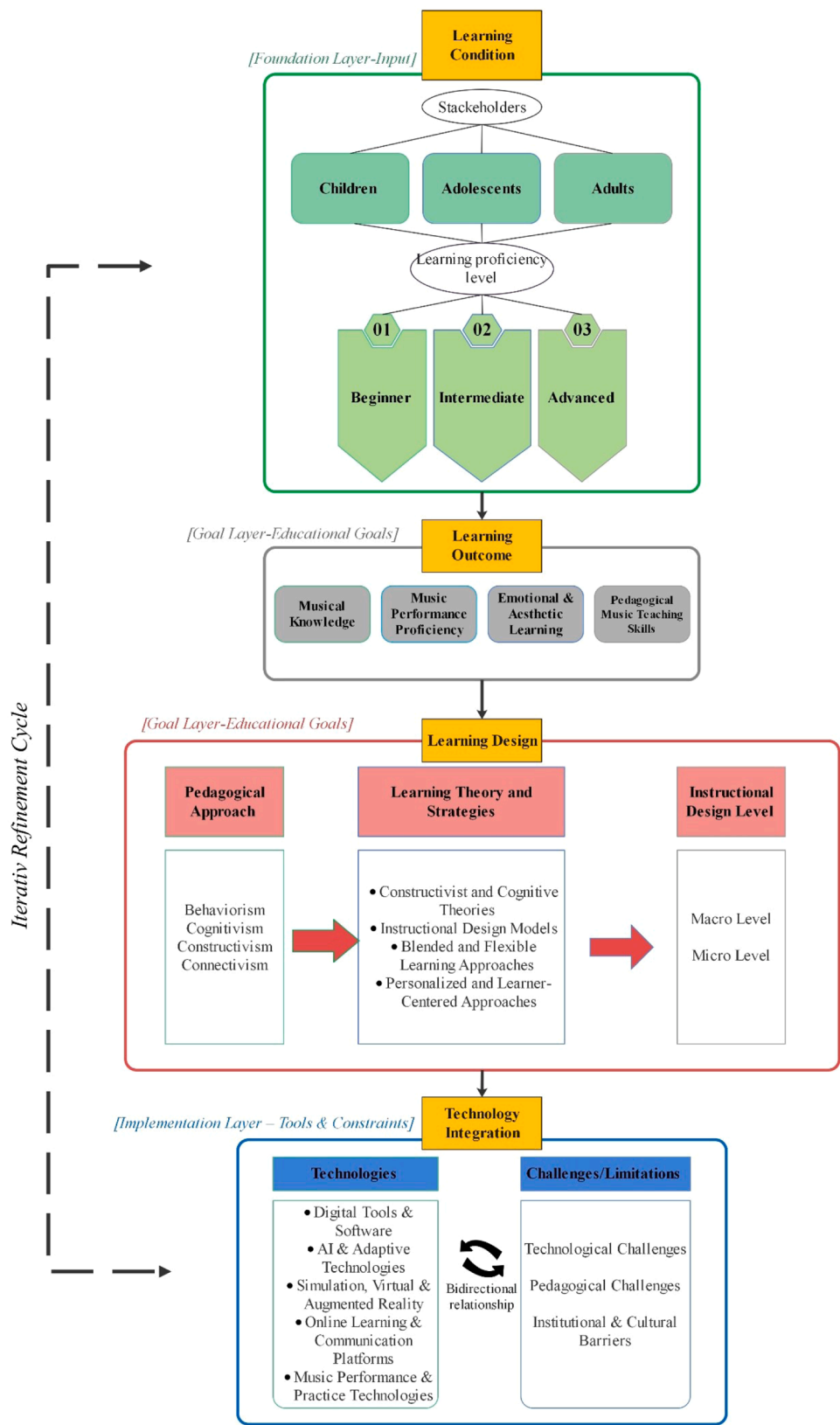


Diagram 2. Conceptual Framework for Utilizing Learning Strategies Within TEMLeM.

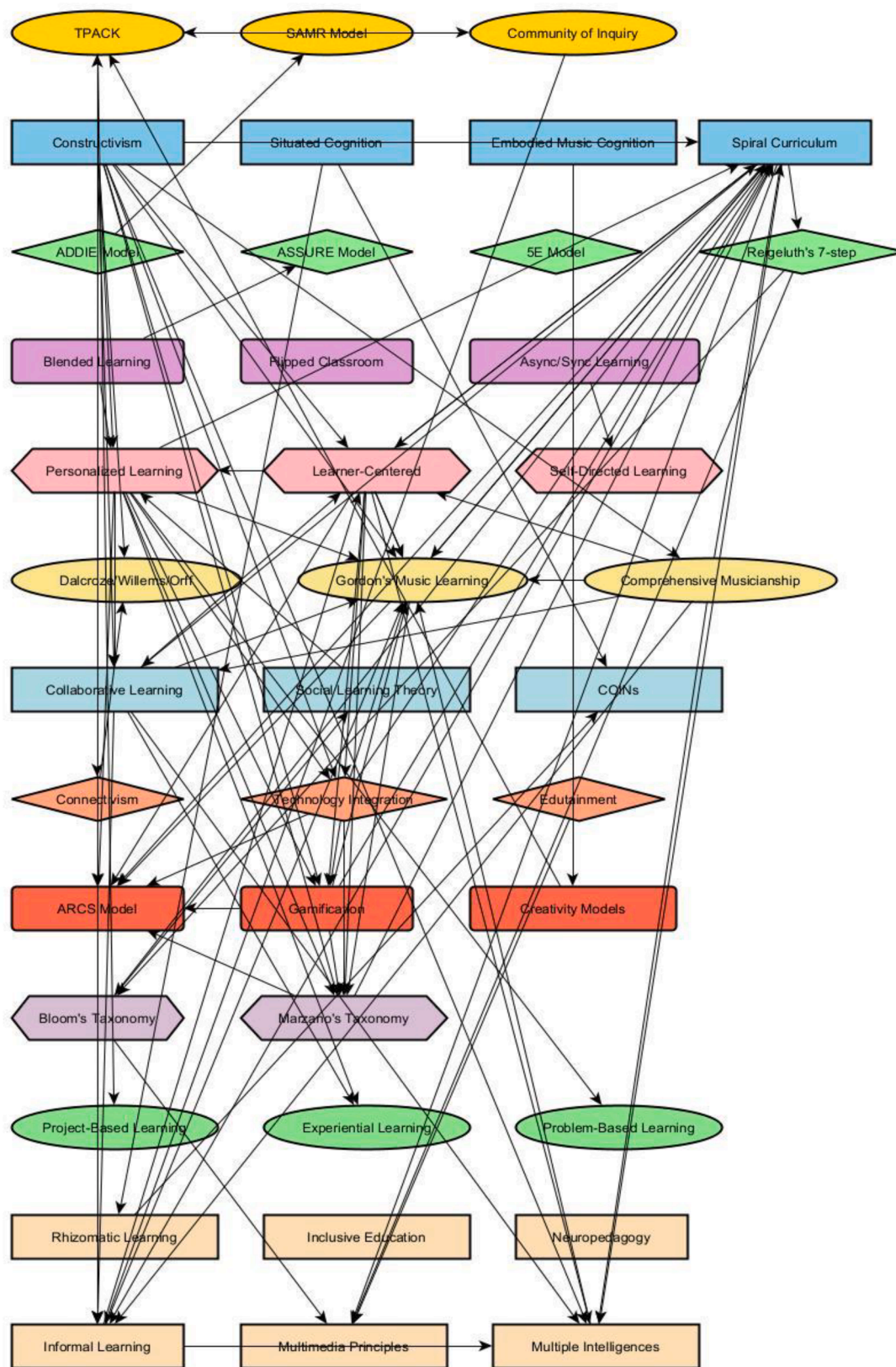


Diagram 3. Learning theories network in TEMLeM.

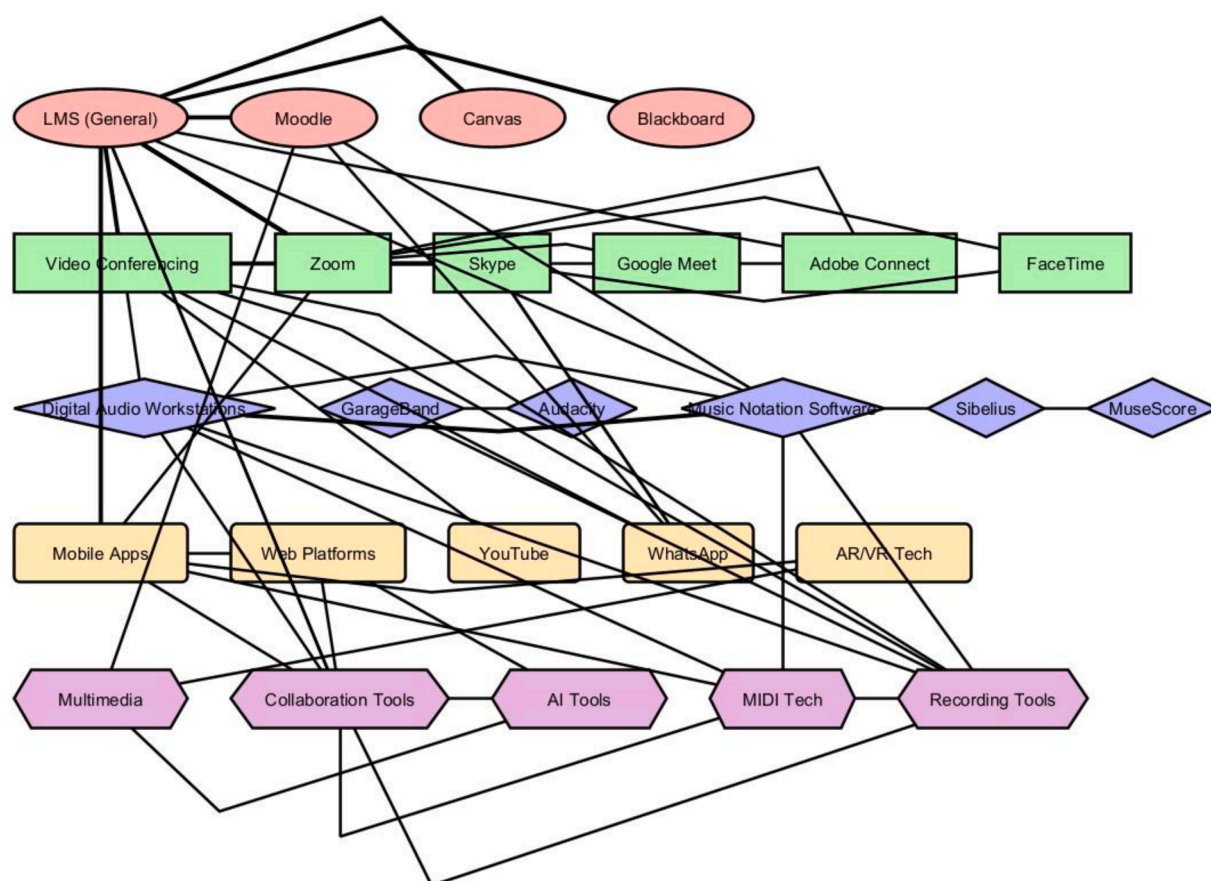


Diagram 4. Technology network in TEMLeM.

Table A1
Characteristics of included publications.

Authors and Year	Publication Type	Language	Country	Research Method	Target Population
Gértrudix Barrio [47]	Doctoral Dissertation	Spanish	Spain	Mixed Methods	High school students
Welch [147]	Doctoral Dissertation	English	USA	Quantitative	Music teachers in Virginia
Dorfman [38]	Journal Article	English	USA	Quantitative	Music education faculty members and pre-service music teachers
Tuisku and Ruokonen [136]	Journal Article	English	Finland	Qualitative	Music students
Cremata [28]	Book chapter	English	USA	Qualitative	Faculties of university and Music students
Behzadaval and Vahedi [13]	Conference paper	English	Iran	Qualitative	Elementary music teachers
Chamila Nishanthi Edward et al. [39]	Journal Article	English	Sri Lanka	Quantitative	High school students
Johnson [64]	Journal Article	English	Australia	Qualitative	Music educators and students in higher education
Tejada and Morel [128]	Journal Article	English	Spain	Mixed Methods	Pre-service music teachers
Aksoy [4]	Doctoral Dissertation	Turkish	Turkey	Mixed Methods	Physically disabled individuals using wheelchairs
Behzadaval [12]	Master's thesis	Persian	Iran	Quantitative	Elementary school students
Loo et al. [77]	Journal Article	English	Malaysia	Quantitative	High school students
Bowman [18]	Doctoral Dissertation	English	USA	Qualitative	Secondary school music teachers
Horton [59]	Doctoral Dissertation	English	USA	Mixed Method	Students with disabilities and digital musical instrument designers
Kibici [67]	Journal Article	English	Turkey	Quantitative	6th grade students
Kuyumcu [71]	Doctoral Dissertation	Turkish	Turkey	Qualitative	Undergraduate classical guitar students
Nedelcut and Pop [97]	Journal Article	English	Romania	Mixed Method	Music students and faculty
Engizli and Uludag [41]	Journal Article	English	Turkey	Qualitative	High school students
Häberlin [52]	Doctoral Dissertation	English	USA	Qualitative	Tertiary music students and educators
Teke and Sever [130]	Journal Article	English	Turkey	Qualitative	Music teachers and students

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Table A1 (continued)

Authors and Year	Publication Type	Language	Country	Research Method	Target Population
Mohammadyan and Purrustaei Ardakani [92]	Journal Article	English	Iran	Mixed Method	Elementary students
Mohammadyan and Pourroostaei Ardakani [91]	Journal Article	English	Iran	Mixed Method	Elementary students
Castellano [24]	Doctoral Dissertation	English	USA	Mixed Method	Primary, secondary, and post-secondary music educators
Nijs and Behzadaval [101]	Journal Article	English	Luxembourg	Qualitative	Beginner and intermediate-advanced music students
Chen [25]	Journal Article	English	Hong Kong	Qualitative	Primary school music teachers
Imperio [60]	Doctoral Dissertation	English	Philippines	Mixed Method	High school students
Mohammadian [90]	Doctoral Dissertation	Persian	Iran	Mixed Method	Gifted middle school students
Pavlenko et al. [108]	Journal article	English	Ukraine	Mixed Method	Music teachers in higher education institutions
Shcherbak et al. [126]	Journal Article	English	Ukraine	Mixed Method	Music teacher trainees
Zhang and Zhang [154]	Journal Article	English	China	Quantitative	Undergraduate students majoring in vocal music

Table A2

Coding scheme to analyze included publications.

Category	Code	Label	Definition
Educational Dimensions Of Music Education Models (RQ1)	Pedagogical Approach (A1)	Behaviorism (A11)	Learning through repetition, reinforcement, and feedback
		Cognitivism (A12)	Focus on mental processes, memory, and structured learning
		Constructivism (A13)	Active, hands-on learning through exploration and experience
		Connectivism (A14)	Learning through networks, technology, and social connections
	Instructional Design Level (A2)	Macro Level (A21)	Broad curriculum design, long-term learning goals
	Learner Proficiency Level (A3)	Micro Level (A22)	Specific lesson planning, short-term learning activities
		Beginner (A31)	Basic knowledge, foundational music skills
	Stakeholders (A4)	Intermediate (A32)	Moderate experience, developing technical skills
		Advanced (A33)	High proficiency, mastery of complex musical concepts
		Children (A41)	6–12 years
Technologies (RQ2)	Learning Theory and Strategies (A5)	Adolescents(A42)	13–18 years
		Adults (A43)	19+ years
		Technological-Pedagogical Frameworks (A51)	Technology integration approaches like TPACK and SAMR model
		Constructivist and Cognitive Theories (A52)	Constructivist and Cognitive Theories
		Instructional Design Models (A53)	Instructional Design Models
		Blended and Flexible Learning Approaches (A54)	Blended and Flexible Learning Approaches
		Personalized and Learner-Centered Approaches (A55)	Student-centered learning
		Music-Specific Pedagogical Theories (A56)	Gordon's Music Learning Theory, Comprehensive musicianship
	Digital Tools & Software(B1)	Traditional music methodologies - Dalcroze, Orff and etc.	
		Video, Picture, Audio, Text, Multimedia	
	AI & Adaptive Technologies(B2)	Finale, Sibelius, MuseScore, Ableton, Logic Pro, GarageBand	
		Yousician, Simply Piano, SmartMusic	
		AI-driven feedback on pitch, rhythm, and technique	
	Simulation, Virtual & Augmented Reality(B3)	AI-assisted performance grading	
		Automated Music Assessment Tools (B22)	
		Audio Analysis & Visualization(B23)	spectrograms, waveform analysis
		Virtual Reality (VR) Applications (B31)	VR piano or instrument simulations
		Augmented Reality (AR) Applications (B32)	AR sheet music, interactive overlays
Learning Outcomes (RQ3)	Online Learning & Communication Platforms(B4)	Game-Based Learning(B33)	Game-Based Learning and Gamification
		Motion Tracking Devices(B34)	Motion Tracking Devices Like Kinect
		LMS and Online Courses(B41)	Learning management system and Online courses
		Video Conferencing Tools(B42)	Zoom, Skype, Google Meet for online lessons
		Collaborative Platforms (B43)	Soundtrap, BandLab, online jamming tools
	Music Performance & Practice Technologies(B5)	Digital Instruments & MIDI Controllers (B51)	electronic keyboards, MIDI guitars, drum pads
		Smart Wearables(B52)	motion-sensing gloves, practice-tracking wristbands
	Musical Knowledge(C1)	Music Theory & Notation	scales, chords, rhythm, harmony, sheet reading
		Music History, Cultural awareness & Styles(C11)	historical context, genres, cultural influences

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Table A2 (continued)

Category	Code	Label	Definition
Challenges/Limitations (RQ4)	Music Performance Proficiency (C2)	Music Analysis & Critical Thinking (C12)	analyzing compositions, interpreting music structures
		Technical And Instrumental Skills (C21)	technique, accuracy, expressiveness, dynamics
		Vocal & Listening Skills(C22)	pitch recognition, rhythm perception, ear training
		Composition & Creativity (C23)	spontaneous music creation, songwriting, arrangement
	Emotional & Aesthetic Learning (C3)	Ensemble & Collaboration(C24)	playing in groups, digital collaboration, live performance
		Emotional Expression in Performance (C31)	conveying feelings through music, emotional connection to sound
		Music Appreciation & Aesthetic Sensitivity(C32)	recognizing beauty in music, personal connection to musical pieces
		Motivation & Engagement C33)	persistence in practice, engagement with music learning
	Pedagogical Music Teaching Skills(C4)	Self-Regulated Learning (C34)	self-efficacy and regulation
		Instructional Strategies(C41)	Methods and techniques used to teach music effectively
	Technological Challenges(D1)	Technology Integration in Teaching and Digital literacy (C42)	Ability to incorporate digital tools, software, and online platforms into music instruction.
		Accessibility & Equality(C43)	Increased accessibility to music education, fostering educational equality.
	Pedagogical Challenges(D2)	Accessibility & Cost(D11)	high cost of hardware/software, limited access in low-resource settings, Digital divide
		Technical Issues & Reliability(D12)	latency, software bugs, system failures, internet dependency
		Compatibility & Integration(D13)	Difficulty integrating digital tools with traditional music education methods
		Lack Of Immediate Feedback(D14)	Lack Of Immediate and Realtime Feedback
		Lack of Human Interaction(D21)	(e.g., reduced teacher-student engagement, over-reliance on technology)
		Lack of Teacher Training(D22)	(e.g., educators' unfamiliarity with technology-enhanced instruction)
		Lack of Digital Literacy & Limited Adaptability(D23)	Lack of Digital Literacy and digital tools not fully accommodating diverse learning styles and skill levels
		Engagement & Motivation Issues(D24)	(e.g., students losing interest, over-reliance on gamification, screen fatigue)
		Limitations in Expressiveness & Aesthetic Depth(D25)	(e.g., difficulty conveying emotions in digital environments, lack of artistic interpretation tools)
		Lack of fundamental and experimental research(D26)	Lack of fundamental and experimental research
	Institutional & Cultural Barriers (D3)	Struggle With Motor Skills(D27)	Struggle With Motor Skills
		Assessment Challenges(D28)	Assessment Challenges
		Anxiety & Stress(D29)	Experience Anxiety and Stress
		Systemic limitations in education policies(D31)	Rigid curricula, lack of policy support
		Resistance to Change(D32)	(e.g., skepticism from educators, preference for traditional methods, reluctance to adopt technology)
		Institutional Constraints and Curriculum Gaps (D33)	(e.g., lack of funding, rigid curriculum structures, absence of policies supporting digital music education)
		Cultural Perceptions(D34)	(e.g., varying attitudes toward digital music learning across different societies and traditions)
		Time Constraints(D35)	Dedicate significant time outside of class

Table A3

Learning Theories and Strategies in TEMLeM utilized in studies.

Authors and Year	Learning Theories and Strategies
Gértrudix Barrio [47]	Socio-constructivism. Constructivism: Piaget's stages of cognitive development. Connectivism: networked resources and online platforms. Active learning methodologies: Dalcroze, Willems, and Orff. Creative interaction Exploration and collaboration Educational Digital Contents (ODEs) TPACK framework (Technological Pedagogical Content Knowledge)
Welch [147]	TPACK
Dorfman [38]	Blended learning
Tuisku and Ruokonen [136]	Personalized learning
Cremata [28]	Situated cognition (Brown, Collins, & Duguid) Rhizomatic learning (Cormier) Collaborative innovative networks (coins)
Behzadaval and Vahedi [13]	ADDIE instructional design model
Chamila Nishanthi Edward et al. [39]	Blended learning approach
Johnson [64]	Blended learning approach

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Table A3 (continued)

Authors and Year	Learning Theories and Strategies
Tejada and Morel [128]	TPACK
Aksoy [4]	Project-Based Learning (PBL)
Behzadaval [12]	Inclusive education principles
	Bloom's taxonomy
	Social Learning Theory
Loo et al. [77]	Edutainment
	Docutainment
	Bransford's multiple learning approach
	Cultural-embedded learning model
Bowman [18]	TPACK
Horton [59]	Csikszentmihalyi's systems model of creativity
	Distributed creativity theory from Glăveanu
	TPACK framework
Kibici [67]	5E model (Engage, Explore, Explain, Elaborate, Evaluate)
Kuyumcu [71]	Flipped classroom model
Nedelcut and Pop [97]	Asynchronous and synchronous learning models
	Utilizing both instructor-led and self-directed learning approaches
Engizli and Uludag [41]	Blended learning theories
	ASSURE instructional design model
Häberlin [52]	Technological Pedagogical Content Knowledge (TPACK)
	Community of Inquiry (CoI)
	Green's informal learning pedagogy
	Shulman's signature pedagogy
Teke and Sever [130]	The ARCS motivation model
Mohammadyan and Purrustaei Ardakani [92]	Bruner Spiral Curriculum
	Reigeluth's 7-step instructional design model
Mohammadyan and Pourroostaei Ardakani [91]	Bruner Spiral Curriculum
	Reigeluth's 7-step instructional design model
	Bloom's Taxonomy
	Mayer's Multimedia principles
Castellano [24]	The ADDIE Model
	SAMR Model
	TPACK Framework
Nijs and Behzadaval [101]	Embodied Music Cognition
	Embodied Music Pedagogy
	Conceptual Metaphor theory
	Embodied Musical Creativity
	Theories on affordances
	Participatory sense-making
	Constraints-led approach
Chen [25]	Social learning mode
	Personal learning model
	Information-processing learning model
	Behavioral learning model
Imperio [60]	Social constructivism (primary theory)
	Comprehensive musicianship
	Spiral curriculum (based on Jerome Bruner's work)
	Cooperative learning theories
	Informal and formal learning approaches
	Ethnomusicological approaches to music education
	Learner-centered pedagogy
	Howard Gardner's multiple intelligences theory
	Edwin Gordon's Music Learning Theory
Mohammadian [90]	Constructivism
	Learner-Centered Approach
	Self-Efficacy, Self-Regulation, and Autonomy
	Personalization
	Learning Network (or Networked Learning)
	Technology Integration
	Motivation and Gamification
	Edwin Gordon's Music Learning Theory
	Marzano and Kendall's Taxonomy of Educational Objectives
	Bruner's Spiral Curriculum
	Keller's ARCS Motivational Model
Pavlenko et al. [108]	Personalized Educational
	Environment
	Postmodern educational theory
	Competency paradigm of education
	Integration of distance and face-to-face training
	Interactive and problem-based teaching methods
Shcherbak et al. [126]	Neuropedagogy
Zhang and Zhang [154]	Personalized learning theory
	Collaborative learning (through student mutual evaluation)
	Experiential learning

Table A4
Utilized technologies in TEMLeM.

Authors and Year	Technology
Gértrudix Barrio [47]	Educational Digital Contents (ODEs) via the MOS portal Interactive Multimedia Online Platforms
Welch [147]	Moodle (Learning Management System) multimedia presentations audio-video supplementary material
Dorfman [38]	Not specified
Tuisku and Ruokonen [136]	Optima(LMS) Rockway - An online music learning service
Cremata [28]	AdobeConnect, Zoom, FaceTime, and Skype. Learning Management Systems (LMSs) Music collaboration tools: Indaba Music, Soundation, LoopLabs, JamStudio, UJam Digital Audio Workstations (DAWs) Internet MIDI and Classroom Maestro Video-based reflection tools: FlipGrid (www.flipgrid.com) Artificial intelligence tools: Yousician
Behzadaval and Vahedi [13]	Digital media/technologies instructional media Note books
Chamila Nishanthi Edward et al. [39]	LMS SchoolNet with WAN Multimedia presentations Online discussion forum
Johnson [64]	Learning Management Systems (LMS) such as Blackboard, Moodle, Canvas Zoom, Skype, Google Hangouts, Adobe Connect email, discussion forums audio/video recording tools (GarageBand, Audacity, iMovie) collaborative tools (Google Docs) blogs/websites (WordPress) multimedia applications (VoiceThread, Evernote)
Tejada and Morel [128]	Learning Management System (Moodle) Score editing software (open-source) Digital Audio Workstation (DAW) software Microphones and recording hardware MIDI sequencing tools Video recording and editing software Digital sound banks
Aksoy [4]	Skype WhatsApp Video conferencing YouTube for online concert
Behzadaval [12]	Interactive multimedia software augmented reality mobile application online platform for virtual classes
Loo et al. [77]	Mobile learning video application Visual and auditory accompaniments Asynchronous learning model adapted from karaoke concept
Bowman [18]	Digital keyboard connected to Finale software for performance recording Video conferencing software (Zoom, Google Meet) Digital Audio Workstations (DAWs) Music notation software Drill-design software online music teaching platforms
Horton [59]	Noteflight (web-based music composition platform) Digital Musical Instruments (DMIs) Adaptive Digital Musical Instruments (ADMIP) (Max/MSP/Jitter and TouchOSC)
Kibici [67]	Online platforms Digital assessment tools Online interaction tools
Kuyumcu [71]	(Edmodo) 13 mobile applications for guitar learning Zoom platform (smartphones and tablets)
Nedelcut and Pop [97]	(ANMGD-MEET, Zoom, Skype) Learning management systems (Moodle, didamgd.ro) Music notation software (Sibelius, Muscores, flat.io) Recording/editing software (Audacity, Reason, Reaper, Cakewalk) Specialized databases and multimedia applications (D.I.M.A. multimedia terminology anthology)
Engizli and Uludag [41]	Web 2.0 tools (Thinglink, Plickers, Kahoot) Mobile games (Rhythm Cat, NoteWorks)
Häberlin [52]	Video conferencing platforms Learning management systems Low-latency audio transmission technology (LoLa)

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Table A4 (continued)

Authors and Year	Technology
Teke and Sever [130]	Mobile learning applications
	Recording technologies for asynchronous performance sharing
	Online collaboration tools
	(Zoom)
	Screen sharing and drawing tools
	Video recording and sharing applications
	Digital accompaniment tools
Mohammadyan and Purrustaei Ardakani [92]	Mobile applications for recording and playback
	Web-based content sharing (YouTube)
	Online concert platforms
	Gaming applications
Mohammadyan and Pourroostaei Ardakani [91]	web-based learning system called "Nuance
	LMS
	Multimedia
	Computer - smartphone - laptop - tablet
Castellano [24]	web-based learning system called "Nuance
	LMS
	Multimedia
	Computer - smartphone - laptop - tablet
Nijs and Behzadaval [101]	Learning Management Software (Canvas)
	MusicFirst
	Music notation software
	Multiple AR technologie
Chen [25] Imperio [60]	Head-Mounted Displays (HMDs) like Microsoft HoloLens, HTC Vive, Nreal Light
	Marker-based and markerless AR
	Motion tracking devices (Leap Motion, Kinect)
	Mobile AR applications (smartphones and tablets)
	Projection-based AR systems
	GarageBand application on iPads/mobile devices
	Video conferencing platforms (Zoom, Skype, FaceTime)
	Learning Management Systems (LMS)
	Music notation software (Flat)
	Collaboration tools (BandLab, Soundtrap)
	MIDI technology (Internet MIDI)
	Digital piano/keyboard instruments
	Learning apps for ear training and music theory
	Social media platforms for student interaction
	Smartphone apps for music practice
Mohammadian [90]	Video recording and editing tools
	LMS
	Mobile learning technology
	Mobile app
	PWA
	Audio signal processing
	Realtime feedback
	Online collaborative platform
	Digital portfolio
	E-assessment
Pavlenko et al. [108]	Music and Computer Technologies (MCT)
	Digital content and electronic educational resources
	Electronic Musical Instruments (EMI) and Music Computers (MC)
	MOODLE
	Communication tools like Viber, WhatsApp, Skype, Zoom
Shcherbak et al. [126]	Digital whiteboards like Padlet
	Distance learning technologies
	Music education software including EarToner, Tete, GNU Solfege, and InPitch
Zhang and Zhang [154]	Artificial Neural Networks (ANNs)
	Online video teaching platform
	Artificial-intelligence technology
	Multimedia technology
	Real-time interaction.

Table A5

Key Insights for Framework Implementation.

Key Area	Finding	Insight/Recommendation
Constructivist Imbalance	83 % of studies used constructivism, but only 10 % incorporated behaviorism or cognitivism	Deliberately integrate multiple pedagogical approaches. For foundational skills (music theory, technique), incorporate behaviorist elements despite the field's constructivist dominance. Technical skills were the most successful outcome (53 %), suggesting structured approaches have merit.
Underserved Learner Segments	Children represented only 17 % of studies despite documented benefits of early music education	The framework's Learning Conditions component should actively guide educators toward addressing gaps. Since 63 % focused on adults and 57 % on

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Table A5 (continued)

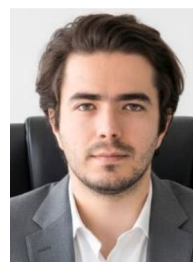
Key Area	Finding	Insight/Recommendation
Generic vs. Specialized Technologies	Generic tools (LMS, video conferencing) appeared in 90 % of studies, while specialized music technologies like AI (10 %) and VR/AR (17 %) remained underutilized	beginners, there's a critical need to develop pathways for children and advanced learners. Start with familiar platforms but progressively integrate specialized tools. The temporal data showing AI emergence only in 2024 suggests the field is ready for more sophisticated implementations.
Beyond Technical Proficiency	Technical skills dominated (53 %) while emotional expression (10 %) and aesthetic sensitivity (7 %) were neglected	Use the framework's comprehensive Learning Outcomes component to ensure balanced curriculum design. The data reveals a "performance paradox" - high technical achievement but limited artistic development.
Pedagogical vs. Technical Challenges	Pedagogical challenges (93 %) exceeded technological ones (87 %), with teacher training and digital literacy both at 40 %	When implementing the framework, allocate more resources to pedagogical preparation than technical infrastructure. The data contradicts assumptions that technology is the primary barrier.
Feedback-Rich Environments	Lack of immediate feedback appeared in 17 % of studies	Prioritize technologies that provide real-time feedback, especially for performance skills. The success of technical skill development suggests immediate feedback is a critical factor.
Accessibility Design	Only 7 % of studies addressed accessibility and equality despite 53 % reporting cost/access barriers	Use the framework's Technology Integration component to explicitly evaluate each technology choice for accessibility implications. The data reveals a gap between stated goals and actual implementation.
Instructional Design Scale	Both macro (63 %) and micro (57 %) instructional design levels were well-represented	The framework's balanced approach to instructional design levels is validated by the data. Implement both curriculum-wide integration and classroom-specific applications simultaneously.

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