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Breaking the sound barrier: Spectrum–based pedagogies in modern vocal music education

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ABSTRACT

The integration of spectrum–based pedagogies in vocal music education presents promising advancements in enhancing vocal instruction through technology–driven feedback. The importance of spectrum analysis tools in modernizing vocal pedagogy is examined in this systematic literature review, which was carried out with 28 articles that adhered to PRISMA principles. Spectrum–based tools such as Fourier transforms, spectrographs and neural networks are increasingly used to provide real–time visual feedback on vocal elements like pitch, resonance, breath control, and vocal fold vibrations. Findings demonstrate that these tools facilitate a more precise and scientific approach to vocal training by enabling students to visualize vocal mechanics and adjust their technique accordingly. By demystifying vocal production processes, spectrum–based pedagogies foster deeper student understanding and engagement, resulting in improved retention of technique and a heightened standard of performance. This review underscores the transformative potential of spectrum–based methods in vocal pedagogy, highlighting implications for educators, curriculum designers, and technology developers interested in advancing music education through data–driven, interactive learning environments. The study concludes with recommendations for further research on the long–term effects of spectrum–based pedagogies on vocal training outcomes.

Keywords: spectrum analysis, systematic review, pedagogy, vocal music education, vocal technique

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INTRODUCTION

Vocal music education is a multifaceted discipline that requires students to master not only singing techniques but also the ability to interpret and convey the emotional content of the music. As Li (2020) and Jiang (2023) note, effective singing encompasses a blend of solid vocal skills, theoretical knowledge, and a strong interpretive ability. This holistic approach allows students to express the rich emotions embedded in vocal work, enhancing both their performance and connection to the music. Consequently, educators must prioritize cultivating emotional expression alongside technical proficiency in their teaching methods.

Traditionally, vocal music pedagogy has relied on a one–on–one teaching model, where instructors assess students' abilities primarily through subjective evaluation. However, early–stage vocal students often struggle to understand their vocal capabilities and the physiological mechanics behind sound production. As Wang (2023) highlights, this lack of understanding can hinder their ability to effectively regulate and control their vocal tone.

The advancement of computer technology has ushered in new possibilities for integrating innovative teaching methodologies into vocal music education. Specifically, spectrum analysis technology provides a powerful tool for visualizing sound, transforming abstract vocal concepts into tangible computer graphics. This shift from traditional pedagogical approaches to a more hybrid model, termed the “mouth–ear–nose” teaching mode, enables students to engage with their

voices more vividly (Chi 2017). By using sound visualization, educators can represent various frequencies and amplitudes of vocal sounds, thereby enhancing students' understanding of their vocal production.

The application of spectrum analysis technology not only enriches the learning environment but also mobilizes student enthusiasm and engagement. According to McQuade (2020), spectrograms serve as visual representations of the acoustic properties of singing, allowing for a deeper exploration of vocal techniques. The use of visual feedback in conjunction with traditional teaching methods has been shown to improve learning outcomes, as supported by studies conducted by Lã and Gill (2014) and Herbst (2011). Such pedagogical strategies align with contemporary educational goals that emphasize student–centered learning, fostering critical reflective abilities and self–regulation (Lennon & Reed 2012). Furthermore, digital music technology has the potential to enhance student autonomy and interactivity within the classroom, significantly transforming learning styles and methodologies (Haiyan et al. 2020; Liu 2019). By enriching the traditional teaching framework, digital tools make music education more intuitive, lively, and engaging, ultimately improving teaching effectiveness and student outcomes (Paek et al. 2019; Bai 2019).

Previous research has demonstrated how technology can revolutionize learning environments, especially in the arts. However, there remains a notable gap in research specifically exploring the integration of spectrum analysis in vocal music education (Wu & Kang 2024). While studies have examined various technological interventions in music, the unique application of spectrum–based pedagogies in enhancing vocal training warrants further investigation.

Examining the incorporation of spectrum-based pedagogies in contemporary vocal music education is the goal of this systematic study, addressing key questions regarding the impact of these methods on student learning outcomes, the acoustic features that can be effectively visualized for instructional purposes, and students' perceptions of technology in their vocal training. Through this exploration, the present study aims to contribute significant insights into the dynamic landscape of vocal music pedagogy and its prospective trajectories. In particular, it endeavors to address the following research questions: 1) What role does music technology play in enhancing the teaching of vocal music? 2) How can spectrum–based tools be integrated into modern music education to improve vocal pedagogy outcomes? 3) What acoustic features are most useful in providing visual feedback to vocal students to enhance their learning experience? 4) How do spectrum–based pedagogies influence student engagement and learning outcomes in vocal music classes.

METHOD

This study utilizes a systematic literature review to investigate the role of spectrum-based pedagogies in modern vocal music education. The PRISMA guidelines were meticulously followed throughout the review process (Bamiro et al., 2023; Page et al., 2021; Utaminingsih et al., 2023). Specifically, this study employed the PRISMA 2020 checklist, a structured tool for systematic literature reviews (Tugwell & Tovey, 2020; Bamiro et al., 2024), which enabled a comprehensive assessment focused on understanding how music technology can enhance vocal music teaching, the integration of spectrum-based tools to improve pedagogical outcomes and the identification of acoustic features that provide effective visual feedback to enhance vocal students' learning experiences.

The search process began with selecting Scopus as the primary academic database for this systematic review. Known for its vast collection of peer-reviewed academic sources, Scopus was chosen due to its extensive indexing across diverse scholarly and scientific publications. Rosário and Raimundo (2024) noted that Scopus is widely regarded for its broad multidisciplinary coverage, which includes approximately 70 million records and over 21,600 peer-reviewed journals from more than 4,000 international publishers. This makes it an ideal resource for obtaining a wide-ranging view of academic contributions across multiple fields. Scopus's high ranking as a premier abstract and citation database for peer-reviewed literature further underscores its value in systematic reviews (Moher et al., 2015; Salisu et al., 2024). Its advanced

search features, including Boolean operators, allow for precise filtering by author, subject, publication date, document type, and recent publications, facilitating a refined and targeted literature search (Fajrie et al., 2024; Komalasari et al., 2023). While Scopus primarily indexes English-language publications, its global reach and broad subject coverage provide an unmatched perspective on academic and scientific research. The choice of Scopus was motivated by the study's international and interdisciplinary scope (Rosário & Raimundo, 2024). Although other scholarly databases were not utilized due to specific methodological considerations, this may introduce some limitations in the study's scope. To address this, supplementary articles were retrieved from Google Scholar to ensure a more comprehensive literature review.

Language, time frame, document type, and thematic focus were the search parameters used in this investigation. We focused on English-language works that discussed how music technology, and more especially spectrum-based pedagogies, can improve instruction in vocal music. The search covered studies from 2015 to 2024, focusing on peer-reviewed academic articles up to October 2024. A TITLE-ABS-KEY search through the Scopus database using the initial keywords "music technology," "spectrum-based tools," and "vocal music education" produced 4,182 documents. By applying inclusion criteria with an emphasis on "pedagogy," "acoustic feedback," and "learning outcomes," we were able to refine these results and narrow the set down to 780 documents. There were 660 results when the search was further restricted to peer-reviewed, English-language publications. Following the PRISMA checklist, we documented titles, abstracts, keywords, and study types for each entry.

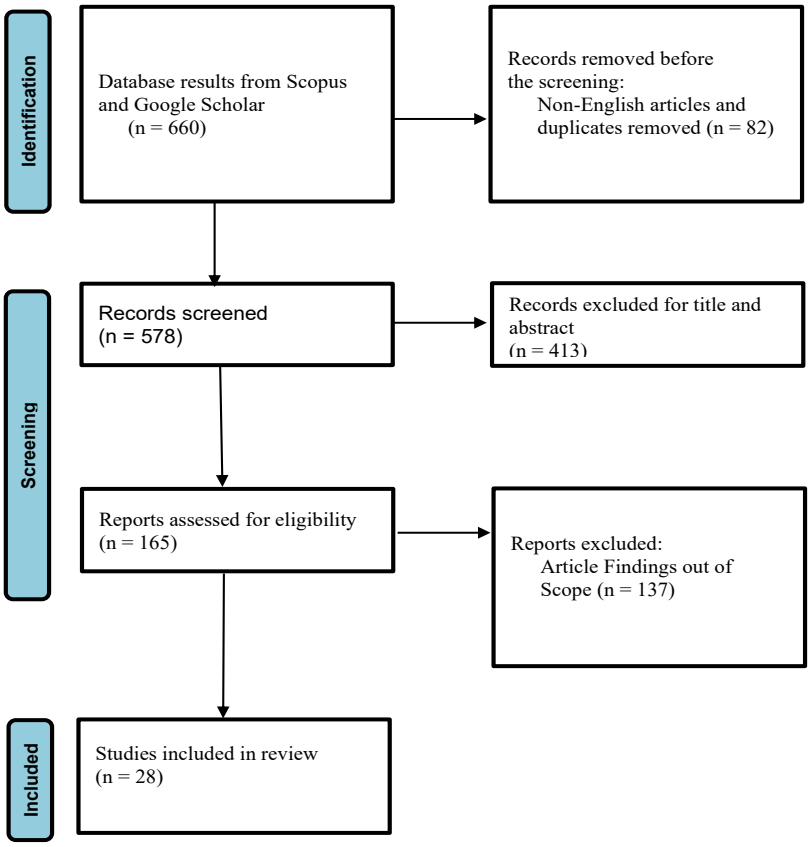

Figure 1. PRISMA Flow Diagram

To manage the large dataset, we downloaded a CSV file of the search results and utilized Excel for its accessibility and functionality. Excel's filter and duplicate functions facilitated the removal of redundant records, enabling quick access to article abstracts for review. This approach streamlined the review process and facilitated efficient data management. Identifying relevant studies was challenging due to ambiguous titles. The study employed a two-step screening

procedure to guarantee relevance: first, studies that did not fit our criteria were filtered out using titles and abstracts; next, full-text reviews were performed to choose articles that directly address our research questions. Articles sourced from Google Scholar were subjected to the same criteria for consistency. The time frame of 2014–2024 was selected due to the recent growth in music technology applications, particularly spectrum-based tools in vocal music education. Ultimately, after applying the inclusion criteria and excluding irrelevant studies, 28 articles were selected as the basis for systematic analysis. Articles excluded from the final selection were those unrelated to the study's objectives and research questions. Figure 1 displays the PRISMA flow diagram that describes the screening procedure.

This phase involved a comprehensive analysis of the progression of scholarly interest in spectrum-based pedagogies within vocal music education, examining the temporal evolution of research focus, key thematic areas, geographical distribution of research contributions, prominent publications, and influential studies and authors in alignment with the core research questions. Data analysis from the collected records was organized into the following categories: distribution and examination of identified research clusters, year of publication, academic discipline, countries of contributing authors, and the most impactful sources within this field.

FINDINGS AND DISCUSSION

Findings

An overview of the current research on spectrum–based pedagogies in vocal music education is given in the results section, which also highlights important findings and identifies important gaps. These findings cover the distribution and research clusters, year of publication, academic discipline, countries of contributing authors, and the most impactful sources within this field (See Table 1).

Articles publication by year

The search strategy primarily focused on publications from the past decade. However, the majority of articles on spectrum-based pedagogies in vocal music education have emerged in recent years. The growing scholarly interest in this field is demonstrated by the fact that only two of the 28 reviewed articles were published between 2014 and 2019, with the remaining 26 appearing between 2020 and 2024. As shown in Figure 2, 2024 had the most publications with 14 articles, followed by 2023 with 9. This trend reflects an increasing focus on how music technology can enhance vocal pedagogy and support student learning.

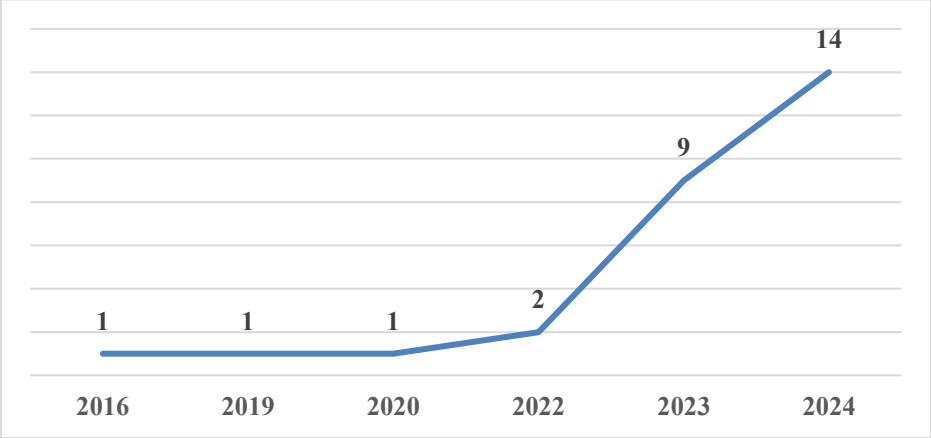

Figure 2. Articles Publication Year

Methodology analysis of the reviewed articles

The research methods employed to investigate spectrum-based pedagogies in vocal music education vary across studies, reflecting a range of methodologies. Among the articles reviewed, 64% utilized quantitative methods, involving structured assessments, experimental designs, and

technological data processing techniques such as cepstrum and Fourier transform for analyzing vocal frequency signals. 18% employed qualitative methods, primarily using interviews and student feedback to gather insights on instructional experiences and engagement. Additionally, 18% adopted mixed-method approaches, combining qualitative interviews with quantitative performance metrics to provide a more comprehensive understanding of the impact of spectrum-based pedagogies. This methodological diversity highlights the multifaceted nature of research efforts aimed at exploring the influence of spectrum-based pedagogies on student engagement and learning outcomes in vocal music education. Figure 3 graphically illustrates the methodology analysis.

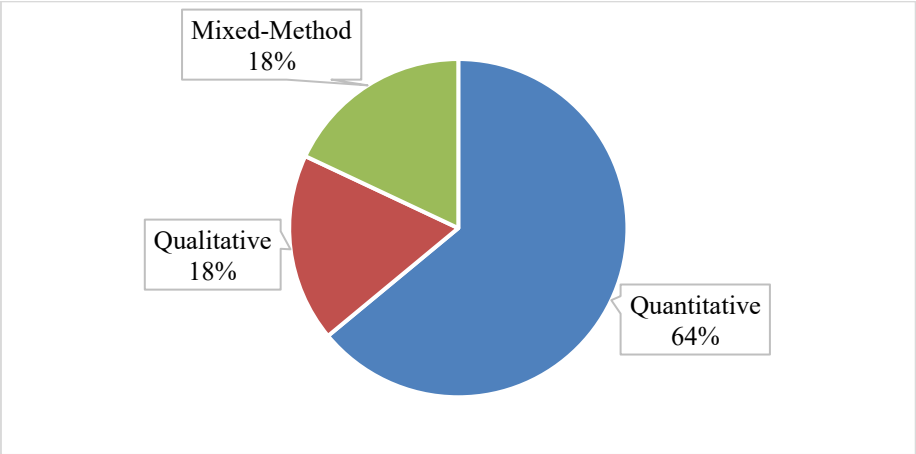

Figure 3. Methodology Analysis

Research country affiliation

The analysis of the research country affiliation of the reviewed articles reveals a significant concentration of studies in China, which accounts for 22 out of 28 articles, indicating a strong emphasis on spectrum–based pedagogies within the Chinese context of vocal music education. The preponderance implies that China is leading the way in investigating novel methods of teaching music by utilizing contemporary technology and pedagogical techniques. In comparison, other nations had fewer studies: Greece, the Philippines, South Korea, and Spain each contributed one article, while the USA produced two. This discrepancy emphasizes the necessity of more extensive international cooperation and investigation of spectrum–based pedagogies in various educational contexts, since the limited participation of other nations may limit the applicability of results and methods in various cultural and educational contexts. The concentration of research in China presents an opportunity for further comparative studies that could enhance the understanding of how these pedagogical strategies may be adapted and applied in various international frameworks (Figure 4).

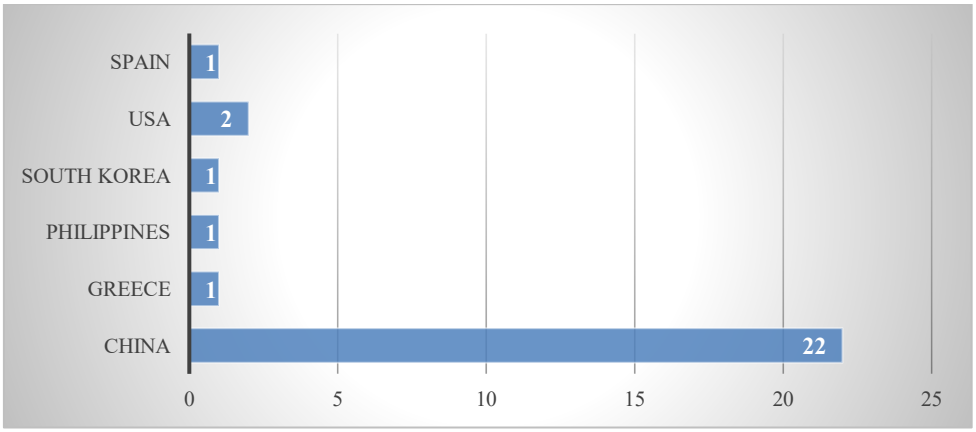

Figure 4. Research Country Affiliation

Table 1. Data extraction table

S/N	Authors' name & year	Methodology	Country	Journal	Quartile	Cluster Contribution
1.	Zhang (2023)	Quantitative	China	Applied Mathematics and Nonlinear Sciences	Q1	1
2.	Cui and Chen (2024)	Quantitative	China	Soft Computing	Q2	1
3.	Paschalidou (2024)	Qualitative	Greece	Education Sciences	Q2	1
4.	Lei (2024)	Mixed-Method	China	Education and Information Technologies	Q1	1
5.	Zhang (2023)	Quantitative	China	Applied Mathematics and Nonlinear Sciences	Q1	2 &1
6.	Zhang (2024)	Quantitative	China	International Journal of Wireless and Mobile Computing	Q4	2
7.	Xie (2024)	Quantitative	China	Journal of Commercial Biotechnology	Q4	2
8.	Kou (2023)	Quantitative	Philippines	Applied Mathematics and Nonlinear Sciences	Q1	1
9.	Wang (2023)	Quantitative	China	Applied Mathematics and Nonlinear Sciences	Q1	1
10.	Bu and Natayakulwong (2024)	Mixed-Method	China	Korean Journal of Research in Music Education	N/A	1
11.	Li (2024)	Mixed-Method	China	Applied Mathematics and Nonlinear Sciences	Q1	1
12.	Zhou and Kim (2024)	Quantitative	South Korea	Education and Information Technologies	Q1	1
13.	Shi (2024)	Mixed-Method	China	Applied Mathematics and Nonlinear Sciences	Q1	1
14.	Liang (2024)	Mixed-Method	China	Interactive Learning Environments	Q1	1
15.	Wu and Kang (2023)	Quantitative	China	Applied Mathematics and Nonlinear Sciences	Q1	1
16.	Hou et al. (2023)	Quantitative	China	Applied Mathematics and Nonlinear Sciences	Q1	1
17.	Sun and Wang (2024)	Quantitative	China	Journal of Computational Methods in Sciences and Engineering	Q4	1
18.	Yang (2024)	Quantitative	China	Interactive Learning Environments	Q1	1
19.	Li and Wang (2024)	Quantitative	China	International Journal of Human-Computer Interaction	Q1	1
20.	Campanini (2023)	Qualitative	USA	Journal of Popular Music Education	N/A	1
21.	McQuade (2020)	Qualitative	USA	Journal of the Association for Technology in Music Instruction	N/A	1 & 3
22.	Lã and Fiuza (2022)	Qualitative	Spain	Applied Sciences	Q2	1 & 2
23.	Liu et al. (2016)	Qualitative	China	International Journal of Emerging Technologies in Learning	Q1	1, 2, & 3
24.	Hao (2022)	Quantitative	China	Wireless Communications and Mobile Computing	Q2	2
25	Sun (2019)	Quantitative	China	EURASIP Journal on Image and Video Processing	Q2	1 & 2
26	Fang (2024)	Quantitative	China	Applied Mathematics and Nonlinear Sciences	Q1	3
27	Liu (2023)	Quantitative	China	Applied Mathematics and Nonlinear Sciences	Q1	2
28	Chen (2023)	Quantitative	China	Applied Mathematics and Nonlinear Sciences	Q1	3

Authors' country affiliation

According to Figure 5, the authors' country affiliation analysis, China made a significant contribution, 31 authors from the nation represented the group, and demonstrated a strong interest in spectrum-based pedagogies in the teaching of vocal music. This significant representation underscores China's leadership and commitment to advancing research and pedagogical practices in this field. Spain and the United States each contributed two authors, while the other nations contributed fewer. Thailand, South Korea, the Philippines, and Greece each contributed one author. The global landscape in vocal music education research is varied but uneven, as evidenced by this distribution, with China's dominance pointing to the possibility of more profound understandings and inventive teaching strategies. The sparse contributions from other nations highlight how crucial it is to promote international discussion and cooperation in the investigation of spectrum-based pedagogies, since these alliances may improve the diversity of research viewpoints and instructional strategies in various cultural contexts.

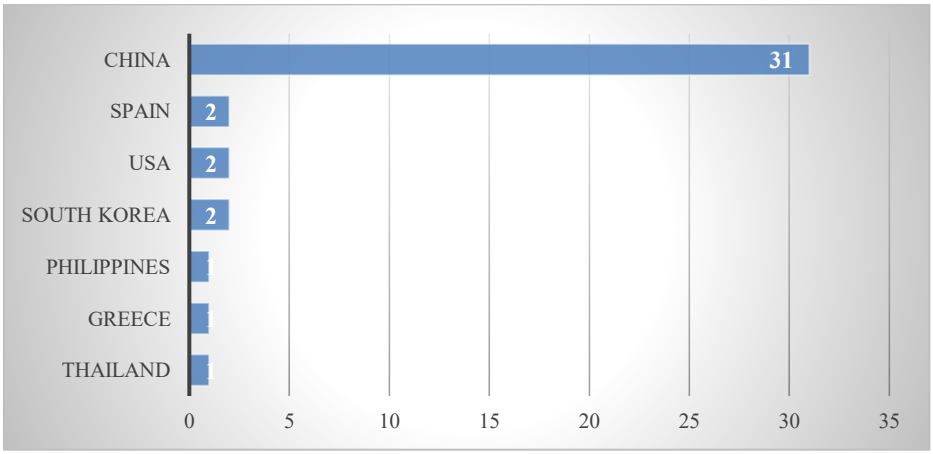

Figure 5. Authors' Country Affiliation

Journal distribution

The Journal of Applied Mathematics and Nonlinear Sciences emerges as a predominant publication outlet in the field under examination, with the majority of the reviewed articles originating from this journal. Additionally, both Education and Information Technologies and Interactive Learning Environments each contribute two publications to the corpus of literature. Other journals represented in the review are limited to a single publication. This distribution underscores the significant influence of the Journal of Applied Mathematics and Nonlinear Sciences on the discourse surrounding the subject matter, while also highlighting the presence of diverse contributions from additional academic sources. This is seen in Table 2.

Cluster analysis

After refining the Scopus records, we imported the data into VOSviewer to analyze and group various study areas relevant to spectrum-based pedagogies in modern vocal music education. VOSviewer was selected for its capability to generate user-friendly graphical representations that emphasize key terms and relationships within the research field. Cluster mapping provided a visual overview of thematic areas, enabling the reorganization of related subjects into broader categories based on keyword co-occurrence and relevance.

Figure 6 illustrates a map of 3 clusters comprising multiple elements. The most frequently occurring keywords are "music education," "students," "music technology," "acoustics," and "virtual reality." These terms reveal interconnected themes, underscoring how technology and acoustic tools can support music education by enhancing the learning experience. The clusters demonstrate the diverse aspects of modern vocal music education, including the role of real-time audio visualization, student engagement through interactive technologies, and the use of spectrum-based feedback as a pedagogical tool. This visual categorization allows for a holistic

understanding of the field, showcasing the potential of spectrum-based approaches in transforming traditional vocal pedagogy.

Table 2. Journal distribution

Journal	Number of Publication	Quartile
Applied Mathematics and Nonlinear Sciences	11	Q1
Soft Computing	1	Q2
Education Sciences	1	Q2
Education and Information Technologies	2	Q1
International Journal of Wireless and Mobile Computing	1	Q4
Journal of Commercial Biotechnology	1	Q4
Korean Journal of Research in Music Education	1	N/A
Interactive Learning Environments	2	Q1
Journal of Computational Methods in Sciences and Engineering	1	Q4
International Journal of Human-Computer Interaction	1	Q1
Journal of Popular Music Education	1	N/A
Journal of the Association for Technology in Music Instruction	1	N/A
Applied Sciences	1	Q2
International Journal of Emerging Technologies in Learning	1	Q1
Wireless Communications and Mobile Computing	1	Q2
EURASIP Journal on Image and Video Processing	1	Q2

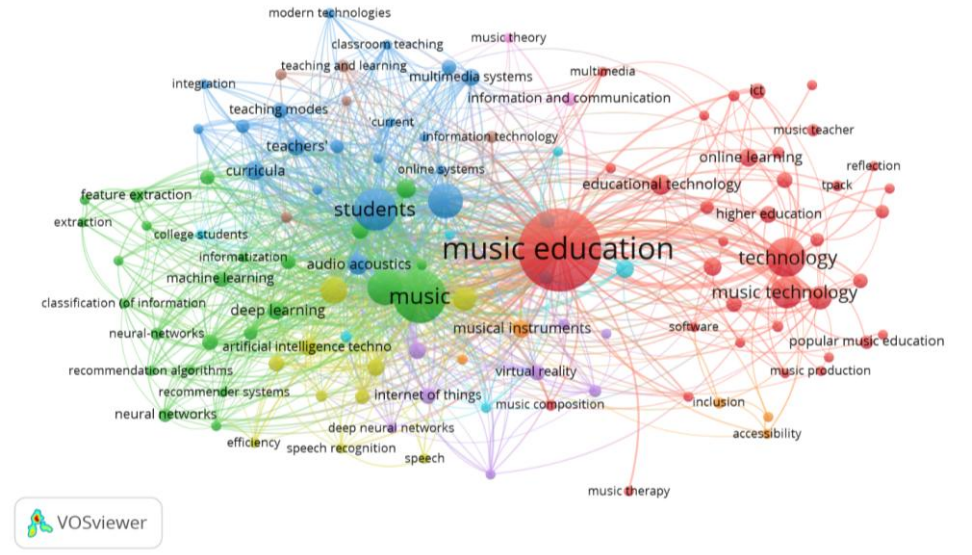

Figure 6. Cluster Map of Research Topic

Cluster 1 (red cluster): Music education and technology

Important keywords in this cluster include music education, technology, educational technology, online learning, ICT, and higher education. This cluster appears to revolve around the integration of technology in music education, highlighting how digital and online tools can enhance the learning experience for vocal students. Topics within this cluster address how educational technologies and ICT are leveraged to support teaching methods in vocal music, including online platforms and resources that facilitate remote music instruction. This focus on technological integration emphasizes the shift towards a digital learning environment and the opportunities it presents for expanding access to music education.

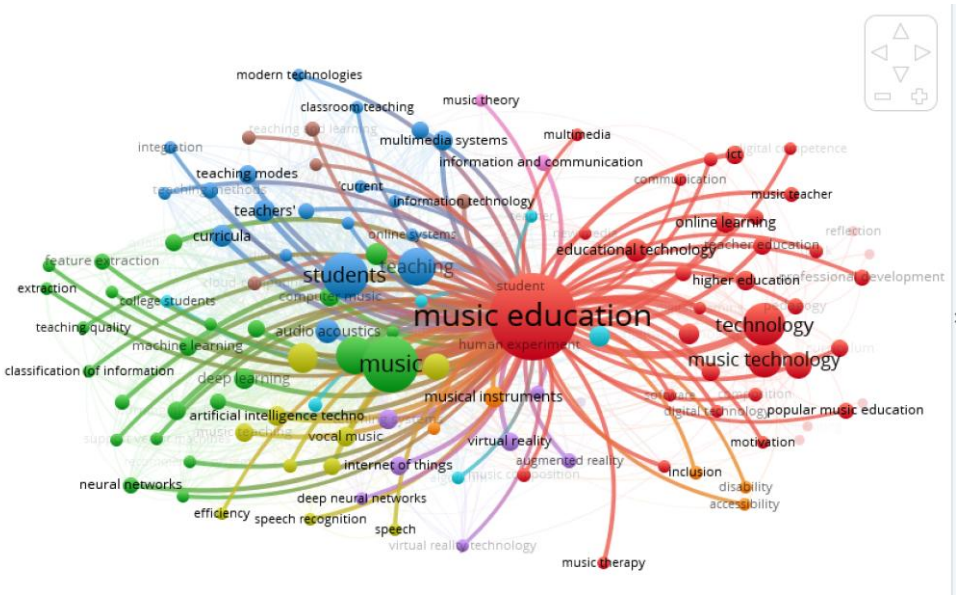

Figure 7. Cluster 1 Map (Red Cluster)

Cluster 2 (green cluster): Acoustics and music analysis

Important keywords in this cluster include audio acoustics, deep learning, neural networks, feature extraction, machine learning, and classification. This cluster centers on the intersection of acoustics and machine learning in music, specifically how acoustic features can be analyzed to improve vocal training. By examining audio patterns through advanced machine learning techniques, such as neural networks and feature extraction, educators and researchers can develop tools that provide feedback to vocalists. This cluster highlights a data-driven approach to vocal pedagogy, focusing on the potential for acoustic analysis to personalize and refine vocal instruction.

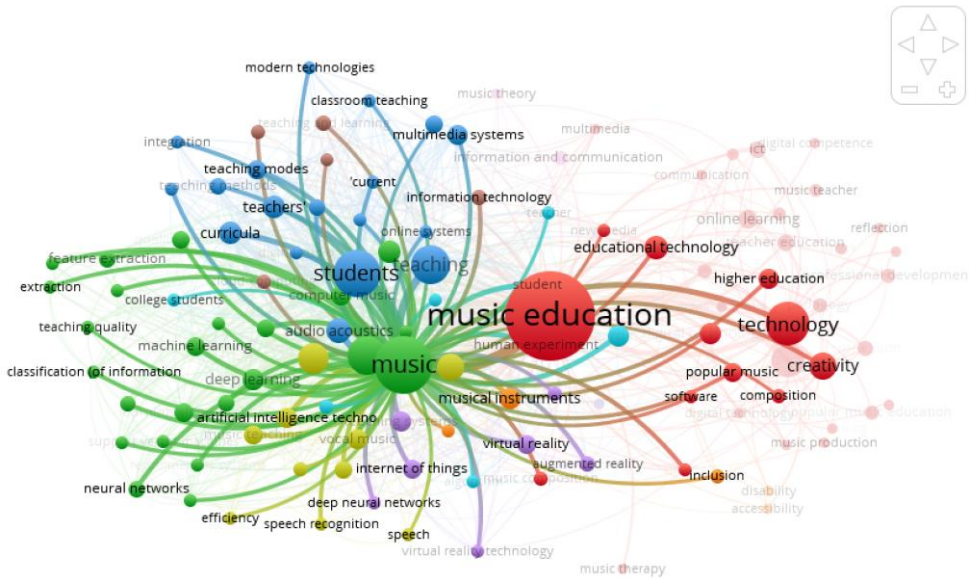

Figure 8. Cluster 2 Map (Green Cluster)

Cluster 3 (blue cluster): Student engagement and learning methods

Important keywords in this cluster include students, teaching modes, curricula, integration, classroom teaching, and teaching and learning. This cluster is concerned with pedagogical strategies that foster student engagement in vocal music education. It emphasizes the need for curricula that integrate spectrum-based tools and diverse teaching modes to enhance learning

outcomes. This cluster focuses on how teaching methods can be adapted to maximize student participation and engagement, with an emphasis on incorporating interactive elements and personalized feedback to make the learning experience more impactful.

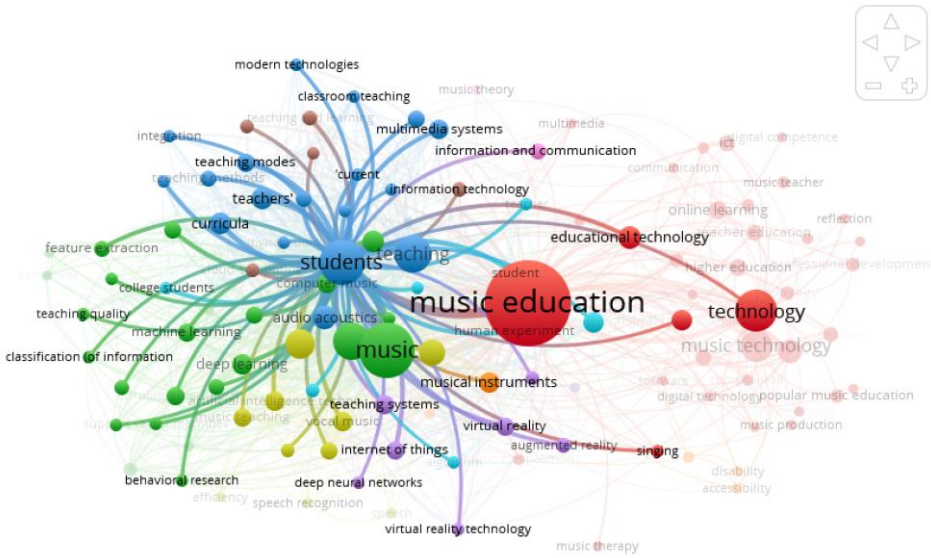

Figure 9. Cluster 3 Map (Blue Cluster)

Discussion

Music education and technology

This cluster unraveled music technology's role in enhancing the teaching of vocal music. Integrating music technology into vocal music education has demonstrated significant potential in enhancing both teaching and learning outcomes. Nineteen studies highlight the diverse applications of technology, each contributing uniquely to vocal pedagogy. Several studies emphasize the role of AI and machine learning in providing precise and personalized feedback to students. For instance, Zhang (2023) discusses the application of artificial intelligence, such as endpoint detection and Mel frequency cepstrum coefficients, to identify key vocal elements with high accuracy, enabling accurate feedback that aids in performance improvement. This is further supported by Cui and Chen (2024), who developed an autonomous learning framework with neural networks, which not only provides precise feedback (97.4% accuracy) but also encourages independent learning among music education majors. Similarly, Li and Wang (2024) demonstrate that AI-enabled tools, like chatbots, enhance vocal training, albeit modestly, suggesting the potential of AI in improving student engagement and outcomes.

In addition to AI, the use of spectrum analysis and frequency-based technology has also proven beneficial. Wang (2023) employs Fourier transform and wavelet analysis to assess vocal skills objectively, finding improvements in fluency, flexibility, and originality among students in technology-enhanced curricula. Zhang (2023) also highlights the role of Fourier transform analysis in identifying patterns in vocalization that can guide instructional methods, such as correcting air leakage or missing frequencies.

Another key focus of music technology in vocal education is the promotion of interactive and multimodal learning experiences. According to Xie (2024), cloud-based platforms combining digital health tools with traditional music emphasize both skill development and cultural heritage, providing a comprehensive and scalable approach to vocal education. This is echoed by Yang (2024), who illustrates the effectiveness of OSC-based interactive learning systems in improving rhythmic abilities, further demonstrating how interactive digital tools can foster practical skills and engagement. Music technology also facilitates the preservation and adaptation of cultural music traditions in digital spaces. Paschalidou (2024) explores the adaptation of oral music genres, like Hindustani music, to technology-mediated platforms, making music education more accessible. Although challenges remain in preserving the multi-sensory cues of traditional pedagogy, the study underscores the potential of technology to bridge cultural heritage and

modern education. Bu and Natayakulwong (2024) extend this concept by showing how digital media supports cultural dissemination, rejuvenating traditional teaching methodologies, and promoting cultural accessibility.

Studies like those of Kou (2023) and Hou et al. (2023) point to the customization and personalization capabilities of music technology. Kou's research on a personalized teaching resource system using collaborative filtering algorithms shows over 70% of students felt their learning improved through tailored resources. Similarly, Hou et al. highlights that music visualization, while challenging for some, adds a creative dimension to teaching, which can significantly enhance the learning environment by making it more engaging and effective.

Several researchers address the impact of technology on student creativity and musical exploration. Liang (2024) demonstrates that digital tools enable flexibility and experimentation within vocal ensembles, fostering a creative learning environment. This focus on creativity is further illustrated by Shi (2024), whose integration of AI and multimedia resources improves rhythm and creativity by up to 30%, showing that digital tools enhance learning and inspire innovation in vocal music education. It's evident from these findings that music technology plays a multi-faceted role in enhancing vocal music education. From providing precise feedback and fostering personalized learning experiences to promoting cultural heritage and creativity, technology offers tools that align with contemporary educational needs, ultimately enriching vocal music education's teaching and learning processes.

The cluster further provides how spectrum-based tools are integrated into modern music education to improve vocal pedagogy outcomes

According to a growing body of research with six authors, incorporating spectrum-based tools into contemporary music education can greatly improve vocal pedagogy by offering data-driven, visual feedback that helps teachers and students improve vocal technique and comprehension. According to Zhang (2023), Fourier transform analysis can pinpoint significant variations between students' and professional singers' performances, especially in terms of pitch and frequency. Through the analysis of time-frequency signals, this method allows teachers to identify technical problems such as air leakage, tone production, and pitch control, and provide focused interventions to enhance students' vocal skills. Building on this, Zhang (2024) highlights the potential of pulse-coupled and convolutional neural networks, achieving nearly 98% accuracy in music theory notation recognition. This accurate identification improves teaching methods by enabling educators to evaluate students' knowledge of music theory and increase the efficacy of online training. In a related study, McQuade (2020) shows how spectrographic analysis can revolutionize vocal training by enabling students to see acoustic characteristics, enhancing the interactive and visually captivating nature of singing, which is typically an auditory experience. By offering real-time feedback on pitch, tone, and vocal qualities, spectrographic analysis supports efficient vocal adjustments and promotes artistic and technical growth.

Lã and Fiuza (2022) emphasize the benefit of visual tools, such as electroglottography and subglottal pressure meters, which enable singers to monitor and adjust their breathing, phrasing, and vibratory patterns with precision. This real-time feedback deepens students' awareness of their vocal mechanisms, leading to improvements in intonation, consistency, and expressiveness. Liu et al. (2016) further validates the value of spectrogram analysis technology in vocal pedagogy, as it visualizes critical aspects of singing, like breathing patterns and articulation. By incorporating a harmony search algorithm, the technology enhances students' ability to address vocal issues systematically, aligning with an integrated "mouth-to-ear-nose" teaching approach that fosters innovation and skill development. Sun (2019) opined that using spectrum image analysis techniques, including FFT and wavelet transform algorithms, in vocal lessons provides real-time visualizations of pitch, frequency, and harmonics. By moving beyond auditory feedback, these tools offer a structured, data-driven approach to vocal instruction that allows students to self-assess and continuously refine their skills, enriching traditional pedagogical methods with modern, technology-enhanced practices.

These findings underscore the transformative potential of spectrum-based tools in vocal pedagogy, bridging traditional music education with advanced technology to support enhanced learning outcomes and more precise, expressive vocal performances.

Acoustics and music analysis

This cluster addresses the acoustic features that are most effective in providing visual feedback to vocal students, thereby enhancing their learning experience and improving technique comprehension. According to Lã and Fiuza (2022), spectrographs, electroglottography, and subglottal pressure meters are used to make physiological acoustic characteristics visible, such as lung volume, subglottal pressure, and vocal fold vibratory patterns. This visibility promotes a more knowledgeable and controlled approach to vocalization by helping students comprehend the mechanics of their voices, such as breath support and pitch stability. According to Liu (2023), legato execution and consonant articulation are crucial components of visual feedback. By analyzing Mel spectrum data with convolutional neural networks, Liu's study quantitatively assesses pronunciation and vocal technique, highlighting areas where students can improve. Features like vowel pitch and consonant clarity are scored, enabling targeted feedback that directly enhances vocal quality. Resonance patterns, vocal fold articulation, and respiration dynamics are highlighted by Liu et al. (2016) as being essential for visual feedback. Students can observe and modify elements of their vocal production, such as resonance placement and breathing depth, through spectrogram analysis, enabling more accurate technical adjustments and enhanced singing performance.

Hao (2022) underscores the utility of features like pitch, tonal quality, and tuning via an audio spectrum analysis system that uses BP neural networks and fast Fourier transform algorithms. This setup not only offers real-time adjustments but also enables students to understand tonal precision, enhancing their engagement with immediate visual feedback in the classroom. Sun (2019) identifies frequency, pitch, overtones, harmonics, and singer formants as particularly beneficial when visualized. Spectrum-based tools enable students to gain real-time insights into pitch accuracy and resonance control, transforming abstract aspects of vocal techniques into tangible metrics, thus accelerating skill development.

This cluster points out that providing visual feedback on specific acoustic features, such as lung volume, pitch, resonance, and articulation, offers vocal students concrete insights into their vocal mechanics. This approach fosters a deeper understanding of technique, facilitating targeted improvements and enhancing the overall learning experience in vocal pedagogy.

Student engagement and learning methods

This cluster addresses how spectrum-based pedagogies impact student engagement and learning outcomes in vocal music classes by offering visual, data-driven feedback that fosters deeper understanding and motivation. Spectrum-based pedagogies, like spectrogram analysis, greatly improve student engagement and learning by visualizing vocal characteristics like breath control and resonance (Liu et al., 2016). This immediate, accessible feedback allows students to adjust their techniques with greater intuition and accuracy, transforming abstract vocal concepts into comprehensible visuals. Students' motivation and active engagement rise as a result, and their vocal quality and technique retention significantly improve, highlighting the long-term advantages of spectrum-based tools in vocal pedagogy. According to McQuade (2020), spectrographic analysis transforms vocal performance into a visual experience that appeals to tech-savvy students, revolutionizing traditional vocal instruction. By allowing students to see real-time acoustic data, it creates a more stimulating and interactive classroom environment. By giving students, the ability to monitor their development quantitatively, this method encourages deeper engagement and understanding of vocal techniques, which eventually improves learning outcomes and the vocal music education experience for students.

According to Zhang (2023), Fourier transform analysis improves student engagement by providing thorough feedback on air control and pitch, highlighting gaps and differences between students and professional singers. Students gain self-awareness and are inspired to actively improve their methods by this real-time feedback, which creates a more dynamic learning

environment and gives them the confidence they need to overcome particular obstacles. As demonstrated by Fang (2024), spectrograms offer precise, tailored feedback by clearly visualizing articulation, breathing, and resonance. By comparing fundamental frequencies, students gain direct insights into their vocal production, which supports a more intuitive and engaging learning experience. As they visualize and adjust their vocal techniques, students achieve a deeper understanding of their capabilities, improving both technical skills and overall vocal performance. Chen (2023) finds that spectrum-based methods such as cepstrum analysis and audio signal correction significantly enhance learning outcomes by improving students' vocal accuracy and alignment with standard vocal measurements. This data-driven approach led to an average score increase in vocal assessments, evidencing that spectrum-based feedback actively engages students, helping them refine their techniques more effectively.

This cluster underscores that spectrum-based pedagogies transform vocal education by providing immediate, visualized feedback on key acoustic features. This approach not only facilitates deeper student engagement but also enhances learning outcomes, making vocal techniques more accessible, comprehensible, and retainable for students.

CONCLUSION

Spectrum-based pedagogies present a transformative approach in vocal education by bridging traditional methods and modern acoustic analysis. This systematic review of 28 articles, conducted according to PRISMA guidelines, reveals that the integration of spectrum analysis tools (such as spectrographs and Fourier transformers) has a significant impact in three main areas. First, precise and scientific feedback: These tools enable educators to diagnose vocal production issues (such as pitch stability, breath control, and resonance) objectively. By visualizing acoustic features like vocal fold vibratory patterns and harmonics, abstract vocal concepts become tangible and comprehensible for students, guiding them toward a more controlled and refined singing technique. Second, enhanced engagement and learning outcomes: This approach aligns with the preferences of a tech-savvy generation. The interactive and immersive learning environment facilitated by real-time spectral feedback boosts motivation, technique retention, and overall vocal quality. Third, a foundation for future innovation: These findings hold broad practical implications. For educators, these tools simplify the teaching of complex concepts. For curriculum designers, this is a call to modernize vocal pedagogy and align it with the STEAM approach. For technology developers, there is an opportunity to create more user-friendly and accessible tools. Spectrum-based pedagogies promise a more informed, engaging, and student-centered vocal learning experience. Continued collaboration among stakeholders is essential to fully realize its potential in driving innovation in vocal music education.

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