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A Systematic Literature Review and Guide to Interdisciplinary Studies on Timbre in Traditional Instruments

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Abstract: This study addresses the lack of comprehensive literature on timbre analysis in traditional and ethnic musical instruments by examining interdisciplinary approaches across diverse cultural contexts. Using a systematic literature review guided by PRISMA, the study analyzes 48 sources from SCOPUS and Web of Science. These sources span acoustics, cognitive science, and cultural studies, reflecting the interdisciplinary scope of timbre research. The analysis identifies eight primary themes: timbral characterization, instrument design, automatic classification, psychoacoustic perception, sound synthesis, performance techniques, cultural interpretation, and musicological analysis. Findings indicate that harmonic structure, spectral and energy-based features, and nonlinear behaviors are central descriptors that differentiate traditional instruments, while vibrational modes and material properties shape their acoustic identity. Cultural factors also influence timbre perception, reinforcing the integration of technical and interpretative frameworks. The study highlights the need for further research on underrepresented regions, including South America, Africa, and the Middle East, to broaden the field's cultural scope. This review offers a foundation for future studies on timbre's acoustic and cultural dimensions.

Keywords: Timbre analysis; traditional musical instruments; acoustic properties; cultural expression; interdisciplinary review.

Uma revisão sistemática da literatura e guia para estudos interdisciplinares sobre timbre em instrumentos tradicionais

Resumo: Este estudo aborda a escassez de literatura sobre a análise do timbre em instrumentos musicais tradicionais e étnicos, examinando abordagens interdisciplinares em contextos culturais diversos. Por meio de uma revisão sistemática orientada pela metodologia PRISMA, analisa 48 fontes da SCOPUS e da Web of Science. Essas fontes abrangem acústica, ciência cognitiva e estudos culturais, refletindo o escopo interdisciplinar da pesquisa sobre timbre. A análise identifica oito temas: caracterização tímbrica, construção de instrumentos, classificação automática, percepção psicoacústica, síntese sonora, técnicas de performance, interpretação cultural e análise musicológica. Os resultados indicam que estrutura harmônica, características espectrais e energéticas e comportamentos não lineares são descritores centrais que diferenciam instrumentos tradicionais, enquanto modos vibracionais e propriedades materiais moldam sua identidade acústica. Fatores culturais influenciam a percepção do timbre, reforçando a integração de estruturas técnicas e interpretativas. O estudo destaca a necessidade de pesquisas sobre regiões sub-representadas, incluindo América do Sul, África e Oriente Médio, para ampliar o escopo cultural. Esta revisão oferece base para estudos futuros sobre as dimensões acústicas e culturais do timbre.

Palavras-chave: Análise de timbre; instrumentos musicais tradicionais; propriedades acústicas; expressão cultural; revisão interdisciplinar.

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Timbre, often described as the "color" or unique quality of sound, fundamentally distinguishes one sound from another, independent of pitch, loudness, or duration (Siedenburg; Saitis; McAdams, 2019). More than merely an attribute, timbre conveys rich information about the sound source's material, shape, and method of excitation, making it central to auditory perception (Caetano; Saitis; Siedenburg, 2019. Siedenburg; McAdams, 2017). Siedenburg and McAdams (2017) highlight timbre's role in enabling sound source identification and as a distinct perceptual quality that operates on multiple levels. Beyond its role in source differentiation, timbre is also crucial for perceptual grouping, auditory scene analysis, and musical expressivity, influencing how listeners organize and interpret complex auditory stimuli. The complex interplay of physical, acoustic, and perceptual dimensions makes timbre a multifaceted area of study, challenging researchers to identify its core acoustic characteristics across sounds as varied as musical instruments, voices, and environmental noise (McAdams et al., 1995). By bridging psychoacoustics, MIR, and ethnomusicology in a single framework, timbre emerges as a unifying concept that illuminates both technical and cultural dimensions of sound.

Timbre analysis has evolved through various feature extraction methods, from early time-domain and frequency-domain techniques, each capturing specific sound characteristics, to more advanced deep learning-based approaches that identify complex patterns and nuances in audio data, supporting applications like instrument classification and acoustic scene analysis (Peeters, 2004. Sharma; Umapathy; Krishnan, 2020). Early methods, such as spectral centroid and attack time descriptors, focused on spectral and temporal dimensions, which remain foundational in audio analysis today. However, as research in timbre expanded, new approaches incorporated perceptual models that better align with how humans experience and differentiate sounds. Siedenburg et al. (2016) illustrate how timbre descriptors are extensively applied in MIR for tasks such as musical instrument classification, where high computational efficiency is prioritized. This technical focus, however, contrasts with the interpretive and perceptual frameworks seen in psychology and other disciplines, where there's a greater emphasis on understanding the subjective nature of timbre perception. The emphasis on feature extraction within MIR underscores the challenge of aligning robust, task-oriented methods with perspectives that highlight the perceptual and interpretative dimensions of timbre, as explored in psychology and music cognition (Caetano; Saitis; Siedenburg, 2019). An integrative approach that unites these computational and perceptual viewpoints is therefore essential for a fuller understanding of timbre's complexity.

Timbre is also deeply rooted in cultural, musicological, and historical contexts, making it an inherently interdisciplinary field. Aguirre-Fernández et al. (2021) highlight how timbre is integral to shaping the sonic identity of traditional musical instruments and preserving cultural heritage. Studies in music anthropology, ethnomusicology, and computational ethnomusicology (Beauguitte, 2019. Born, 2020. Tzanetakis, 2014) demonstrate that timbre analysis extends beyond acoustics and digital signal processing, intersecting with other disciplines to examine how sound contributes to identity and meaning within diverse musical practices. As Born (2020) suggests, MIR and related fields can benefit from addressing social and epistemological dimensions that emphasize the diversity of musical expression, including the sociocultural dimensions of sound. The study of timbre in traditional and non-Western instruments presents unique methodological challenges, as many conventional analytical frameworks are designed around Western

musical structures. This interdisciplinarity, involving the integration of psychoacoustic, ethnographic, and computational approaches, offers a more holistic view of timbre that encompasses both its acoustic features and its broader cultural implications.

Despite a growing body of research on timbre, to our knowledge, there are no literature reviews that comprehensively address the analysis of timbre in traditional and ethnic instruments. The review by Gunjawate et al. (2018), while useful, focuses specifically on the acoustic analysis of singing voice, with limited exploration of traditional or culturally specific singing styles. Furthermore, it does not address the intersection of timbre analysis with cultural or ethnomusicological concerns. Similarly, much of the existing timbre research prioritizes Western instruments, leaving significant gaps in the study of non-Western musical traditions. This gap highlights the need for a review that synthesizes timbre research across these areas, reflecting the field's interdisciplinary scope and its potential contributions to understanding timbre in non-Western contexts.

This study seeks to address this gap by conducting an integrative literature review that examines timbre analysis in traditional musical instruments from interdisciplinary and cross-cultural perspectives. By synthesizing research across psychoacoustics, MIR, ethnomusicology, musicology, anthropology, performance techniques, instrument design and construction, vibroacoustics, physical and virtual modeling, and digital sound synthesis, this review aims to deepen understanding of how timbre functions as a marker of cultural identity and expression. Such a focus allows for a more nuanced appreciation of timbre that aligns with Born's (2020) call for interdisciplinary approaches, facilitating not only technical advancements but also insights into the cultural and perceptual dimensions of sound. In the sections that follow, we first present our methodology followed by a comprehensive categorization of results focused on the research questions, then structure our discussion around the predominant timbral features and the role of timbre analysis, culminating in a conclusion that outlines potential directions for future research. This study contributes to the field by offering a comprehensive overview that bridges technical methodologies with interpretative frameworks, expanding the understanding of timbre in a global and culturally diverse context. We posed questions that guided the study throughout all its phases:

- What are the predominant timbral features measured in timbre analysis of traditional music instruments?
- What is the role of timbre analysis in accordance with the aim of each source?

1. Methodology

The sources compiled in this review were analyzed using a descriptive approach under the PRISMA methodology framework. This methodology "can provide syntheses of the state of knowledge in a field, from which future research priorities can be identified" (Page *et al.*, 2021, p. 1), which is the broader aim of this study. In applying PRISMA, we tracked each step of the selection process in a transparent manner, documenting reasons for exclusion and resolving any screening discrepancies through discussions among the research team. This approach was chosen because the nature of the research questions calls for a qualitative assessment of sources and because the articles involved utilize a wide variety of

methodologies (Moher *et al.*, 2015) due to the interdisciplinary nature of the field. The search was conducted in January of 2025 using the SCOPUS and Web of Science databases. These databases were chosen because an initial exploration revealed that the literature on timbre analysis of musical instruments is dispersed across various disciplines, including engineering, acoustics, physics, digital signal processing, anthropology, musicology, psychoacoustics, machine learning, and music information retrieval. SCOPUS and Web of Science are known for their comprehensive coverage and reliability, making them suitable for capturing a representative sample of the most important journals in these fields. Additionally, many academic events related to timbre analysis publish conference proceedings that contain relevant information but do not disclose the evaluation process of these papers. By using these databases, relevant conference papers were automatically selected based on the standards of the parent source and the databases. The search was performed using the following compatible search equations:

Web of Science	SCOPUS
(((TS=(timbr* analysis)) OR TS=(acoustic* analysis)) OR TS=(spectr* analysis)) AND TS=(music* instrument*)	(TITLE-ABS-KEY(timbre AND analysis OR acoustic* OR spectral) AND TITLE-ABS-KEY(music* AND instruments))

Table 1. Search equations in databases. Source: Own work.

Although this review focuses on traditional instruments, a broader search using the term “music instruments” was conducted. This approach was necessary due to the varied definitions and synonyms for “traditional”, such as autochthonous, indigenous, folk, ethnic, and non-western. These terms emphasize different aspects of the origins and contexts of the instruments and are understood differently in various contexts. Additionally, titles, abstracts, and keywords often did not mention these terms, instead relying on the names of the instruments or their countries of origin. Therefore, our broader search ensured consistency and increased the likelihood of capturing studies that might have used alternative terminology or placed greater emphasis on cultural context.

By broadening the search term, we mitigated the risk of missing relevant studies that might not explicitly use specific terms associated with traditional instruments. This inclusive strategy ensured that most relevant literature on musical instruments was captured. The identification and categorization of specific traditional instruments was addressed at a later stage of the review process. In cases where definitions overlapped or were ambiguous, we relied on consensus among the researchers to categorize the instrument as “traditional” or otherwise.

To narrow down our search to fit the research questions we used the following inclusion and exclusion criteria:

Inclusion Criteria
Voice studies where the singing is part of an autochthonous musical tradition
Studies of historical and prehistoric traditional musical instruments
Psychoacoustic studies with timbral elements related to specific traditional musical instruments

Exclusion Criteria
Acoustic analysis not directly related to timbre analysis
No timbre analysis of a specific traditional musical instrument
Published in languages other than English, Spanish, and Portuguese
Lack of detailed information on timbre analysis in methods and/or results
Studies on prototypes, experimental, or toy musical instruments
Studies on historical and present Western musical instruments
Studies where traditional instruments are a minority in the timbre analysis

Table 2. Inclusion and exclusion criteria of sources. Own work.

These criteria were refined through iterative pilot testing on a small batch of papers, ensuring that the final inclusion and exclusion standards closely aligned with the research questions. This process resulted in 117 unique entries regarding individual instruments, instrument families, ensemble-related labels, archaeological sound-producing objects, and vocal traditions. The corpus is strongly concentrated in Asia, which accounts for 105 entries: 61 from East Asia, 23 from South Asia, 20 from Southeast Asia, and 1 from the Middle East. Outside Asia, the corpus includes 4 entries from Europe, 4 from North America, 3 from South America, and 1 from Africa.

2. Results

48 sources were identified as shown in Appendix B.

3. Discussion

The objective of this literature review was to identify the predominant timbral features of

traditional musical instruments and determine their roles within the context of the studies analyzed. Following an inductive content analysis, we identified eight themes that represent the main areas of focus: characterization of instrument's timbre; informing instrument design and construction; automatic classification and recognition; psychoacoustics and perceptual understanding; supporting sound synthesis; performance techniques and analysis; cultural, historical, and ethnomusicological interpretation; musicological and theoretical analysis. While many of the studies reviewed are interdisciplinary in nature and have overlapping categories, each was grouped according to its primary objective as stated by the researchers.

3.1. Characterization of Instrument's Timbre

The characterization of timbre in traditional musical instruments is a multidimensional endeavor, integrating harmonic content, vibrational interactions, material properties, and cultural influences. While each study reviewed here approaches this task from a different angle, they share a common goal of identifying the defining acoustic features of their respective instruments. Some focus on harmonic structures as a key component, while others explore vibrational modes, nonlinear behaviors, or tuning systems, demonstrating that timbre is shaped by both the instrument's physical properties and the cultural context in which it is used. Despite these differences, all studies contribute to a deeper understanding of timbre as more than a simple descriptor of sound but rather as a dynamic interaction between acoustical, material, and perceptual factors.

A primary approach in timbre characterization involves the analysis of harmonic structures and their role in defining an instrument's sonic identity. Ando (1993) highlights odd harmonic dominance in Japanese instruments, showing how harmonic content is not only an acoustic feature but also a reflection of cultural aesthetics. This contrasts with Zainal et al. (2009), who focus on the interaction between primary and secondary rattles in the angklung, where the production of additional harmonics and inharmonicity contributes to timbre by shaping both pitch perception and tonal texture. In a similar vein, Krueger et al. (2010) and Shete and Deshmukh (2023) examine how vibrational modes and nonlinear coupling define timbre beyond harmonicity alone. Krueger's vibroacoustic analysis reveals how mode coupling generates beating effects (ombak) in gamelan gongs, contributing to a rich and dynamic timbral experience. Shete and Deshmukh (2023) expand on this by incorporating overtone mapping, demonstrating how tuning practices and resonant interactions shape the tabla's distinctive timbral qualities.

Other studies approach timbre complexity from the perspective of nonlinear behaviors and emergent properties. Sengupta et al. (2010) employ fractal and correlation dimensions to analyze the interaction between drone, playing, and sympathetic strings, highlighting how these elements generate a dynamically evolving sound environment. Datta et al. (2019) similarly emphasize double decay and string-resonator coupling, offering a more physical perspective on complexity, where the decay characteristics of different partials contribute to the instrument's overall tonal quality. These studies underscore that timbre is not merely a sum of frequencies but a dynamic process shaped by multiple interacting factors.

Tuning and material properties also play an essential role in defining timbre, as seen in the

studies by Hamdan et al. (2024). Their first study takes a holistic approach, selecting descriptors such as harmonicity, affinity, brightness, and monotony to assess the timbral identity of the Peking Gamelan, reinforcing the connection between acoustic perception and cultural significance. Their second study links the physical attributes of bamboo in the Pratuokng to its timbral properties, illustrating how material-dependent partials, influenced by variations in thickness and density, interact with tuning adjustments to shape the instrument's sound. By considering the role of materials alongside tuning systems, these studies reinforce the idea that timbre emerges from an interplay between physical acoustics and cultural conventions.

Throughout these studies, timbre characterization remains the central theme, transcending any single analytical method. Whether through harmonic analysis, vibrational modeling, nonlinear behavior, or material properties, each study contributes to a more comprehensive understanding of how traditional musical instruments produce their unique sonic signatures. By integrating physical, mathematical, and perceptual perspectives, these approaches demonstrate that timbre is not only a measurable acoustic property but also a bridge between the instrument's physical construction, its sonic function, and its cultural significance.

3.2. Informing Instrument Design and Construction

The studies reviewed in this section emphasize how timbre analysis informs and optimizes the design and construction of traditional instruments, specifically focusing on the Sarasvati Veena. Both studies by Chauhan et al. (2021) and Chauhan et al. (2023) underscore the critical role of physical components—such as the bridge and resonator—in shaping the timbre of the instrument. These studies, while focused on different components, converge on the broader theme of how specific design choices influence the harmonic content and tonal complexity of the instrument.

A central similarity between the studies is their demonstration of how physical alterations to the instrument's design lead to changes in harmonic richness and energy distribution among harmonics, directly affecting the brightness and resonance of the timbre. Both the bridge and resonator are key to sustaining and amplifying harmonics, although they do so in different frequency ranges and at different stages of the sound's evolution. For example, Chauhan et al. (2023), focusing on the bridge, show that changes in the slope and curvature of the bridge primarily impact the clarity and sustain of higher harmonics, contributing to the Veena's bright, ringing timbre. The study demonstrates that the revival of higher harmonics over time—a crucial feature in the perceived richness of the instrument—relies on the precise geometric configuration of the bridge.

Conversely, Chauhan et al. (2021) highlight how the resonator affects the tonal depth and overall harmonic structure by amplifying the lower and mid-range frequencies and supporting microtonal intervals (srutis) that are fundamental in Indian classical music. The resonator's modal frequencies are shown to enhance specific harmonics that correspond to important musical intervals, thus enriching the lower harmonics and contributing to the fullness of the timbre. Unlike the bridge, which directly influences the higher harmonics and their sustain, the resonator shapes the instrument's ability to resonate with subtle microtonal nuances, providing a crucial foundation for the cultural and musical aspects of the instrument's

sound.

While both studies focus on improving the harmonic content, the bridge and resonator serve distinct roles in shaping the instrument's timbre. The bridge primarily governs the clarity, sustain, and energy distribution of higher harmonics, enhancing the spectral brightness and ringing quality of the instrument. On the other hand, the resonator contributes more to the amplification of harmonics across a broader frequency range, especially in the lower and mid-range frequencies, and supports the rich tonal depth that characterizes the Veena's sound.

In conclusion, these studies provide a complementary understanding of how different components of the Sarasvati Veena contribute to its distinctive timbre. The bridge refines the clarity and sustain of higher harmonics, while the resonator enhances the overall fullness and supports the nuanced microtones essential to Indian classical music. Together, they highlight how timbre analysis can inform the design and construction of traditional instruments, guiding precise modifications that result in an acoustically optimized sound.

3.3. Automatic Classification and Recognition

Across the studies on automatic instrument recognition, cepstral coefficients (MFCCs) and spectral features like spectral centroid and spectral rolloff emerge as fundamental descriptors for capturing timbral properties. These features provide essential information about harmonic content and brightness, proving effective in distinguishing between different instrumental families. Studies such as Joshi and Nadgir (2014) and Gunasekaran and Revathy (2008) demonstrate the centrality of MFCCs in representing perceptual attributes of timbre, while Shelke and Chitre (2015) and Joshi and Chitre (2015) show that spectral features help capture the energy distribution across frequencies, making them key for classification.

Despite these shared foundations, approaches to segmentation and classification vary significantly. Gunasekaran and Revathy (2008) introduce fractal dimension analysis, a novel method that enhances feature extraction by focusing on relevant signal segments. This method is particularly beneficial for handling polyphonic or duet performances, where distinguishing overlapping timbral elements presents a significant challenge. Other studies, such as Nurdiyah et al. (2024) and Xu et al. (2023), adopt deep learning techniques, particularly convolutional and recurrent neural networks, to process more complex, polyphonic textures. These approaches allow for more accurate recognition in challenging conditions, particularly where timbral overlap complicates classification.

The diversity in classification techniques further highlights distinct methodological directions. While k-Nearest Neighbor (k-NN) and Support Vector Machines (SVM) remain widely used, their effectiveness varies depending on the complexity of the task. Joshi and Chitre (2015) demonstrate that Feedforward Backpropagation Neural Networks (FFBNN) offer a significant boost in performance, achieving near-perfect accuracy in some cases. This shift toward more advanced neural network architectures is evident in Nurdiyah et al. (2024), where deep learning models are leveraged to refine timbral feature extraction, improving classification even in environments with substantial polyphonic overlap.

A slightly different but complementary approach is taken by Gowriprasad et al. (2022), who

focus on rhythm-based segmentation in Tabla solo performances. Their study applies MFCCs alongside self-similarity matrices (SSM) for segment boundary detection, demonstrating the role of rhythmic structures in timbre analysis. While their primary focus is segmentation rather than instrument classification, their work reinforces the broader trend of combining timbral and rhythmic features to improve recognition accuracy. This aligns with the findings of Gunasekaran and Revathy (2008), whose segmentation techniques enhance classification performance by ensuring that extracted features correspond to musically meaningful segments.

Taken together, these studies illustrate both convergence and divergence in the field of timbre-based instrument recognition. The shared reliance on MFCCs and spectral features underscores their robustness across different musical traditions and classification tasks. However, the varying approaches—from fractal-based segmentation to deep learning and self-similarity analysis—highlight ongoing efforts to refine recognition methods, particularly for non-Western instruments, polyphonic textures, and structurally complex performances.

3.4. Psychoacoustics and Perceptual Understanding

The studies in this category reveal a complex, multifaceted relationship between timbral features and human perception, with several shared themes and a few key differences. Central to the discussion is how spectral and temporal features influence perceptual attributes such as consonance, pitch, and emotional affect, all of which are mediated by the timbral characteristics of traditional instruments.

A common thread among the studies is the influence of spectral centroid and inharmonicity on listeners' perception. Wang et al. (2021) and Durojaye et al. (2021) both demonstrate that brightness, often measured by spectral centroid, plays a crucial role in emotional and cultural interpretations of sound. For instance, in Wang et al.'s cross-cultural analysis, brightness was linked to pleasantness, where higher spectral centroids in Chinese and Western instruments correlated with perceptions of happiness. Similarly, in Durojaye et al., brightness helped distinguish speech-like from music-like qualities in the Nigerian dùndún drum, with sharper timbres perceived as more dynamic or energetic. Jingying (2017) also highlights brightness as a key perceptual dimension in distinguishing Chinese traditional instruments, with higher brightness contributing to a sharper, more penetrating timbre.

In contrast, Chin and Berger (2010) focus on inharmonicity, a timbral feature arising from non-harmonic partials, and its effect on pitch perception. Inharmonicity shifted perceived pitch higher, especially in lower-pitched instruments like the pipa, demonstrating how timbral structure impacts cognitive processing. This parallels Jiang et al. (2020), where harmonicity and the harmonic-to-noise ratio contributed to perceptions of "coarse" versus "pure" timbres. These studies suggest that harmonic complexity influences both pitch perception and timbral clarity, with increased inharmonicity leading to pitch shifts and less consonant timbres.

Spectral flatness, indicative of noisiness, also emerged as a critical factor. Wang and Gong (2012) found that lower spectral flatness—reflecting more harmonic, less noisy sounds—led to higher consonance ratings in Chinese plucked instruments. Similarly, Chen et al. (2018) used MFCCs to quantify the Guqin's timbral purity, finding that lower noise content correlated with higher perceived quality. Jingying

(2017) reinforces this, identifying low energy as another factor shaping perception, where instruments with lower energy and brightness were perceived as mellower.

While these studies converge on the importance of spectral attributes, they diverge in cultural and instrumental contexts. Wendt and Bader (2019) highlight auditory roughness in Javanese gamelan tunings, where higher roughness did not reduce perceived consonance, challenging Western models. Paquier et al. (2016) similarly illustrate cultural specificity in Great Highland Bagpipe drones, where reed material affected brightness and harmonic emphasis but not perceived quality.

Across all these studies, the balance between brightness and temporal dynamics shapes timbral perception, yet cultural context mediates these effects. Attack time was crucial in Jiang et al. (2020) and Wang and Gong (2012), where faster attacks were linked to sharper, more vigorous sounds. However, in the pipa, inharmonicity was the dominant perceptual factor. In summary, while brightness, inharmonicity, and spectral flatness consistently shape timbral perception, their impact is context-dependent. Cultural and instrumental differences mediate how these features interact, offering a nuanced view of timbre as a multidimensional, culturally informed phenomenon.

3.5. Supporting Sound Synthesis

This category examines how timbral feature analysis informs sound synthesis across different studies. While each study focuses on a specific instrument, all emphasize the importance of analyzing key timbral features to develop realistic synthesis models.

Erkut et al. (2002) focus on nonlinear string vibrations and harmonic beating in the kantele, identifying tension modulation as crucial for synthesis. Their digital waveguide model replicates how the interaction between horizontal and vertical string vibrations influences timbre. Similarly, Puranik and Scavone (2023) emphasize reed vibrations and body resonance in the harmonium, using a source-filter model to simulate the interplay between excitation and filtering. While both studies deal with nonlinear acoustic phenomena, the kantele model centers on string tension effects, whereas the harmonium synthesis focuses on the resonance introduced by the instrument's wooden enclosure.

By contrast, Xue et al. (2023) analyze spectral flux and MFCCs in Guzheng music, identifying these features as critical for distinguishing performed from synthesized sounds. Their findings suggest that accurately modeling spectral variations over time is key to improving synthesis. This emphasis on spectral dynamics is also evident in Chen and Huang's (2011) work on the pipa, where techniques such as pitch bending and tremolo require precise control over inharmonicity and damping filters to model string decay and sustain. Unlike the Guzheng study, which focuses on distinguishing real and synthesized timbres, the pipa model integrates spectral and physical modeling to create a flexible real-time synthesis framework.

The study by Ismail et al. (2006) differs by focusing on the kompang, a percussive membranophone with non-harmonic partials. Instead of harmonic relationships, its timbral variation is defined by differences in attack and decay between center-strike and edge-strike techniques. Capturing these variations in synthesis requires modeling energy distribution and spectral density over time, ensuring the dynamic qualities of the instrument are preserved.

Despite these differences, all studies emphasize the necessity of analyzing time-domain and frequency-domain features to support sound synthesis. Whether through nonlinear interactions (kantele, harmonium), spectral evolution (Guzheng, pipa), or energy-based variations (kompang), timbral analysis plays a central role in shaping synthesis models. Across all cases, the challenge lies in replicating the dynamic and evolving nature of timbre, demonstrating the essential role of detailed acoustic analysis in developing expressive and authentic digital instruments.

3.6. Cultural, Historical, or Ethnomusicological Interpretation

The reviewed studies in this category highlight the intricate connections between sound production and cultural meaning across a diverse range of musical traditions. A key feature across all studies is the use of timbre analysis to reveal the cultural, symbolic, or ritual significance embedded in traditional musical instruments.

Davin et al. (2023) explore how bone aerophones from ancient Natufian culture mimic raptor calls, where high-pitched frequency analysis not only demonstrates intentional sound design but also suggests the role of these aerophones in hunting rituals or symbolic communication. Similarly, Sanchez Santiago (2021) examines Preclassical whistling vessels from Oaxaca, where the analysis of harmonic structures and turbulent noise connects their timbral qualities to ritual practices and supernatural symbolism, suggesting that sound, with its raw, turbulent characteristics, was integral to Mesoamerican burial rituals.

Meyer and Moore (2013) provide a unique perspective by analyzing the Gavião instruments, where timbre closely mirrors the tonal patterns of the tribe's language. Here, the pitch and harmonic analysis directly ties into the cultural practice of "speaking" instruments, where music and language are deeply intertwined in Gavião ritual and social life. Meyer and Moore (2021) further document how this interconnection is maintained through specific instruments like the kotiráp flute, iridináp mouth bows, and totoráp bamboo clarinets, which replicate speech rhythms and tonal contours, preserving oral heritage in instrumental form. This dual role of Gavião music underscores both its aesthetic and practical significance in sustaining cultural memory. In contrast, Zalaquett et al. (2019) investigate Maya ocarinas and whistles, showing how their tonal-dissonant harmonics were designed to evoke bird sounds and were likely used in public or ceremonial settings, reinforcing sound's role in social hierarchy and ritualistic performances.

Koumartzis et al. (2015) focus on the reconstruction of ancient Greek lyres, where advanced timbral analysis of spectral centroid and smoothness reveals similarities in sound production between reconstructed lyres and their ancient counterparts. This study shows how the timbre of instruments is directly tied to mythological and educational roles in ancient Greek society, reflecting cultural values surrounding music and learning.

Overall, timbre analysis across these studies informs cultural understanding by connecting acoustic features to symbolic practices, revealing how different societies used sound not just as music but as a medium of communication, ritual expression, and cultural identity. Differences in methodology, from frequency and harmonic analysis to language integration, highlight the diversity in how timbre reflects cultural context across ancient civilizations.

3.7. Performance Techniques and Analysis

In the studies examined, timbral feature analysis plays a pivotal role in informing and refining performance techniques across various musical traditions, focusing on both vocal and instrumental practices.

Gaikwad and Sircar (2019) demonstrate how harmonic content, spectral centroid, and the relative strength of harmonics contribute to determining the optimal tonic note for Indian classical singers. Their findings suggest that a tonic note aligned with a singer's natural timbral profile enhances vocal projection, clarity, and consistency across octaves. By analyzing the spectral balance of different notes in a singer's range, they show how timbral features can inform intonation choices, ensuring better control over vocal dynamics and resonance, ultimately improving the singer's expressive capabilities.

Zhang (2018) shifts the focus to ensemble performance, analyzing how harmonic structure, spectral energy distribution, and dynamic response affect loudness balance in a Chinese national orchestra. The study highlights disparities between instruments such as the qudi (with its strong high-frequency harmonics, resulting in a bright timbre) and the erhu (which has a more mid-frequency dominant, mellower timbre). The findings emphasize how performers and composers must adjust playing techniques and orchestration strategies to achieve a balanced sound, ensuring that no instrument overpowers the ensemble, particularly in heterogeneous timbral settings.

Kuswanto et al. (2015) explore timbre preservation in the adaptation of gamelan instruments, comparing the electronic demung (ED) and the original demung (OD). Their spectral analysis reveals that the electronic demung produces fewer overtones and has a higher fundamental frequency than the traditional instrument, leading to a simplified, less resonant timbre. This timbral reduction impacts performance by limiting expressive depth and altering the traditional harmonic richness of gamelan music. While the electronic version offers portability and accessibility, the study underscores how the loss of complex overtones in electronic instruments affects traditional playing techniques and the authenticity of performance.

Kovačić et al. (2005) examine timbral differences in two Croatian folk singing styles, klapa and dozivački, through long-term average spectrum (LTAS) analysis. They find that klapa singing lacks a singer's formant, resulting in a timbre resembling speech, which aligns with its smooth, blended vocal style. In contrast, dozivački singing exhibits a strong spectral peak between 3.0 and 3.8 kHz, indicative of a "shouter's formant", which enhances projection and audibility over long distances. This suggests that timbre influences vocal technique, with klapa requiring controlled, resonant blending, while dozivački relies on high-energy vocal production to maintain clarity in loud, open environments.

Across these studies, timbral analysis not only characterizes the acoustic properties of different musical traditions but also provides valuable information on how performers adapt their techniques to achieve clarity, expressivity, and balance within their specific musical contexts.

3.8. Musicological and theoretical analysis

In the studies reviewed under the category of musicological and theoretical analysis, timbre

plays a central role in both structural and interpretative dimensions of musical traditions, though the approaches vary significantly. Haron et al. (2021) analyze the spectral content of the rebab, focusing on the highest magnitude partials, spectral peaks, and dissonance curves. Their study reveals how these timbral characteristics align with just intonation in Makyung music, demonstrating that the instrument's tuning system is shaped by its timbre rather than external pitch frameworks. This approach links the spectral properties of the rebab to broader questions of tuning and consonance in oral traditions.

Similarly, Chauhan et al. (2021) emphasize the harmonic structure and vibrational modes of the Sarasvati veena's resonator. Their analysis highlights harmonic enhancement, the revival of higher harmonics, and the broad spectral range extending up to 2800 Hz. While Haron et al. focus on tuning validation through spectral alignment, Chauhan et al. examine how the resonator's timbral properties sustain microtonal intervals (srutis) crucial to Carnatic ragas. Here, timbre is not only a result of instrumental acoustics but also an active factor in shaping melodic structures, showing a different perspective on the interaction between timbre and musical form.

Gardiner and Lim (2014) take a contrasting approach by analyzing the evolution of timbral progressions in Noh music rather than focusing on harmonic content. Using spectrographic imaging, they examine overtones, nonharmonic bands of noise, attack onsets, and formant regions across instrumental and vocal textures. Their concept of "chromatopes" describes how these timbral shifts structure the temporal flow of Noh performances. Unlike the other studies, which focus on timbre's role in pitch organization, Gardiner and Lim demonstrate how timbral density, spectral energy, and rhythmic articulation function as primary structuring elements, revealing an alternative role for timbre in defining musical form.

Thus, while Haron et al. and Chauhan et al. explore timbre's role in tuning systems and melodic frameworks, Gardiner and Lim present timbre as a dynamic, time-based structural force. These differences highlight the diverse ways timbral analysis contributes to understanding traditional music across distinct cultural contexts.

4. Limitations

This review is limited to studies published in English, Spanish and Portuguese, which may exclude significant research in other languages, potentially narrowing the cultural scope of timbre analysis on traditional instruments. Furthermore, the study relies on data from a limited range of academic databases, which, while comprehensive, might overlook relevant studies from regional or specialized repositories. The broad methodological scope of this review, encompassing various instrument types and analytical approaches, may also generalize findings, potentially obscuring detailed insights into specific timbral characteristics unique to certain instrument families or cultural contexts. Additionally, terminology such as "timbre" and "traditional" varies in definition across disciplines and regions, which may have limited the retrieval of studies using alternate descriptors. Future work could focus more narrowly on particular instrument types, analytical methods, or cultural nuances to gain deeper insights into specific aspects of timbre and its role in musical traditions.

Conslusions

This review synthesizes a wide range of research on timbre analysis in traditional musical instruments, emphasizing the interdisciplinary methods that characterize the field. Across 48 studies, recurring themes highlight the critical importance of acoustic, perceptual, and cultural factors in defining timbral identity. The findings reinforce the centrality of features like harmonic structures, spectral descriptors, and energy dynamics in capturing the complex acoustic signatures of traditional instruments.

Spectral characteristics, including spectral centroid, rolloff, and harmonic structures, play a significant role in distinguishing tonal and textural qualities. Inharmonicity and spectral irregularities are also critical in characterizing timbral complexity, particularly in instruments with unique tonal profiles shaped by non-Western traditions. Time-domain features such as attack time and amplitude envelope provide complementary insights into transient dynamics, underscoring their relevance in analyzing percussive and plucked instruments.

Energy-based features, such as resonance and decay rates, highlight the interplay between an instrument's material properties and its acoustic output. These metrics help uncover the ways construction methods influence tonal richness and sustain, shedding light on how traditional craftsmanship shapes timbral characteristics. Additionally, studies demonstrate how vibrational modes and coupling effects contribute to dynamic timbral properties, revealing the intricate interplay between acoustic behavior and instrumental design.

The review also underscores the significance of contextual and cultural dimensions. Timbre often mirrors aesthetic values and functional roles within specific traditions, reflecting the sociocultural identity embedded in instruments. However, current research disproportionately focuses on Asian instruments, leaving a gap in understanding the timbral qualities of instruments from regions such as South America, Africa, and the Middle East. Broadening the geographical scope of timbre studies would enhance the global representation of traditional instruments and illuminate a wider range of acoustic and cultural practices. Investigating these underrepresented regions could also provide valuable insights into unique playing techniques, tuning systems, and material choices that shape timbral features in ways yet to be fully understood.

Methodological diversity is another key takeaway. While the interdisciplinary nature of timbre research fosters innovation, it also highlights the challenges of integrating and standardizing diverse analytical approaches. Emerging techniques, such as machine learning and deep neural networks, show potential for advancing the precision of timbre analysis, particularly in handling complex datasets and polyphonic textures. Yet, such advancements could align with perceptual and ethnomusicological frameworks to ensure culturally sensitive interpretations. Greater collaboration across disciplines could facilitate the development of more comprehensive frameworks, combining technical precision with cultural relevance.

By expanding regional diversity, future studies could capture a fuller range of timbral qualities, broadening our understanding of traditional instrument acoustics globally. Ultimately, this review

establishes a foundation for more focused analyses, encouraging future work to deepen its scope into specific instrument families, playing techniques, and regional traditions. Such targeted efforts would not only enrich technical knowledge but also preserve the cultural significance of traditional music for future generations, ensuring its relevance in a rapidly changing musical landscape.

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Appendix A: Study Selection Process According to PRISMA

The initial search in the mentioned databases yielded 1,695 results. After removing duplicates and retracted papers, the count was reduced to 1,685. Each entry was then screened by two members of the research team, who reviewed the titles and abstracts to exclude those clearly unrelated to the field of study or deviating from the proposed topic. As expected, due to the inclusiveness of the search terms, most entries were excluded, leaving a total of 110 eligible studies. Of these, the full text of four studies could not be retrieved, resulting in a total of 106. At this point, the full text of each study was read by two researchers and included or excluded according to the criteria shown in Table 2 in the text. From this final screening, 48 studies were selected. Figure A1 shows the process in more detail. Any disagreements were resolved through discussion, and when necessary, a third researcher was consulted to achieve consensus, thus reinforcing the reliability of our selection process.

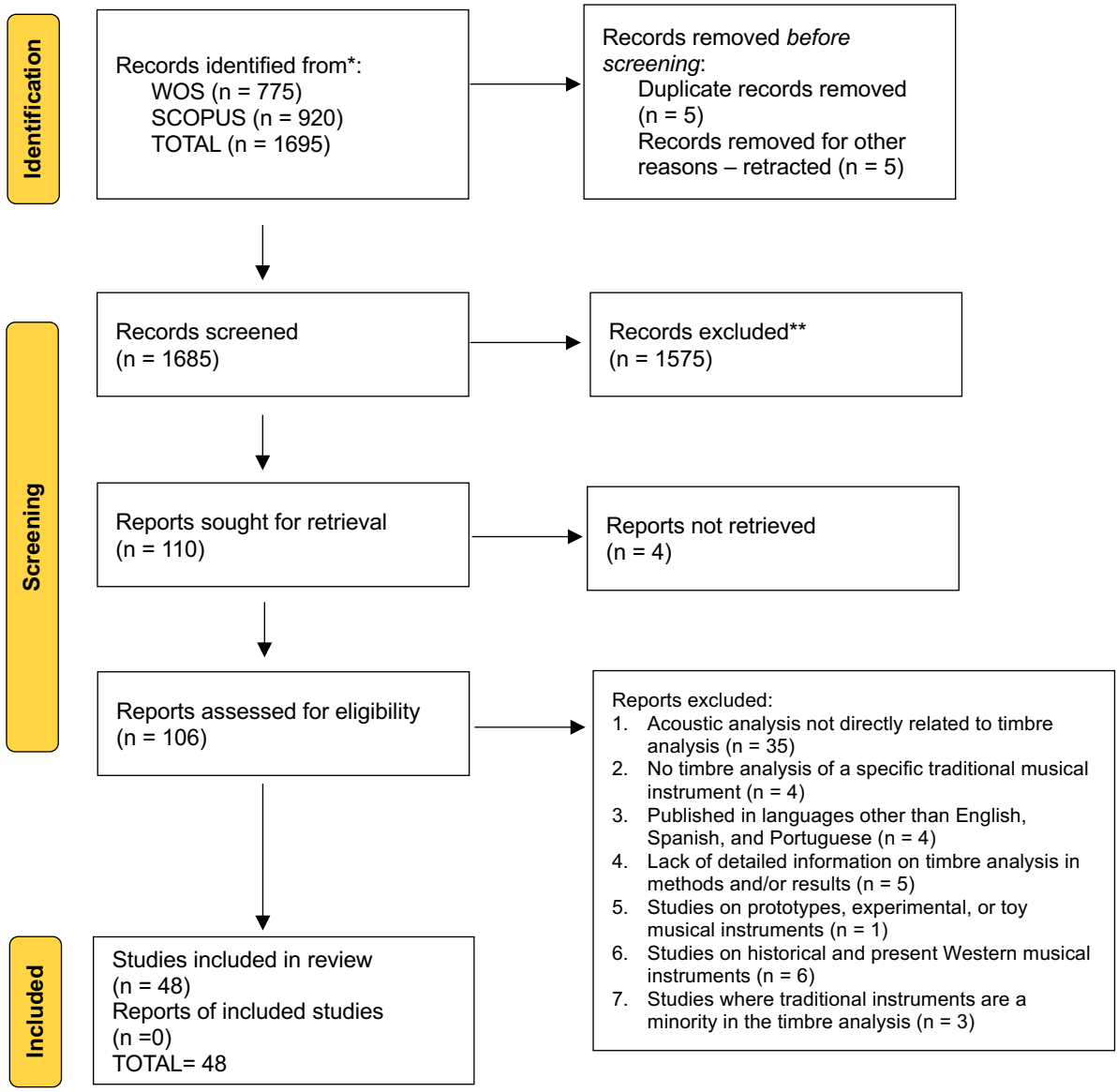

Fig. A1. Identification of studies via databases and registers. Source: Page et al. (2021)

Data analysis utilized a modified version of a pre-designed form previously employed in a similar systematic literature review by Gunjawate et al. (2018). This form encompassed several key characteristics: publication details, which included the document type, year, authors, title, country or region, and database; study details, which comprised the aim of the study, type of study, instruments involved, organology, and sample details; and outcomes, which covered the type of timbral analysis conducted, the timbral features measured, other significant methodological tools or instruments used, and the key conclusions drawn from the study. Building on this detailed organization, an inductive content analysis approach, which involves identifying themes and patterns that naturally emerge from the data, was applied to uncover recurring elements in timbre analysis of traditional instruments. This method was well-suited to the study's exploratory goals, allowing for a systematic interpretation of both explicit and underlying content in the literature (Khirfan; Peck; Mohtat, 2020). Through this approach, key timbral features, tools, and methodological trends were identified, offering a structured view of the field and highlighting areas for further research.

Appendix B: Results

Source	Instrument/ Tradition Origin	Instrument(s)	Timbre features measured	Role of timbre analysis according to aim	Disciplinary approaches
Characterization of Instrument's Timbre					
(Ando, 1993)	Japan	Nohkan, Shamisen, Biwa, Shakuhachi	Time-Domain: pitch control mechanisms Spectral/Frequency Domain: fundamental frequency, harmonic structure, inharmonic components, odd harmonic dominance Energy Based: decay rate of harmonics, resonance characteristics	Characterize instrument's timbre Identify common timbre aesthetics across different musical traditions	Physical acoustics Performance and techniques/devices Musicology
(Zainal *et al.*, 2009)	Malaysia	Angklung	Time-Domain: waveform analysis Spectral/Frequency Domain: fundamental frequency, harmonic analysis, inharmonic peaks Time-Frequency Based: spectrogram analysis	Characterize instrument's timbre	Performance and techniques/devices
(Krueger; Gee; Grimshaw, 2010)	Indonesia	Gamelan Gongs	Time-Domain: peak displacement, transient signal Spectral/Frequency Domain: power spectral density (PSD), frequency ratio, harmonics, sum and difference frequencies, nonlinear mode coupling, amplitude-dependent frequencies, beating frequencies Time-Frequency Based: spectrogram analysis Energy Based: amplitude of vibrations, acoustic response levels	Characterize instrument's timbre Identify and describe the modal response of the instrument	Vibroacoustics
(Sengupta *et al.*, 2010)	India	Sitar	Time-Domain: waveform analysis Spectral/Frequency Domain: spectral energy Time-Frequency: spectrogram analysis Energy Based: spectral energy correlation	Characterize and quantify the signal's complexity	Performance and techniques/devices
(Datta *et al.*, 2019)	India	Tanpura	Time-Domain: waveform analysis Spectral/Frequency Domain: fundamental frequency, spectral content, Brightness, Tristimulus, Odd/Even Relation, Irregularity, Spectral Centroid Time-Frequency Based: spectrogram analysis Energy Based: Energy Ratio, Resonance Balance	Quantify, compare, and understand the acoustic properties of the instrument	Physical Acoustics Performance and techniques/devices Psychoacoustic
(Shete; Deshmukh, 2023)	India	Tabla	Time-Domain: Fundamental frequency Spectral/Frequency Domain: Overtones, Harmonics, Inharmonicity, Power spectral density Energy Based: Power spectral density of overtones, Signal energy	Characterize the sound of the instrument	Performance and techniques/devices Vibroacoustics Physical acoustics Musicology and Ethnomusicology
(Hamdan; Sinin; *et al.*, 2024)	Indonesia	Peking Gamelan instruments	Spectral/Frequency Domain: Fundamental frequency, Spectral Centroid, Affinity, Harmonicity, Brightness (Sharpness), Mean Contrast, Monotony	Quantify and characterize the sound properties of the instruments	DSP

(Hamdan; Said; *et al.*, 2024)	Malaysia	Pratuokng	Spectral/Frequency Domain: Fundamental frequencies, partial frequencies, first overtone, harmonic partials, non-harmonic partials, frequency spectrum, frequency analysis Time-Frequency Based: Spectrogram analysis	Characterize the instrument's sound	Instrument Design and Construction Performance and techniques/devices
Informing Instrument Design and Construction					
(Chauhan; Singru; Vathsan, 2023)	India	Sarasvati Veena	Spectral/Frequency Domain: Harmonic content, Distribution of energy among harmonics, Relative energy content in the harmonics, Spectrum analysis, Revival of higher harmonics Time-Frequency Based: Temporal change in the spectrum, Revival of harmonics with time Energy Based: Energy distribution among harmonics, Energy content, Transfer of energy to higher harmonics, Sustenance of energy in the revived harmonics	Quantify and understand how the physical characteristics of the instrument, specifically the bridge, contribute to its unique sound quality	Physical and Virtual Modeling Physical acoustics Vibroacoustics Instrument Design and Construction
(Chauhan; Singru; Vathsan, 2021a)	India	Sarasvati Veena	Spectral/Frequency Domain: Harmonic content, Energy redistribution among higher harmonics, Harmonics development over time Energy Based: Energy content in formants, Redistribution of energy among formants	Aid to establish a relationship between the instrument's bridge and its sound characteristics	Physical and Virtual Modeling Physical acoustics Instrument design/construction
Automatic Classification and Recognition					
(Gunasekaran; Revathy, 2008)	India	Sitar, rudra veena, santoor, kamaicha, mirudhangam, edakkai, pakhawaj, indian flute, shehnai, surnai	Time-Domain: fundamental frequency – f0, auto-correlation coefficients (12 values), zero crossing rate, log-attack time, temporal centroid Spectral/Frequency Domain: spectral centroid, spectral skewness, spectral roll-off, spectral spread, spectral kurtosis, spectral slope, spectral decrease, spectral variation, spectral flatness (4 values), spectral crest (4 values), max-energy FFT bin Cepstral Domain: MFCC (13 values), DELTA-MFCC (13 values), DELTA-DELTA-MFCC (13 values) Energy Based: energy of the signal Perceptual Features: perceptual spectral centroid, perceptual spectral spread, perceptual spectral skewness, perceptual spectral roll-off, perceptual spectral kurtosis, perceptual spectral slope, perceptual spectral decrease, perceptual spectral variation, perceptual spectral tristimulus (3 values), perceptual spectral odd-to-even ratio	Facilitate the recognition and classification of musical instruments (enhance segmentation and feature extraction)	Automatic classification/recognition, machine learning
(Joshil; Nadgir, 2014)	India	Flute, Harmonium, Dholaki, Santoor, Sanai	Time-Domain: zero crossing rate (ZCR), root mean square (RMS) Spectral/Frequency Domain Features: Spectral flux, spectral centroid, spectral roll-off, spectral bandwidth Cepstral Domain: Mel Frequency Cepstral Coefficients (MFCCs), MFCC variants Energy Based: short time energy (STE) Wavelet Based: short time energy (STE)	Lay the groundwork for instrument recognition and classification	Automatic classification/recognition, machine learning

(Joshi; Chitre, 2015)	India	Flute, Harmonium, Sitar	Time-Domain: zero crossing rate (ZCR), root mean square (RMS), periodicity Spectral/Frequency Domain: Spectral centroid, spectral roll-off, spectral bandwidth Cepstral Domain: Mel Frequency Cepstral Coefficient (MFCC)	Serve as the input for machine learning models, which then use these features to accurately identify and classify the instruments based on their unique timbral characteristics	Automatic classification/recognition, machine learning
(Shelke; Chitre, 2015)	India	Wooden Flute, Harmonium, Sitar	Time-Domain: zero crossing rate (ZCR), periodicity, amplitude, amplitude envelope Spectral/Frequency Domain: Spectral centroid, spectral roll-off, spectral flux Energy Based: Average power	Facilitate the automatic recognition and classification of musical instruments	Automatic classification/recognition, machine learning
(Gulhane; Shirbahadurkar; Badhe, 2021)	India	Tavil, Santoor, Shankh	Spectral/Frequency Domain: Spectral flux, Spectral kurtosis, Spectral skewness, Spectral pitch similarity, Roughness, Inharmonicity Cepstral Domain: Mel Frequency Cepstral Coefficient (MFCC)	Provide the essential data that drives the performance of the proposed classification system	Automatic classification/recognition, machine learning
(Zhang, Lei, 2022)	China	Guzheng, Pipa, Flute, Erhu, Suona	Spectral/Frequency Domain: Mel Spectrum Time-Frequency Based: Mel Spectrogram Deep features: Generative Adversarial Network (GAN) features, Convolutional Neural Network (CNN) features	Facilitate the transformation of Guzheng music into other genres while preserving its unique timbral identity	Automatic classification/recognition, machine learning
(Ananthanarayana; Bhattacharjee; Rao, 2023)	India	Tabla	Time-Domain: Onset detection (related to the attack of the sound) Spectral/Frequency Domain: Fundamental frequency (F0) contours, Upward F0 modulation Time-Frequency Based: Spectrogram, Log-scaled mel-spectrogram Deep features: Convolutional neural networks (CNN)	Enable the classification of instrument strokes by leveraging differences in spectral content, pitch modulation, and onset characteristics	Performance and techniques/devices Automatic classification/recognition, machine learning
(Xu *et al.*, 2023)	China	Gaohu, Tenor Sheng, Pipa, Erhu, Bass Sheng, Yangqin, Zhonghu, Soprano Suona, Alto Ruan, Banhu, Tenor Suona, Bass Ruan, Bangdi, Bass Suona, Guzheng, Qudi, Soprano Guan, Guqin, Xindi, Tenor Guan, Konghou, Xiao, Bass Guan, Sanxian, Xun, Bawu, Yunluo, Soprano Sheng, Liuqin, Bell chimes	Spectral/Frequency Domain: Mel-Frequency Cepstral Coefficients (MFCC) Deep features: Features learned by Convolutional Recurrent Neural Network (CRNN)	Provide the foundational data necessary for both instrument recognition and timbre space regression	Automatic classification/recognition, machine learning Performance and techniques/devices

(Nurdiyah *et al.*, 2024)	Indonesia	Saron barung, Demung, Peking, Bonang barung, Bonang penerus, Slenthem, Gong, Gendang	Spectral/Frequency Domain: Spectral centroid, spectral roll-off, spectral flux, spectral skewness, spectral moment, spectral kurtosis, spectral entropy, spectral slope, spectral bandwidth Time-Frequency Based: Spectrogram, scalogram Cepstral Domain: Mel Frequency Cepstral Coefficient (MFCC) Energy Based: Root mean squared of energy distribution	Extract and structure distinctive characteristics for accurate instrument recognition in overlapping soundscapes	Automatic classification/recognition, machine learning
Psychoacoustics and Perceptual Understanding					
(Chin; Berger, 2010)	China	Pipa	Spectral/Frequency Domain: spectral analysis, inharmonicity coefficient estimation, peak-picking algorithm, analysis of shifts in partial frequencies Perceptual Features: listening test, pitch perception analysis, response surface methodology	Understand pitch perception of timbre's instrument	Psychoacoustics Physical acoustics
(Wang; Gong, 2012)	China	Liuqin, Pipa, Zhongruan, Yangqin	Time-Domain: attack time, temporal centroid, zero-cross, low energy rate, temporal kurtosis Spectral/Frequency Domain: spectral centroid, spectral spread, spectral skewness, spectral kurtosis, spectral slope, spectral decrease, spectral roll-off, spectral brightness, spectral flatness, roughness	Facilitate the understanding and evaluation of consonance	Psychoacoustics Musicology
(Paquier; Koehl; Moign, 2016)	Scotland	Great Highland Bagpipe	Spectral/Frequency Domain: spectral centroid, spectral skewness, spectral kurtosis Time-Frequency Based: Temporal Evolution of Fundamental Frequency Energy Based: sound pressure levels Perceptual Features: Clarity, aggressiveness, warmth, volume, immersion	Understand how changes in the physical properties of reeds translate into perceptual differences	Psychoacoustics Instrument design/construction
(Jingying; Lingyun, 2017)	China	Erhu, Jinghu, Gaohu, Dizi, Xiao, Xun, Sheng, Hulusi, Bawu, Suona, Pipa, Liuqin, Daruan, Yangqin, Sanxian, Zhongruan, Guzheng, Guqin	Time-Domain: Log-attack time (Lg) Spectral/Frequency Domain: Spectral centroid (Ct), Brightness (Bt) Energy Based: Low energy (Lw)	Bridge the gap between the physical properties of musical sounds and the subjective experience of timbre	Psychoacoustics
(Chen; Yu, 2018)	China	Guqin	Cepstral Domain: Mel-Frequency Cepstral Coefficients (MFCC), Delta MFCC (ΔMFCC)	Establish a scientific and objective framework for evaluating the timbre of the Guqin	Psychoacoustics
(Wendt; Bader, 2019)	Indonesia	Saron 1, Saron 2, Demung, Peking, Bonang Barung, Kenong, Ketuk,	Spectral/Frequency Domain: Fundamental frequencies, spectral content, frequency difference (related to auditory roughness), amplitude of frequencies (used in roughness calculations).	Explain why certain tunings, despite having higher roughness, might still be preferred or perceived as more in tune within the cultural context	Musicology Psychoacoustics

		Gong Suwukan, Gong Ageng			
(Jiang *et al.*, 2020)	China	Gaohu, Erhu, Zhonghu, Gehu, Bass Gehu, Jinghu, Banhu, Bangdi, Qudi, Xindi, Soprano Sheng, Tenor Sheng, Bass Sheng, Soprano Suona, Alto Suona, Tenor Suona, Bass Suona, Soprano Guan, Alto Guan, Bass Guan, Doublebass Guan, Xiao, Xun, Bawu, Liuqin, Pipa, Yangqin, Guzheng, Guqin, Konghou, Sanxian, Sihu, Matouqin, Ejieke, Chaoxian Suona, Hulusheng, Hulusi, Dutaer, Rewapu, Gayageum, Chaoer, Dacen	Time-Domain: Log Attack Time, Temporal Increase, Temporal Decrease, Temporal Centroid, Effective Duration, Signal Auto-Correlation Function, Zero-Crossing Rate Spectral/Frequency Domain: Spectral Centroid, Spectral Spread, Spectral Skewness, Spectral Kurtosis, Spectral Slope, Spectral Decrease, Spectral Roll-off, Spectral Variation, Harmonic Spectral Centroid, Harmonic Spectral Spread, Harmonic Spectral Skewness, Harmonic Spectral Kurtosis, Harmonic Spectral Slope, Harmonic Spectral Decrease, Harmonic Spectral Roll-off, Harmonic Spectral Variation, Odd-to-Even Harmonic Ratio, Harmonic Spectral Deviation, Tristimulus, Spectral Flatness, Spectral Crest, Inharmonicity, Spectral Flux Cepstral Domain: Mel-frequency Cepstral Coefficients (MFCC), Delta MFCC, Delta Delta MFCC Energy Based: Total Energy, Total Energy Modulation, Total Harmonic Energy, Total Noise Energy, Loudness, Relative Specific Loudness, Perceptual Spectral Envelope Shape Perceptual Features: Sharpness, Spread, Perceptual Spectral Centroid, Perceptual Spectral Spread, Perceptual Spectral Skewness, Perceptual Spectral Kurtosis, Perceptual Spectral Slope, Perceptual Spectral Decrease, Perceptual Spectral Roll-off, Perceptual Spectral Variation, Band Spectral Deviation, Band Tristimulus, Noisiness	Quantify, model, and predict how timbre is perceived, leading to a deeper understanding of the auditory characteristics that define different musical instruments	Psychoacoustics Automatic classification/recognition, machine learning
(Durojaye *et al.*, 2021)	Nigeria	Dùndún	Time-Domain: Inter-onset interval (IOI), Pulse clarity, Amplitude envelope Spectral/Frequency Domain: Mean pitch, Pitch height Time-Frequency Based: Amplitude modulation spectrum (AMS) Energy Based: Intensity, mean intensity, Mean intensity change	Understand how listeners use acoustic cues, such as timbre, to differentiate between music and speech in different performances of the instruments	Psychoacoustics Performance and techniques/devices
(Wang *et al.*, 2021)	China	Erhu, Pipa, Dizi	Time-Domain: Attack time, Decay time, Effective duration, Event density, Frequency modulation, Amplitude modulation Spectral/Frequency Domain: Spectral centroid, Spectral brightness, Spectral spread, Spectral skewness, Spectral kurtosis, Spectral flatness, Spectral entropy Time-Frequency Based: Spectral flux Energy Based: Frame energy of ERB	Quantify and model the relationship between acoustic features and the perceived emotional impact of music	Psychoacoustics
Supporting Sound Synthesis					
(Erkut *et al.*, 2002)	Finland	Kantele	Time-Domain: envelope trajectories Spectral/Frequency Domain: fundamental frequency, frequency, Harmonics and Beating of Harmonics Time-Frequency Based: beating of harmonics	Characterize instrument's timbre Validate theoretical models Inform sound synthesis Support instrument design and construction	Physical acoustics Performance and techniques/devices Instrument design/construction

(Chen; Huang, 2011)	China	Pipa	Time-Domain: decay characteristics, time responses of tones, time responses of synthetic tones Spectral/Frequency Domain: spectra of plucked tones, inharmonicity coefficients, spectra representing the pipa body, frequency response of body filter, spectrogram of push and pull tones, spectrogram of wheel tones Time-Frequency Based: spectrogram of push tones, spectrogram of wheel tones Energy Based: damping filter gain adjustment, energy enhancement function Perceptual Features: listening tests for similarity and acceptability, subjective evaluation of timbre	Inform sound synthesis Validate the accuracy of the instrument's synthetic sounds in auditory perception	Physical and Virtual Modeling Performance and techniques/devices Psychoacoustics
(Gunasekera; Wijayakulasooriya; Perera, 2016)	India	Santoor, Sarod	Time-Domain: zero crossing rate (ZCR), root mean square (RMS), amplitude envelope Spectral/Frequency Domain: Spectral centroid, harmonic content	Assist in the synthesis process and validate the accuracy of the synthesized sounds against the real instrument sounds	Computer music
(Puranik; Scavone, 2023)	India	Harmonium	Spectral/Frequency Domain: LTAS, frequency response	Inform the modeling and synthesis of the instrument's sound	Physical and Virtual Modeling Physical acoustics Performance and techniques/devices Computer music
(Xue *et al.*, 2023)	China	Guzheng	Time-Domain: jitter Spectral/Frequency Domain: spectral flux, spectral slope, alpha ratio, amplitude, frequency Cepstral Domain: MFCC Energy-Based: alpha ratio	Uncover the subtle discrepancies that exist between the synthesized and performed music in the instrument	Automatic classification/recognition, machine learning Performance and techniques/devices
(Ismail *et al.*, 2006)	Malaysia	Kompang	Time-Domain: attack and decay periods, amplitude envelope detection, waveform analysis Spectral/Frequency Domain: frequency content Time-Frequency Based: spectrogram analysis	Characterize instrument's timbre Inform sound synthesis	Digital sound synthesis Performance and techniques/devices Modal analysis
Cultural, Historical, or Ethnomusicological Interpretation					
(Koumartzis *et al.*, 2015)	Greece	Tortoise Lyre	Time-Domain: RMS energy. Spectral/Frequency Domain: Spectral centroid, spectral standard deviation, spectral skewness, spectral kurtosis, spectral roll-off, and spectral smoothness. Cepstral Domain: Mel-Frequency Cepstral Coefficients (MFCCs).	Assesses and compare the sound properties of the reconstructed instruments Validate the reconstruction accuracy and ensure quality control	History, archaeology and anthropology Instrument design/construction
(Zalaquett *et al.*, 2019)	Mexico	Whistles, Ocarinas, Flutes	Time-Domain: Envelope Spectral/Frequency Domain: Fundamental frequency, Harmonics, Spectral intensity, Spectral peaks, Frequency of resonance	Bridge acoustic characterization, organological understanding and cultural interpretation	History, archaeology and anthropology

			Time-Frequency Based: Spectrogram		Instrument design/construction Performance and techniques/devices Musicology
(Meyer; Moore, 2021)	Brazil	Iridináp musical mouth bows, Kotiráp flute, Totoráp clarinets	Time-Domain: Waveforms, Amplitude envelope Spectral/Frequency Domain: Fundamental frequency, Harmonics Time-Frequency Based: Spectrograms	Demonstrate the acoustic similarities between the sounds produced by these instruments and the phonetic and tonal characteristics of the Gavião language	Ethnomusicology Performance and techniques/devices Linguistics
(Meyer; Moore, 2013)	Brazil	Iridináp musical mouth bows, Kotiráp flute, Totoráp clarinets	Time-Domain: Waveforms, Amplitude envelope Spectral/Frequency Domain: Fundamental frequency, Harmonics Time-Frequency Based: Spectrograms	Understanding the instruments' role in the Gavião's "verbal art."	Ethnomusicology Performance and techniques/devices Linguistics
(Sanchez Santiago, 2021)	Mexico	Whistling Vessels	Spectral/Frequency Domain: Fundamental frequency, Harmonics, Spectral content. Time-Frequency Based: Spectrogram analysis.	Determine the acoustic characteristics of the instruments and to interpret their cultural and functional significance	History, archaeology and anthropology Physical acoustics
(Davin *et al.*, 2023)	Israel	Bird Bones	Spectral/Frequency Domain: Spectral content (frequencies ranging from 2500 to 12,000 Hz)	Characterize the acoustic properties of the aerophones, formulating hypotheses regarding their functional roles and interpreting their cultural significance	Instrument Design and Construction History, archaeology and anthropology
Performance Techniques and Analysis					
(Kovačić; Boersma; Domitrović, 2003)	Croatia	klapa and dozivački singing	Spectral/Frequency Domain: long-term average spectrum (LTAS), spectral envelope and trend lines, spectral slope, singer's formant, spectral peaks and regularity Energy Based: sound levels, loudness differences	Distinguish vocal characteristics and formant structures between singing styles	Voice acoustics Physical acoustics
(Kuswanto *et al.*, 2015)	India	Electronic Demung	Time-Domain: waveform analysis Spectral/Frequency Domain: fundamental frequency, overtones analysis, spectrum peaks Time-Frequency Based: spectrogram analysis	Determine usability in performance and educational contexts of electronic version of the instrument	Performance and techniques/devices Music education
(Zhang, Youchuan, 2018)	China	Qudi, Zhongruan, Paigu, Erhu	Spectral/Frequency Domain: Fundamental tone energy, Harmonics quantity, Spectrum signature Time-Domain: Loudness dynamics (ppp, p, f, fff) Time-Frequency Based: Spectrum characteristics (register partitioning by spectrum)	Serve as a foundational element for developing a system to balance and match loudness among instruments	Physical Acoustics Performance and techniques/devices
(Gaikwad; Sircar, 2019)	India	Hindustani classical singing	Spectral/Frequency Domain: Harmonic Spectral Centroid, Relative Strengths of Odd/Even Harmonics, Fundamental Harmonic Power, Power Spectra	Select the most appropriate tonic note for a singer by evaluating the voice's quality,	Performance and techniques/devices Musicology

			Energy Based: Total Power in the Note	stability, and harmonic content across different pitches	
(Gowriprasad ; Aravind; Murthy, 2022)	India	Tabla	Time-Domain: Average Stroke Density (ASD), Short-Time Energy (STE) Time-Frequency Based: Rhythmogram, Auto-correlation function (ACF) Cepstral Domain: Mel-frequency cepstral coefficients (MFCC), MFCC derivatives (MFCC ∆), MFCC double derivatives (MFCC ∆∆) Deep Features: Features extracted by Convolutional Neural Networks (CNN)	Aid in the detection of structural boundaries, section labeling, and stylistic performances	Performance and techniques/devices Automatic classification/recognition, machine learning
Musicological and theoretical analysis					
(Gardiner; Lim, 2014)	Japan	Nohkan, Kotsuzumi, Ōtsuzumi,Voice	Time-Domain: attack noise Spectral/Frequency Domain: formant regions, fundamental frequencies Time-Frequency Based: spectrogram analysis, registral descent Energy Based: intensity changes	Analyze acoustic and musical structure Characterize interactions and texture Explore intensity and dynamics Enhance multisensory perception	Musicology Performing arts: theatre, dance, music, costume, and poetry Performance and techniques/devices
(Chauhan; Singru; Vathsan, 2021b)	India	Sarasvati Veena	Spectral/Frequency Domain: Harmonic content, enhancement of specific harmonics, natural frequency of the resonator, sound pressure peaks Time-Frequency Based: Revival of harmonics, time-dependent increase in harmonic amplitude, ringing effect. Energy Based: Maximum sound radiation	Connect the vibrational characteristics of the veena and the acoustic behavior of its resonator to the instrument's role in shaping and supporting the musical scales and microtones	Vibroacoustics Physical acoustics Musicology
(Haron; Onn; Hin, 2021)	Malaysia	Rebab	Time-Domain: melody extraction, frequency wobble estimation, pitch set detection Spectral/Frequency Domain: dissonance curve fitting	Understand the relationship between the timbre of the instrument and the tuning system used	Performance and techniques/devices Musicology

Table B1. Analysis of sources. Source: Own work