Digitization and Virtualization of Minahasan Bamboo Instruments: Development of a Culturally-Informed Virtual Studio Technology Plugin

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Abstract

Traditional musical instruments are an important component of intangible cultural heritage, yet many remain underrepresented in contemporary digital music production. In particular, Minahasan bamboo instruments face limited accessibility due to the lack of digital instrument representations. This study addresses this issue by developing a culturally informed Virtual Studio Technology (VST3) plugin that digitizes and simulates the characteristic sounds of Minahasan bamboo music. The proposed approach combines field recording, digital audio processing, and sample-based virtual instrument development using the JUCE framework. The resulting plugin was evaluated through functional, compatibility, performance, and cultural fidelity testing across multiple digital audio workstations. Experimental results demonstrate accurate MIDI-to-audio translation, low-latency performance, stable operation, and efficient CPU usage. User evaluations further confirm the authenticity of the sound and the usability of the interface. The findings indicate that VST-based digitization offers a practical and transferable solution for preserving traditional musical instruments while enabling their integration into modern music production workflows.

Keywords— Bamboo Instruments, Traditional Music Technology, Cultural Heritage Digitization

1. INTRODUCTION

Traditional musical instruments play a central role in the continuity of intangible cultural heritage. They serve not only as artistic expressions but also as mediums through which communities transmit identity, shared memory, and social values across generations. UNESCO emphasizes that intangible heritage, including traditional music, functions as a foundation for cultural resilience and intergenerational knowledge transfer [1]. Yet in many regions, traditional musical practices have experienced a gradual decline. The forces of modernization and urbanization, coupled with changing lifestyles, have shifted younger audiences toward globally mediated musical cultures supported by digital technology [2].

At the same time, advances in digital technology have created new possibilities for cultural preservation. Developments in digital archiving, virtual reconstruction, and immersive media allow endangered cultural expressions to be documented, represented, and disseminated through accessible digital formats. Virtual heritage has emerged as a relevant approach, offering immersive environments that convey both the material and experiential qualities of cultural artifacts and practices [3]. Despite its potential, digital preservation efforts often face obstacles, including limited policy support, inadequate technological infrastructure, and concerns about sustainability in long-term heritage management [2], [4].

The transformation of musical practice throughout the twentieth and twenty-first centuries further underscores the impact of technology on sound creation and perception. Innovations in electronic instruments, sound synthesis, and computer-based production have expanded the timbral palette beyond the constraints of acoustic instruments [5], [6]. These developments have enabled the virtualization of traditional instruments, allowing their sonic characteristics to be captured, modeled, and incorporated into contemporary digital audio workstations. Research in digital music and cultural informatics shows that virtual instruments can contribute meaningfully to heritage preservation while supporting new modes of creative expression that remain grounded in cultural authenticity [7], [8].

Minahasa, a region in North Sulawesi, Indonesia, is known for its rich cultural heritage, including bamboo-based musical instruments such as the kolintang bambu, sasesahang, and bamboo flute (suling) [9], [10]. These instruments are distinguished by their physical construction, playing techniques, and unique acoustic characteristics. However, the documentation and digital representation of Minahasan bamboo instruments remain limited. Yet, these instruments have great potential to be introduced both nationally and globally, especially when presented through engaging and educational digital formats.

This study aims to digitize traditional Minahasan bamboo musical instruments through high-resolution audio sampling. The resulting digital assets are expected to provide authentic and accurate representations that can be utilized for cultural preservation, music education, and the development of interactive technologies, such as integration into VST-based virtual instruments.

2. LITERATURE REVIEW

2.1. Previous Study and Related Work

The digitization of traditional musical instruments has emerged as a vital strategy for preserving and revitalizing cultural heritage in the digital era. By converting physical instruments into digital formats, it becomes possible to safeguard their unique sounds and characteristics for future generations. This process not only aids in preservation but also facilitates broader dissemination and accessibility. For instance, a study on the digitization of traditional Sundanese musical instruments using augmented reality demonstrated how digital technologies can enhance the preservation and appreciation of cultural artifacts [11].

Several studies have examined the broader challenges and opportunities of cultural heritage digitization. Adane et al. [2] identify institutional, financial, and technological barriers that often hinder large-scale digitization initiatives, while also emphasizing the potential of digital technologies to enhance accessibility and long-term preservation. Similarly, Ocón [4] discusses the tensions between preservation and replacement in the digitalization of endangered cultural heritage in Southeast Asia, underscoring the importance of sustainable and context-sensitive digital strategies. These studies, however, remain largely policy and framework-oriented and do not propose concrete technical implementations for music digitization.

In the field of music and sound technology, Komarovska et al. [5] analyze how technological innovation throughout the twentieth century has transformed musical expression, particularly through electronic sound synthesis and digital production techniques. Their work demonstrates how technology expands timbral possibilities and enables new forms of interaction between traditional and modern music. Nevertheless, this study remains musicological in nature and does not provide practical tools for preserving traditional instruments in digital production environments. Miranda [6] further explores the technical foundations of computer sound design, offering essential principles for digital sound synthesis and sampling that inform virtual instrument development, though without a specific focus on cultural heritage preservation.

More application-oriented approaches can be found in immersive and interactive studies. Lyu and Zhang [8] developed a virtual reality system that allows users to experience and perform traditional Confucian musical instruments in an immersive VR environment. Their work demonstrates the potential of interactive digital platforms for cultural transmission but relies on specialized VR hardware rather than integration into widely adopted music production workflows. In contrast, Reshma et al. [7] review digitization approaches for performing arts such as dance, highlighting how motion capture and digital modeling contribute to preserving intangible heritage. While their focus is not on musical instruments, the study reinforces the importance of digital representation for sustaining intangible cultural practices.

Closer to the present research context, Nurhidayati et al. [12] examine the digital transformation of Songah music, emphasizing the role of information technology and digital media in maintaining the relevance of traditional music in contemporary society. The study highlights challenges related to authenticity, generational engagement, and cultural continuity, offering insights that are highly relevant to bamboo music digitization efforts. However, the approach primarily addresses sociocultural adaptation and digital dissemination rather than the development of playable virtual instruments.

The study from Tzanetakis and Cook [13] demonstrates how statistical pattern recognition techniques can be applied to real-world audio collections, achieving classification performance comparable to human annotation. While the focus of this research is genre classification rather than instrument digitization, the underlying principles of feature extraction and audio signal representation provide an important foundation for digital music analysis and processing. These approaches inform the broader technological context in which virtual instrument development and sound modeling are situated.

Compared to these studies, the present research adopts a production-oriented approach by developing a VST3-based virtual instrument for Minahasan bamboo music. Rather than relying on immersive environments or media dissemination alone, this work focuses on integrating traditional instrument sounds directly into digital audio workstations through sample-based modeling and JUCE-based plugin development. By combining culturally informed field recording, systematic audio processing, and technical performance evaluation, this study bridges the gap between cultural heritage preservation and practical digital music production, offering a complementary contribution to existing digital heritage and music technology research.

2.2. Minahasa Bamboo Music

Minahasa, a region located in North Sulawesi Province, is home to a rich cultural tradition known as bamboo music. This form of traditional art is categorized as instrumental orchestral music, performed primarily using bamboo-based wind instruments. Its origins trace back to a single type of wind instrument known locally as the bangsing or bamboo flute [14]. Over time, the ensemble evolved to include a variety of bamboo wind instruments such as korno, clarinet, saxophone, and bass instruments like overtone, cello, and tuba. Additionally, non-wind instruments such as the bass drum, snare drum, cymbals, and kapuraca were incorporated to enhance rhythmic structure and harmonic complexity [15].

A typical bamboo music ensemble consists of approximately 20 to 50 members, each playing either a blown instrument (e.g., flute, korno) or a percussive one (e.g., drum, cymbals). These ensembles are central to both ceremonial and recreational functions within the community, often performed during traditional festivities, church services, and cultural events [16]. They are emblematic of Minahasa's ethnic identity, musical innovation, and efforts toward cultural preservation [9], [15]. Figure 1. Minahasa Bamboo Music shows a traditional Minahasan bamboo music ensemble in which multiple bamboo with instruments and supporting percussion are performed collectively.

Figure 1. Minahasa Bamboo Music

2.3. Digitization of Traditional Musical Instruments

The digitization of traditional musical instruments has gained traction as a crucial effort to preserve and revitalize cultural identity in the digital age. Researchers have increasingly explored how digital technology, particularly audio recording, sampling, and multimedia interfaces, can be used to document, simulate, and disseminate the sounds and knowledge embedded in traditional instruments. Digitization efforts allow for long-term preservation and accessibility, ensuring that these instruments continue to exist in virtual forms that can be studied, played, and appreciated by future generations [4].

In the Indonesian context, digital transformation of traditional music has begun to emerge, though it remains an underexplored area. Nurhidayati et al [12] examined the transformation of the traditional Songah music of the Baduy community into digital form as an effort to sustain its relevance in contemporary society. Their research highlights the challenges and opportunities in adapting traditional music to digital platforms, such as the need for authentic representation and community involvement. Meanwhile, acoustic studies by Hamdan et al [17] on bamboo instruments provide a technical foundation for digital modeling, emphasizing the importance of accurate tone mapping and resonance capture when reproducing traditional instruments virtually. Efforts to digitize traditional music have been documented, highlighting the importance of such initiatives in maintaining cultural identity. Ernawati and Munaf [18] emphasized that digitization allows for more effective and efficient protection of fragile cultural heritage artifacts, enabling better documentation and easier digital access compared to manual methods.

2.4. Virtual Studio Technology (VST) and Its Role in Cultural Preservation

Virtual Studio Technology (VST), introduced by Steinberg in 1996, revolutionized digital music production by allowing software-based emulation of musical instruments and effects within digital audio workstations (DAWs) [19]. The flexibility and portability of VST instruments make them ideal for simulating and integrating traditional sounds into contemporary music environments [20]. VST frameworks allow musicians to use virtual replicas of rare or culturally significant instruments via MIDI controllers, thereby extending their usage in both creative and educational settings.

Integrating traditional instruments into VST frameworks involves audio sampling, scripting, and interface design. This process enables the creation of software instruments that can mimic real instrument behavior with high fidelity. A case study on traditional African instruments showed how VST plug-ins can offer an authentic user experience while preserving cultural identity [21]. Scholars have explored the development of VST instruments as a means of cultural preservation. Tanev and Božinovski [22] emphasized how VST plug-ins can support both modern composers and researchers in accessing non-Western instrument sounds in a practical, reproducible format.

3. RESEARCH METHODS

3.1. Research Design

This research adopts a qualitative-technical approach that combines ethnographic methods for cultural documentation and audio engineering techniques for digital sound modeling. The goal is to develop a VST (Virtual Studio Technology) instrument that replicates the acoustic characteristics of Minahasan bamboo instruments. The study integrates fieldwork, sound sampling, signal processing, and VST development stages (Figure 2).

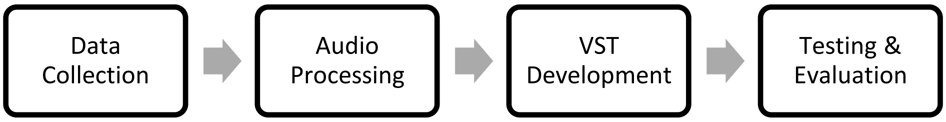

Figure 2. Research Design

3.2. Data Collection

Primary data were collected through direct sampling of traditional bamboo instruments in the Minahasa region, North Sulawesi, Indonesia. Instrument selection was based on their cultural significance and sonic uniqueness. Sampling was conducted in acoustically treated environments to minimize noise interference and ensure fidelity. The recording session involved a bamboo music team and expert bamboo instrument instructors. The recorded instruments included bamboo bass, overtone, tuba, and korno. The instrument was recorded using close-miking techniques with the microphone at a distance of approximately 15 cm to capture tonal nuances.

3.3. Data Processing and Editing

The recorded samples were processed using digital audio workstations (DAWs) such as FL Studio and Logic Pro X. Noise reduction, normalization, looping, and trimming were performed to prepare the samples for integration into a sampler engine. Frequency and spectral analysis were conducted to identify the harmonic profiles and resonant frequencies unique to each instrument.

3.4. VST Instrument Development

The cleaned and labeled samples were imported into a sampler framework (JUCE Framework). The following components were configured. 1) Key mapping: Samples were assigned to corresponding MIDI notes, 2) Velocity layers: Dynamic response was set across multiple velocity zones to mimic natural articulation, 3) Envelope control: ADSR (Attack-Decay-Sustain-Release) parameters were adjusted to simulate realistic decay and resonance behavior, 4) User interface (UI): A simple graphical interface was designed using JUCE or Kontakt UI scripting to allow parameter control.

3.5. Testing and Evaluation

To ensure the accuracy, usability, and musical integrity of the developed VST instrument, a structured testing and evaluation methodology was applied. This involved both technical verification and user-centered evaluation to validate functionality, performance efficiency, and cultural fidelity. This comprehensive evaluation confirmed the plugin's readiness for both creative and ethnomusicological use in modern digital audio environments.

4. RESULT AND DISCUSSION

4.1. Recording and Instrumentation

The recording session was conducted at the Bamboo Music Practice Hall, involving collaboration with a local bamboo music ensemble and expert instructors specializing in Minahasan bamboo instruments. The instruments recorded during the session included Bamboo Bass, Overtone, Tuba, and Korno in various tunings (D, E, G, and C).

Minahasan bamboo music traditionally consists of multiple instruments played harmoniously as an ensemble. These include: 1) Bass, 2) Overtone, 3) Tuba, 4) Tuba (G), 5) Korno (D, E, G, and C). Each instrument possesses its own distinct pitch range and functions within the ensemble.

Figure 3. Recording and Sampling Session

To ensure optimal sound fidelity, recordings were captured using a BM-8000 condenser microphone connected to a U-Phoria UM2 audio interface. Figure 3 depicts the field recording process conducted with a Minahasan bamboo music ensemble, showing musicians performing while audio signals are captured using condenser microphones. The recorded audio was processed in a Digital Audio Workstation (DAW) environment, specifically using FL Studio, for further editing and integration into the VST instrument development workflow.

The recorded pitch range spans from MIDI note 36 (C2) to MIDI note 72 (C5), with each note recorded individually to preserve tonal accuracy and avoid overlap. Recordings were saved in WAV format, and each file was named according to its corresponding MIDI number for ease of mapping in the sampler. Additional mappings were configured as follows: MIDI Note 32: Kick drum simulation, MIDI Note 33: Snare, MIDI Note 35: Cymbal. Table 1. Sample instrument sound and corresponding sample filename present the mapping between recorded instruments, their pitch ranges, assigned MIDI notes, and corresponding sample filenames.

In some cases, multisource samples were recorded, meaning that several instruments were captured simultaneously within a single recording session. This approach aimed to preserve the natural ambient atmosphere and ensemble feel of Minahasan bamboo music, supporting the creation of more immersive and realistic virtual instrument behavior.

Table 1. Sample instrument sound and corresponding sample filename

Instruments	**Note Range**	**Midi Note**	**Sample Filename**
Kick	-	31	31.wav
Snare	-	33	33.wav
Cymbal	-	35	35.wav
Bass, Overtone & Tuba	C2 – C#3	36 – 49	36.wav – 49.wav
Tuba, Tuba (G) & Korno (G)	D3 – B3	50 – 59	50.wav – 59.wav
Korno (D), Korno (E), Korno (G), Korno (C) & Klarinet	C4 – C5	60 – 72	60.wav – 72.wav

4.2. Sample Processing and Editing

After the recorded samples were obtained, the next stage involved processing them using digital audio tools to enhance their quality and prepare them for integration into the sampler engine. Each audio WAV file underwent several processing steps to ensure clarity, consistency, and technical compatibility for virtual instrument development.

Figure 4. Data Processing and Editing Staging illustrates the sequential workflow applied to the recorded audio samples, including pitch adjustment, noise reduction, normalization, and trimming. This staged process ensures consistent audio quality and technical readiness of the samples before their integration into the virtual instrument engine.

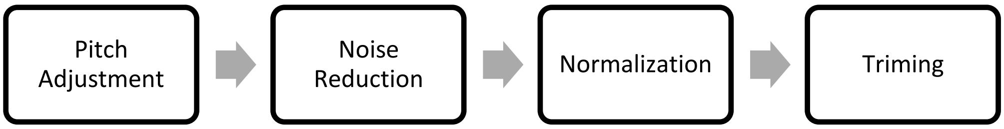

Figure 4. Data Processing and Editing Staging

Pitch Correction was applied when necessary to ensure that each note corresponded to the correct musical frequency. Noise Reduction eliminated background hiss and environmental noise captured during the field recording. Normalization was used to adjust the volume levels of each sample to a consistent peak amplitude, ensuring a uniform decibel (dB) gain across all recordings. Trimming involved cutting excess silence at the beginning and end of each waveform to ensure precise triggering within the sampler.

These steps were carried out in FL Studio using its built-in tools such as Teletronix and Fruity Parametric EQ. The final processed samples maintained a clean signal with appropriate decibel (dB) gain levels and were evenly balanced in amplitude, allowing smooth integration into the sampler engine without phase or volume inconsistencies between notes. Figure 5. Processing samples using FL Studio and built-in tools shows the digital audio processing stage in which recorded instrument samples are edited within FL Studio.

Figure 5. Processing samples using FL Studio and built-in tools.

4.3. VST Instrument Development

Following the sample processing stage, the finalized audio files were integrated into a virtual instrument format using FL Studio's sampler tools. The development of the VST instrument involved sample mapping, velocity layering, envelope design, and basic user interface configuration to replicate the playing characteristics of the original bamboo instruments.

The processed audio samples were utilized to develop a standalone VST plugin using the JUCE (Jules Utility Class Extensions) framework, a C++-based library widely adopted for professional audio plugin development. JUCE enables the creation of cross-platform VST, VST3, AU, and AAX plugins with full control over signal routing, graphical interfaces, and MIDI handling.

4.3.1. Sample Mapping

The cleaned WAV files were imported into FL Studio's DirectWave sampler, where each audio file was mapped to its corresponding MIDI note number. The pitch range spanned from MIDI Note 36 (C2) to MIDI Note 72 (C5). Percussive instrument samples, such as kick, snare, and cymbal, were mapped to MIDI Notes 32, 33, and 35, respectively. Each note was triggered independently, enabling precise control and tonal reproduction when played through a MIDI keyboard or DAW piano roll.

4.3.2. Velocity Layering

To simulate natural dynamics, velocity layers were implemented. Multiple recordings of the same note at different intensities were assigned to velocity zones (e.g., 0–40, 41–90, 91–127). This technique allowed expressive performance and realistic variation in playback depending on the MIDI input strength.

4.3.3. Envelope Shaping and Articulation

Amplitude envelopes were created using FL Studio's Envelope Controller, adjusting attack, decay, sustain, and release (ADSR) values to reflect the acoustic behavior of each instrument. For example, the suling bambu featured a softer attack and longer release to mimic natural breath transitions, while the korno had a sharper attack and quicker decay to reflect its brass-like qualities.

4.3.4. Effects and Ambience

To enhance realism, subtle reverb and stereo imaging were applied to each instrument. The reverb was carefully configured using FL Studio's Fruity Reverb 2, simulating a small performance room to maintain the traditional ensemble's ambient atmosphere without overwhelming the core sound.

4.3.5. Plugin Compilation and Export

After testing and debugging in the development environment, the plugin was compiled for the VST3 format. Exported builds were tested in multiple DAWs (e.g., FL Studio, Ableton Live, and Reaper) to ensure compatibility and playback stability. The plugin supported: 64-bit processing, sample-accurate MIDI handling, and cross-platform builds (Windows/macOS).

4.4. Testing and Evaluation

The testing and evaluation phase was designed to verify the functional accuracy, audio fidelity, performance efficiency, and cultural authenticity of the developed VST instrument. The testing and evaluation process yielded several significant insights regarding the functionality, performance, and authenticity of the developed virtual bamboo instrument. Functional testing across multiple DAWs demonstrated consistent MIDI note triggering, responsive ADSR envelope behavior, and effective parameter control through the user interface. No errors or compatibility issues were observed across Windows and macOS platforms, confirming robust cross-platform support.

4.4.1. Functional Testing

Functional testing was conducted to verify the accuracy of MIDI input interpretation and sound generation by the developed plugin within a Digital Audio Workstation (DAW). Figure 6. MIDI Input Testing illustrates the functional testing of the developed VST plugin, showing the relationship between incoming MIDI note events and the resulting audio waveform output. The figure demonstrates that each MIDI input is accurately translated into a corresponding audio response, confirming correct note triggering, timing, and playback behavior of the virtual instrument.

As shown in Figure 6, the top panel of the testing interface displayed a MIDI data visualization, highlighting Note On and Note Off events, as well as sustain pedal activity. Each white block on the MIDI roll represented the pitch and duration of a played note. The bottom panel showed the resulting audio waveform, generated in real-time by the plugin based on the incoming MIDI instructions. The alignment between MIDI input and waveform output demonstrated that each triggered note was accurately translated into audio, with no timing discrepancies or triggering errors. This confirmed that the plugin reliably interprets MIDI events and produces corresponding audio responses as intended, establishing its functional integrity within a DAW environment.

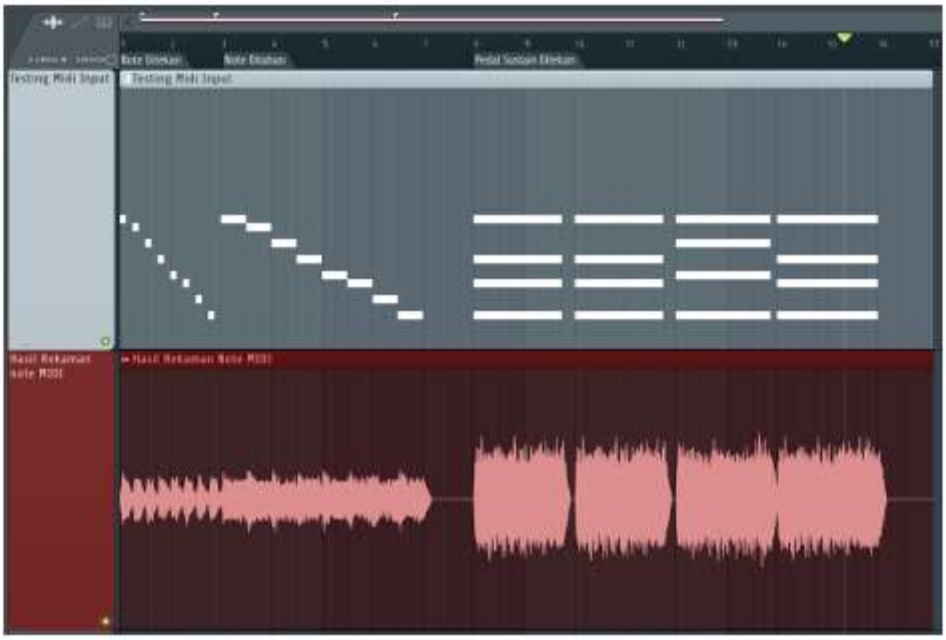

Figure 6. MIDI Input Testing

4.4.2. Compatibility Testing

To assess the cross-platform functionality of the Musik Bambu VST3 plugin, compatibility testing was conducted on three widely used Digital Audio Workstations (DAWs): FL Studio, Ableton Live, and Reaper. The goal was to ensure that the plugin could be loaded and operated smoothly, with all core features—such as MIDI input recognition, audio routing, and ADSR parameter automation—working without latency or crashes.

As summarized in Table 2, the plugin functioned reliably across all platforms. In FL Studio, the plugin loaded seamlessly and supported audio routing and ADSR automation, though MIDI input mapping required manual configuration. Ableton Live showed full compatibility, with successful handling of MIDI features and real-time automation. In Reaper, the plugin also demonstrated robust stability, even under complex sessions with multiple tracks and automation parameters. These findings confirm the VST3 plugin's versatility and readiness for use across different DAW environments, making it adaptable for various production workflows.

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Table 2. Compatibility Testing on Three Different DAWs

Digital Audio Workstation (DAW)	MIDI	Audio Routing	Automation Slider ADSR	Description
FL Studio	✓	✓	✓	Plugin runs stably, all features are usable without issues.
Ableton Live	✓	✓	✓	The plugin is fully compatible with MIDI features and Ableton Live automation.
Reaper	✓	✓	✓	Plugin remains stable in large projects with many tracks and parameters.

4.4.3. Performance Testing

Performance testing was conducted to evaluate the efficiency, responsiveness, and robustness of the Bamboo Music VST plugin under various conditions. The evaluation focused on three main aspects: CPU efficiency, latency, and system stability.

The results of the performance tests are summarized in Table 3 below. CPU Efficiency was assessed by monitoring system resource consumption during complex audio configurations, such as the simultaneous playback of multiple polyphonic voices. The results indicated that the plugin maintained low CPU usage across different DAWs, demonstrating optimized performance without causing a significant computational load. Latency testing measured the delay between receiving a MIDI input and the corresponding audio output. The plugin consistently produced sound with minimal delay, making it suitable for real-time music production environments. Stability was tested by using the plugin in large-scale DAW projects containing multiple tracks and third-party effects. Throughout these tests, the plugin demonstrated consistent performance without crashes or audio dropouts. Additionally, the plugin was evaluated for compatibility with varying audio buffer sizes. It was able to adapt to different buffer settings without exhibiting performance degradation or playback issues.

Table 3. Performance Testing Results

Aspect	Testing Method	Result
CPU Efficiency	Measuring CPU usage at 8, 16, 32, up to 64 polyphonic voices	CPU usage remained below <10% for up to 64 polyphonic voices
Latency	Latency measurement with different buffer sizes: 256, 384, 512, 1024, 2048 samples	Larger buffers showed only minor differences, with an average latency of 5–10 ms
Stability	Tested on large-scale projects using up to 20 additional plugins in one session	DAWs maintained stable performance with no signs of errors or crashes.

4.4.4. Cultural Fidelity Review

To assess the cultural authenticity and usability of the Bamboo Music plugin, a user-centered evaluation was conducted involving musicians, music producers, and sound engineers familiar with traditional Indonesian music. Overall, participants reported that the plugin offered an intuitive and accessible interface, allowing both novice and experienced users to engage with its features effectively. The plugin demonstrated consistent performance across complex projects with multiple audio layers, maintaining operational stability without crashes or technical issues.

In terms of cultural fidelity, respondents highlighted the plugin's ability to authentically replicate the tonal character of traditional bamboo instruments. The sampled sounds were perceived as realistic and sonically rich, preserving the nuanced acoustic qualities essential for traditional music compositions. Parameter controls, such as the ADSR envelope, were commended for their flexibility, enabling users to fine-tune the expressive characteristics of each instrument.

Feedback gathered through questionnaires revealed positive user experiences. Musicians appreciated the plugin's ease of use and found it particularly suitable for educational and creative purposes. Sound engineers valued the authenticity and clarity of the sampled audio, noting its effectiveness for both traditional and contemporary musical applications.

For future development, respondents recommended expanding the instrument library to include a broader array of traditional sounds, incorporating more built-in effects such as reverb and delay, and refining the user interface for enhanced visual appeal. Additionally, there were suggestions to further explore and document the tonal variations of bamboo instruments to deepen their expressive range and cultural representation. This review underscores the plugin's potential as a culturally faithful and technically robust tool for digital music production involving traditional Indonesian instrumentation.

5. CONCLUSION

The development of the Bamboo Music VST plugin demonstrates that traditional musical heritage can be effectively preserved and integrated into contemporary digital music production environments. Through a structured workflow encompassing field recording, digital audio processing, VST development using the JUCE framework, and systematic testing, this study has produced a virtual instrument that is both culturally authentic and technically reliable.

The bamboo instrument samples from Minahasa were carefully recorded and processed to ensure clarity, pitch accuracy, and clean signal quality. Their integration into a VST3 format enabled the creation of a flexible and responsive virtual instrument, equipped with user-controlled parameters such as ADSR and effects, making it suitable for a wide range of creative and educational applications. Comprehensive testing and evaluation, including functional, compatibility, and performance assessments, confirmed that the plugin operates efficiently with low latency and stable performance across multiple digital audio workstations, such as FL Studio, Ableton Live, and Reaper. In addition, the cultural fidelity review validated that the plugin preserves the distinctive sonic identity of Minahasan bamboo music and meets the expectations of musicians, producers, and sound engineers.

Beyond its specific contribution to Minahasan bamboo music, this research establishes a methodological framework with strong potential for replication. The workflow applied in this study is transferable and can be adapted to other traditional musical instruments with different sound production mechanisms. With appropriate adjustments to sampling strategies, articulation mapping, and envelope configuration, the approach can be extended to string, membranophone, or idiophone instruments. This positions the proposed method as a reusable model for ethnomusicological documentation, audio technology development, and digital cultural preservation.

6. RECOMMENDATIONS

Based on the findings of this study, several directions are recommended for future research and development. First, the virtual instrument library can be expanded by incorporating a broader range of traditional instruments, particularly from different regions of Indonesia, to represent a more diverse musical heritage. Second, the implementation of advanced sampling techniques, such as round-robin layering and additional articulations, is recommended to enhance the realism and expressive depth of the virtual instruments.

Further development may also explore the integration of machine learning-based tone modeling or AI-assisted sound shaping to provide more adaptive and intuitive control for users. Improvements to the user interface and the inclusion of additional built-in effects could further increase usability and creative flexibility. Finally, interdisciplinary collaboration with ethnomusicologists and cultural practitioners is strongly recommended to ensure that future digital representations remain aligned with cultural contexts, performance practices, and ethical considerations, thereby strengthening the role of virtual instruments as sustainable tools for cultural preservation.

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