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Calibrated Acoustic Evidence: Legal and Methodological Advances in Forensic Voice Comparison for Indonesia

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ABSTRACT: Forensic voice comparison (FVC) is gaining global recognition as a scientific method for speaker identification in legal proceedings. In Indonesia, however, the application of FVC remains underdeveloped, despite increasing reliance on digital and audio based evidence in criminal cases. This study presents a legally and methodologically robust framework for implementing FVC within the Indonesian judicial context. The research integrates Indonesian legal standards (KUHAP Articles 183–184, UU ITE) with international forensic protocols, including ISO/IEC 27037 for digital evidence handling. A combination of acoustic features MFCCs, F0, formants, and VTLN was extracted from disputed and reference voice samples. Likelihood ratios (LRs) were calculated using Gaussian Mixture Models, with score calibration via logistic regression. Results showed mean log LR values of 2.1 for genuine trials and –1.8 for impostor trials, with an ROC AUC of 0.91. Visual tools, including Tippett plots and ROC curves, were used to interpret and communicate evidence reliability. The findings confirm that calibrated, probabilistic FVC methods are feasible and legally admissible in Indonesia. However, challenges remain in handling low quality recordings, maintaining chain of custody, and bridging communication gaps between scientific experts and legal practitioners. The study recommends structured training, standardized protocols, and the use of visual aids to enhance evidentiary transparency. This framework lays the foundation for a scalable, court ready FVC system aligned with national law and global best practices. It supports interdisciplinary cooperation aimed at strengthening Indonesia's forensic infrastructure.

Keywords: Forensic Voice Comparison, Likelihood Ratio, Indonesia, Acoustic Features, Speaker Identification, Expert Testimony, Digital Evidence.

INTRODUCTION

Forensic Voice Comparison (FVC) is increasingly important in forensic science as digital communication dominates both daily life and criminal activity. Globally, FVC has developed into a methodological tool that strengthens legal processes by ensuring authenticity and clarity in audio evidence. Globally, the application of FVC reflects a sophisticated methodological development

aimed at supporting the legal process with scientifically grounded tools. These tools are particularly essential in an era where the authenticity, attribution, and interpretability of audio evidence can directly affect the outcome of legal proceedings.

In the global forensic landscape, FVC has achieved methodological standardization, particularly through the use of Likelihood Ratios (LR), calibrated acoustic models, and chain of custody protocols. According to a survey by Gold & French (2019), 39 forensic laboratories and practitioners across 23 countries use standardized methods for speaker comparison, with emphasis on transparency and replicability. These standards enhance the scientific credibility of FVC and bolster its judicial acceptability. In Southeast Asia, although statistical reporting is sparse, anecdotal evidence and emerging trends suggest a growing reliance on digital evidence in law enforcement (Gully et al., 2022). This regional momentum sets the stage for countries like Indonesia to further explore and institutionalize FVC.

In the Indonesian context, however, the incorporation of FVC faces structural and perceptual challenges. Legal institutions in Indonesia have traditionally emphasized conventional forms of evidence such as witness testimony and physical documentation under the Criminal Procedure Code (KUHAP), particularly Articles 183 and 184 (Kusnanto, 2021). While these articles recognize expert testimony as a valid form of evidence, judicial receptiveness to emerging forensic methods remains uneven. Djafri et al. (2024) argue that the judiciary often hesitates to engage with non traditional forensic tools like FVC, mainly due to a lack of standardized procedures and familiarity with the technology. The absence of institutional mechanisms to assess or validate FVC findings exacerbates this hesitancy.

These institutional limitations are compounded by gaps in technical expertise and infrastructural readiness. Ferragne et al. (2024) observe that effective interpretation of voice evidence requires specialized training in both linguistics and acoustic phonetics, areas still underdeveloped in the Indonesian forensic system. Furthermore, societal and cultural factors have shaped skepticism toward new forensic methods. While certain legal circles welcome FVC as an innovation, others remain cautious due to previous inconsistencies in forensic evidence outcomes and limited public awareness about its benefits (Ferragne et al., 2024).

Nevertheless, Indonesia has demonstrated a willingness to adapt its legal infrastructure to contemporary digital realities. Reforms in the Electronic Information and Transactions Law (UU ITE), particularly the reaffirmation of electronic documents as valid evidence under Pasal 5, have expanded the scope for using audio and digital recordings in court (Nema, 2025). These legislative changes, though still facing technical and interpretive challenges (Santoso, 2024), offer a legal foundation for integrating FVC into the broader evidentiary framework.

Despite these advancements, several practical challenges persist. There is a notable lack of operational guidelines that bridge scientific methods and legal interpretation. Without clear protocols for data collection, processing, and reporting, the reliability of FVC remains vulnerable to contestation. Moreover, as Gully et al. (2022) point out, increasing the acceptance of forensic voice methods requires not only judicial reforms but also public education campaigns aimed at

demystifying the science behind speaker comparison. Gold and French (2019) similarly advocate for judicial training to help legal practitioners understand the probabilistic nature of FVC and its appropriate application.

Taken together, these issues underscore a critical research gap: the need for a standardized, court ready framework for FVC in Indonesia that aligns with existing legal provisions, international forensic standards, and ethical constraints related to privacy and data handling. The present study aims to address this gap by designing a legally compatible, methodologically sound, and practically applicable protocol for implementing FVC in Indonesian judicial proceedings. The proposed framework not only emphasizes technical accuracy through calibrated LR models and forensic acoustic analysis but also ensures procedural transparency via SNI ISO/IEC 27037:2014 for digital evidence handling and compliance with UU PDP No. 27/2022 for data protection.

By situating FVC within this multidimensional context legal, methodological, and cultural this study offers a foundation for both immediate application and long term institutional development. It highlights the necessity of interdisciplinary cooperation between forensic scientists, legal experts, and policymakers to realize the full potential of voice comparison as a legitimate and effective component of the Indonesian legal system.

METHOD

This study adopts a forensic casework oriented design, structured to comply with Indonesian evidentiary requirements as outlined in KUHAP Articles 183–184 and UU ITE Article 5. The analysis followed ISO/IEC 27037:2014 for digital evidence collection and preservation. In line with UU PDP No. 27/2022, privacy safeguards such as data minimization, pseudonymization, and controlled access were applied.

Voice Sample Collection and Handling

The dataset comprises ten disputed voice recordings, each ranging from 5 to 10 seconds, representing conversational or expressive speech from crime related audio evidence. Reference samples were collected from three male suspects, with each providing 5 minutes of speech recorded under controlled conditions. To reduce channel mismatch, the same or equivalent devices were used. Every recording was hashed at acquisition, with device identity, timestamps, and user access logged in a digital chain of custody form, following ISO/IEC 27037 protocols (Cheung & Babel, 2022).

Feature Extraction and Acoustic Profiling

Voice data were pre processed and segmented using Praat and OpenSMILE. Acoustic features included:

- Fundamental frequency (F0): Captures speaker pitch characteristics (Lee et al., 2019).

- Formant frequencies (F1–F3): Reflect vocal tract resonances.
- Mel Frequency Cepstral Coefficients (MFCCs): Extracted over 25ms frames with 10ms overlap, capturing timbral information critical for identification (Geoffrey et al., 2020).
- Vocal Tract Length Normalization (VTLN): Adjusts for anatomical differences in speaker articulation.
- Prosodic elements: Speech rate and stress patterns (Almarshady et al., 2023). This integrated acoustic profile aligns with best practices that emphasize both short term spectral features and prosodic cues in forensic voice identification (Segundo et al., 2017).

Likelihood Ratio Computation and Calibration

The analysis employed Gaussian Mixture Models (GMM) to model voice characteristics and compute log likelihood ratios comparing suspect reference pairs versus suspect nonmatch comparisons(Morrison & Enzinger, 2019). Calibration was performed using logistic regression to adjust raw scores and express probative strength in terms interpretable by courts. Log LR distributions were visualized through Tippett plots and ROC curves. These statistical tools enhance transparency and provide a probabilistic measure of speaker similarity, improving upon categorical identifications (Gold & French, 2019).

Chain of Custody and Documentation

All evidence was managed using a secure digital forensic protocol. Acquisition involved write blockers and immediate hashing; evidence was stored on encrypted drives with restricted access. Chain of custody logs recorded data handlers, timestamps, hardware used, and justification for access. These records are crucial for ensuring the forensic soundness and legal admissibility of voice data in Indonesian courtrooms (Geng et al., 2022).

Expert Report Composition

Expert findings were reported with emphasis on clarity, reproducibility, and legal alignment. Each report included:

- Case background and evidence description
- Methods and tools used (e.g., GMM, Praat, OpenSMILE)
- Calibrated LR values and interpretation bands
- Confidence statements and uncertainty indicators

Legal basis references (KUHAP, UU ITE, UU PDP)
Reports avoided categorical conclusions and included disclaimers on intra speaker variability, device mismatch effects, and sample quality (Segundo et al., 2017).

RESULT AND DISCUSSION

Acoustic Feature Extraction and Statistical Summary

Analysis of disputed and reference recordings produced distinct acoustic profiles. For male speakers, F0 values ranged between 85–155 Hz, aligning with Cavalcanti et al. (2024). MFCCs varied from –40 to +40, while F1 and F2 frequencies ranged between 300–800 Hz and 600–2600 Hz respectively, consistent with reported profiles of Bahasa Indonesia speakers. These results indicate that the data align with established phonetic expectations.

Environmental and device related variability was also noted, affirming that recording conditions significantly influence feature extraction (Bunger et al., 2021). Samples recorded in quiet, controlled conditions (reference set) yielded more stable MFCC and F0 readings, while case recordings captured under unknown field conditions showed greater spectral variance. Vocal Tract Length Normalization (VTLN) values clustered within the range of 0.85–1.15, suggesting inter speaker anatomical differences in resonance, a pattern supported by Schnell & Garner (2019).

Preprocessing steps including noise reduction, signal normalization, and segmentation improved the accuracy and consistency of extracted features, especially under adverse conditions (Singh et al., 2018).

Table 1. Summary of Acoustic Feature Ranges

Feature	Range	Description
Fundamental Frequency (F0)	85–155 Hz	Average pitch range for male speakers
MFCCs (1–13)	–40 to +40	Captures spectral characteristics of speech
Formant Frequencies	F1: 300–800 Hz; F2: 600–2600 Hz	Reflects vocal tract resonance
VTLN	0.85–1.15	Normalized factor for vocal tract length

Likelihood Ratio Performance Analysis

The FVC system produced log likelihood ratio (log LR) values based on Gaussian Mixture Model (GMM) comparisons. Genuine trials (same speaker) averaged a log LR of 2.1 (SD = 0.5), indicating strong support for identity hypotheses, while impostor trials (different speaker) yielded –1.8 (SD = 0.7), suggesting reliable differentiation. These values meet interpretive thresholds wherein LR >10 signifies strong evidentiary support (Morrison & Enzinger, 2019).

Performance calibration was achieved through logistic regression, ensuring that reported scores reflected actual discriminative ability (Cheung & Babel, 2022). Comparison with Probabilistic Linear Discriminant Analysis (PLDA) indicated that GMM achieved an Equal Error Rate (EER) of ~6%, affirming its reliability under current data conditions (Geoffrey et al., 2020).

Table 2. Likelihood Ratio (LR) Results Summary

Trial Type	Mean Log LR	Std. Dev	Interpretation
Genuine	2.1	0.5	Strong support for same speaker identity
Impostor	–1.8	0.7	Clear evidence for different speaker status

Visual Tools and Expert Interpretation

Tippett Plot: The visualized distribution of LR values showed a clear separation between genuine and impostor trials. Consistent with Geng et al. (2022), this visualization effectively conveyed the gradient of evidence strength and highlighted cases with ambiguous similarity scores.

ROC Curve: The ROC curve yielded an Area Under the Curve (AUC) of 0.91, underscoring strong model performance. As noted by Geoffrey et al. (2020), this metric reflects the sensitivity specificity balance essential for forensic reliability.

Communication of these findings emphasized probabilistic reasoning. Instead of categorical statements, expert reports included uncertainty expressions, model limitations, and contextual interpretive notes as advised by Segundo et al. (2017). While Indonesian courts currently show mixed receptiveness to technical visual aids, well structured visual tools were deemed admissible and persuasive when grounded in expert testimony (Geng et al., 2022).

In Indonesia, FVC shows both potential and challenges compared with international practices. The UK and Australia, for example, support FVC with strong legal infrastructures and national guidelines for evidence handling and expert reporting (Villavicencio-Queijeiro et al., 2021). These jurisdictions have moved beyond subjective evaluations by adopting automated acoustic tools and standardized statistical models. By contrast, Indonesia remains in the developmental stages of implementing FVC, with limited national level regulation, sporadic integration in legal proceedings, and an absence of cohesive standards for practice. This disparity illustrates a significant opportunity for Indonesia to strengthen its forensic capacity by aligning its methodologies with internationally endorsed norms.

A critical limitation in the Indonesian context is the reliability of FVC results derived from short, low quality recordings an issue that frequently arises in legal casework involving covert surveillance or casual digital communications. Such recordings, often only a few seconds in length and captured in uncontrolled environments, present considerable challenges for acoustic analysis. Poddar et al. (2017) and Wicaksono et al. (2023) have shown that poor signal quality and limited speech content significantly reduce the viability of speaker specific feature extraction, including MFCCs, pitch contours, and formant patterns. These conditions degrade model performance and amplify the risk of false positives or negatives. According to Morrison (2018), when these technical limitations are not explicitly acknowledged in expert reporting, the credibility of FVC conclusions may suffer, especially in adversarial courtroom settings. Therefore, such recordings should be used with caution, ideally supported by additional corroborative evidence to strengthen the overall probative weight of the case.

Moreover, the evidentiary credibility of FVC depends not only on technical accuracy but also on compliance with procedural safeguards, particularly the maintenance of a verifiable chain of custody. As emphasized by Villavicencio-Queijeiro et al. (2021), the reliability of any forensic method hinges on transparent documentation of evidence acquisition, handling, and analysis. In many Indonesian cases, chain of custody procedures remain underdeveloped or inconsistently applied, which raises questions about the authenticity and legal admissibility of voice recordings. Awan et al. (2024) observe that even minor irregularities in documenting the movement or modification of digital audio can lead to legal disputes, undermining the value of expert testimony. Garrett et al. (2020) further warn that perceptions of forensic unreliability may have systemic consequences, reducing trust in forensic science and diminishing its role in judicial decision making.

Bridging the gap between forensic expertise and legal interpretation necessitates strategic interdisciplinary collaboration. One essential approach is the establishment of judicial training programs that introduce legal practitioners to the foundational principles and limitations of FVC. As noted by Hughes & Wormald (2020), enhancing legal actors' comprehension of forensic methodology improves the evaluation and application of expert findings in court. Visual aids, such as Tippett plots and ROC curves, offer intuitive representations of probabilistic evidence and can aid in translating complex results into meaningful legal arguments (Liu et al., 2021). Incorporating these tools in expert reports helps demystify forensic statistics, fostering a shared understanding between scientific and legal domains.

Equally important is the need for targeted communication training for forensic professionals. Expertise alone is insufficient if findings are conveyed in a manner that is opaque or overly technical. Experts must clearly articulate the scope, methodology, and limitations of their analysis, especially when dealing with complex probabilistic measures like likelihood ratios. Villavicencio-Queijeiro et al. (2021) argue that when communication is clear and contextually grounded, expert testimony can play a decisive role in shaping judicial outcomes. Moreover, when experts acknowledge uncertainty and limitations, rather than overstating conclusions, their credibility is enhanced.

Institutional collaboration is also key to long term reform. Bacci et al. (2021) advocate for the formation of cross disciplinary working groups that include forensic scientists, legal scholars, and policymakers to co develop national protocols for FVC. In the Indonesian context, this would involve establishing academic partnerships, strengthening the role of forensic professional associations, and creating oversight mechanisms to monitor quality and compliance. These steps are essential for embedding FVC within a sustainable forensic infrastructure that reflects both global standards and local legal cultures.

In conclusion, the current status of FVC in Indonesia reveals a dual challenge: the need for technological advancement and the need for systemic integration into the legal framework. While the country has taken preliminary steps, significant progress is still required. By embracing international benchmarks, investing in technical infrastructure, prioritizing communication training, and ensuring rigorous legal compliance, Indonesia can elevate the role of voice comparison as a reliable and admissible form of forensic evidence. Such reforms would not only

enhance case level accuracy but also reinforce the legitimacy of forensic science in the broader judicial system.

CONCLUSION

This study demonstrates that forensic voice comparison (FVC) can be both scientifically reliable and legally admissible within Indonesia's judicial system. By applying calibrated likelihood ratio models and acoustic analyses of features such as MFCCs, F0, formants, and VTLN, the research confirms that speaker identification can achieve robust levels of accuracy when supported by proper protocols and chain of custody compliance.

Despite these strengths, persistent challenges remain. Low-quality recordings, limited awareness among legal professionals, and the absence of standardized operational guidelines hinder the full integration of FVC into Indonesian courts. Addressing these issues requires judicial training, clearer national procedures, and interdisciplinary collaboration to ensure that probabilistic evidence is properly understood and applied.

By aligning international best practices with Indonesian legal provisions, the proposed framework provides a foundation for building a sustainable FVC system. Incorporating visual tools and calibrated reporting enhances transparency, while institutional support and professional cooperation are essential for long-term development. Strengthening these areas will enable FVC to contribute meaningfully to evidentiary reliability and judicial fairness in Indonesia.

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