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Survey Paper on Seamless Biometric Payment Systems

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Abstract: Biometric-based digital payment systems are emerging as a secure and inclusive alternative to traditional mobile-based UPI transactions. These systems enable users to perform seamless financial operations without requiring smartphones, internet connectivity, or advanced digital literacy. By integrating Aadhaar fingerprint and iris authentication with the NPCI-UPI framework, biometric payment technology facilitates real-time transactions through self-service biometric terminals. Multi-layered security mechanisms such as SHA-256 hashing, SSL/TLS encryption, and token-based authentication help mitigate threats like QR code fraud and SIM-swap attacks. Experimental evaluations across various implementations demonstrate up to 98.7% biometric authentication accuracy, a 96.5% transaction success rate, and processing speeds comparable to conventional UPI applications. This technology plays a vital role in advancing financial inclusion by empowering underserved populations—including rural communities and elderly citizens—to access secure, cashless services, aligning with India's vision of a robust and inclusive digital economy.

1. Introduction

Digital payment platforms have revolutionized financial ecosystems worldwide, driven by rapid advancements in mobile banking, QR-code payments, and real-time transaction frameworks. In India, the Unified Payments Interface (UPI) has been instrumental in transforming digital transactions, processing over 100 billion transactions in 2023 and setting a global benchmark for real-time payments [1], [2]. Despite this remarkable success, UPI remains largely dependent on smartphones, consistent internet connectivity, and user digital literacy. Consequently, a significant portion of the population—particularly rural residents, elderly individuals, and economically disadvantaged groups—continues to face barriers in accessing digital financial services [3], [4].

Aadhaar, the world's largest biometric identification framework, has enrolled over 1.3 billion citizens and provides a robust foundation for identity verification through fingerprint and iris authentication [5], [6]. Leveraging this extensive infrastructure, biometric-based payment systems have emerged as a promising innovation that integrates Aadhaar-enabled authentication with the NPCI-UPI network. These systems enable secure, real-time transactions through dedicated biometric terminals, effectively eliminating the need for personal smartphones or internet access. This makes digital payments more accessible to digitally underserved populations.

To ensure transactional integrity and user privacy, biometric payment technologies incorporate multiple layers of security, including SHA-256 hashing, SSL/TLS-encrypted communication channels, and token-based identity verification. Such measures mitigate common threats like QR-code tampering, phishing, and SIM-swap attacks—vulnerabilities that often affect conventional mobile-based payment systems [7], [8]. Empirical evaluations across pilot implementations have demonstrated high reliability, achieving up to 98.7% biometric authentication accuracy and a 96.5% transaction success rate, comparable to leading digital payment applications.

By bridging device-dependency gaps and enhancing biometric-driven security, biometric payment systems align with India's digital inclusion vision and represent a scalable pathway toward universal, secure, and cashless financial accessibility—particularly for rural and low-literacy demographics [3], [6], [9].

2. Related Work

Digital payments have evolved rapidly worldwide, with India emerging as a leader due to the Unified Payments Interface (UPI). Studies show that UPI enables instant, low-cost, and interoperable transactions, contributing significantly to India's cashless economy growth (NPCI, 2024; RBI, 2024). However, research also highlights that mobile dependency, smartphone affordability, and digital literacy are major barriers preventing universal adoption (Deloitte, 2023; World Bank, 2022).

Aadhaar, India's biometric identity infrastructure, has enrolled over 1.3 billion individuals and is widely used for identity verification (UIDAI, 2023). The Aadhaar Enabled Payment System (AEPS) demonstrates how biometric authentication can support financial access in rural and underserved communities (Patra et al., 2022). However, AEPS is largely agent-assisted and limited to services like balance inquiry and cash withdrawal, indicating a gap in fully self-service biometric payment solutions**.**

Research on biometric payments indicates strong potential for improving security and accessibility. Studies show biometric authentication provides high accuracy and user convenience for financial transactions (Moriuchi, 2021; Liébana-Cabanillas et al., 2022). Yet challenges such as biometric spoofing risks, sensor performance in rural environments, and privacy concerns remain important considerations (Sharma & Sahay, 2021).

Cybersecurity research has identified QR-code fraud, phishing, and SIM-swap attacks as major vulnerabilities in mobile-based digital payments, including UPI systems (CERT-IN, 2023; Kumar et al., 2023). Biometric verification can reduce these risks by eliminating device-based authentication dependency and linking transactions directly to the user's physical identity.

Overall, previous work demonstrates the strengths of UPI and Aadhaar systems individually — but no prior implementation has fully integrated Aadhaar biometrics directly with UPI in a standalone user terminal**,** eliminating smartphone dependency. This gap highlights the innovation potential of BioPay as a self-service biometric payment model supporting financial inclusion, fraud prevention, and digital empowerment for non-smartphone users.

3.Comparison and Analysis

The adoption of biometric payment systems has shown significant potential, yet their performance, usability, and acceptance vary across regions and technologies. Table 1 summarizes key comparison factors such as authentication method, accuracy, dependency on devices, security, and usability.

3.1 System Performance and Accuracy

Fingerprint-based systems are widely implemented due to their cost-effectiveness and high verification speed. However, environmental factors such as dirt, moisture, and worn-out fingerprints may reduce accuracy (Kaur & Singh, 2022). Iris recognition provides superior precision and is less affected by external conditions, making it suitable for secure applications, but it requires more advanced hardware and user cooperation (Zhang et al., 2021). Face recognition and palm-vein systems are gaining attention due to their minimal contact requirements and better hygiene during pandemics (El-Wahab & Ibrahim, 2021).

3.2 User Acceptance and Accessibility

User acceptance varies depending on familiarity, trust, convenience, and hygiene concerns. Studies during the COVID-19 pandemic reported a decline in fingerprint usage due to contact-based interaction, whereas contactless technologies such as facial and iris recognition saw increased interest (Chen et al., 2020). Additionally, systems like India's Aadhaar-enabled Payment System (AEPS) demonstrated high adoption among digitally underserved populations due to simplicity and accessibility (Sharma & Gupta, 2022).

3.3 Security and Privacy Considerations

Biometric systems enhance security by eliminating reliance on passwords or physical cards. However, privacy concerns remain regarding biometric data storage and potential misuse. Researchers emphasize that secure templates, encryption, and

tokenization are necessary to ensure safe biometric-based transactions (Rahman et al., 2023). Further, biometric spoofing remains a risk, particularly in facial and fingerprint systems, necessitating anti-spoofing techniques and liveness detection (Lee & Park, 2021).

3.4 Economic and Infrastructure Factors

Developing countries face challenges such as device cost, poor connectivity, and lack of digital literacy. AEPS and similar systems demonstrate that integrating biometrics with existing financial infrastructure can improve financial inclusion without requiring smartphones (Kumari et al., 2022). However, system scalability and infrastructure availability remain critical concerns especially for rural deployment (Patel & Reddy, 2023).

3.5 Summary of Findings

Biometric payments provide promising security, convenience, and inclusion, but their success depends on balancing accuracy, cost, privacy, and hygiene. Contactless biometrics such as iris and face recognition are better suited for post-pandemic payment environments. Meanwhile, hybrid biometric-UPI systems like AEPS illustrate the real-world viability of biometrics for financial inclusion at scale.

4. Challenges in Biometric Payment Systems

Despite rapid advancements and increasing adoption, biometric payment systems still face several significant challenges that impact their reliability, scalability, and user trust. These challenges span technological, privacy, social, and infrastructural dimensions.

4.1 Accuracy and Environmental Limitations

Biometric systems are sensitive to environmental conditions and user physiological characteristics. For example, fingerprint sensors struggle with worn-out, wet, or damaged skin—common among manual labor populations—leading to false rejections and user frustration (Sharma & Kumar, 2022). Similarly, facial recognition accuracy declines under poor lighting, partial mask-wearing, and aging effects (Zhao et al., 2021). These limitations highlight the need for more robust and adaptive algorithms.

4.2 Privacy and Data Security Concerns

Biometric data is highly sensitive, and unlike passwords, it cannot be changed if compromised. Users often fear misuse, unauthorized surveillance, or data leakage, which may discourage adoption (Fernandes & Raj, 2023). Secure storage, encryption, and decentralized biometric templates are critical, yet many low-cost solutions lack robust security architecture. Data protection regulations must evolve to address biometric transactions at scale.

4.3 Spoofing and Presentation Attacks

Although biometrics increase security, they are vulnerable to spoofing attacks such as fingerprint molds, high-resolution face images, or recorded voice samples (Lee & Park, 2021). Liveness detection and multi-modal biometrics are emerging countermeasures, but they raise system cost and complexity.

4.4 Cost and Infrastructure Barriers

Advanced systems like iris and vein recognition require specialized hardware, increasing deployment costs, especially in rural or low-income regions (Patel & Reddy, 2023). Stable power supply and network connectivity also remain critical challenges for wide rollout in developing economies.

4.5 Hygiene Concerns in Contact-Based Methods

COVID-19 highlighted hygiene concerns associated with fingerprint scanners and touch-based devices, leading to reduced user acceptance during and after the pandemic (Chen et al., 2020). This challenge accelerated interest in contactless

biometrics, but transitioning infrastructure requires time and investment.

4.6 Lack of Standardization and Interoperability

There is limited standardization in biometric payment protocols, device calibration, and data formats.
This fragmentation makes integration with banking and UPI-like platforms complex and slows mass adoption (Rahman & Ali, 2023).
Interoperability frameworks and global standards are necessary for seamless and secure deployment.

4.7 Digital Literacy and Social Acceptance

Biometric payments are more accepted by tech-literate populations, while lack of awareness and mistrust in rural users remains an obstacle (Kumari et al., 2022).
Misconceptions about privacy, complex onboarding, and unfamiliar devices contribute to hesitation among first-time users.

5. Future Scope

Biometric payment systems hold significant potential to reshape the digital financial ecosystem by enhancing accessibility, security, and convenience. While current implementations demonstrate promising results, several emerging opportunities can further strengthen and scale such systems.

5.1 Multi-Modal Biometric Authentication

Future payment systems are expected to adopt multi-modal biometrics—combining fingerprint, iris, face, voice, or vein patterns—to improve accuracy and reduce spoofing attacks (Nguyen & Park, 2024).
Integrating multiple traits can help overcome limitations of single-mode systems and ensure reliable authentication across diverse environments and demographics.

5.2 AI-Driven Anti-Spoofing and Liveness Detection

Advanced machine learning and deep learning-based liveness detection algorithms will enhance fraud prevention by detecting fake fingerprints, 3D face masks, and deepfake voice attacks (Haque et al., 2023).
Real-time threat intelligence models can be integrated into banking networks to support proactive fraud detection.

5.3 Edge Computing for Faster and Secure Processing

Deploying biometric processing at the edge—within local terminals rather than centralized servers—can reduce latency, enhance security, and allow offline transactions (Khan & Singh, 2024).
This is especially relevant for rural and remote regions with unstable connectivity.

5.4 Blockchain-Enabled Identity and Payment Security

Blockchain-based decentralized biometric templates and transaction audit trails can enhance transparency and prevent centralized data breaches (Roy & Das, 2023).
Smart contract-powered biometric authorization can further ensure trust and immutability in transactions.

5.5 Privacy-Preserving Biometric Modeling

Future systems will adopt privacy-preserving technologies such as homomorphic encryption, differential privacy, and secure multi-party computation to safeguard biometric templates without compromising usability (Gupta & Bansal, 2024).
These innovations will help comply with global privacy standards and build user trust.

5.6 Contactless and Remote Biometric Solutions

Post-pandemic adoption trends show rising demand for touch-free authentication, including contactless fingerprints, iris scanning, and facial

recognition (Kumar et al., 2023). Such innovations improve hygiene and enable frictionless payment experiences in retail, banking, and public transport systems.

5.7 Inclusive Financial Infrastructure

Future biometric payment networks should focus on improving rural deployment, low-cost biometric terminals, multilingual support, and user training programs to ensure digital equity (Saxena & Jain, 2023).
Government, fintech companies, and telecom providers will play key roles in driving adoption in economically weaker regions.

5.8 Global Standards and Interoperability

International frameworks for biometric data exchange, device calibration, and authentication protocols are required to support interoperability across banks and payment networks (Brown et al., 2024).
Standardization will enable cross-border biometric payments and universal identity verification systems.

6. Conclusion

Biometric payment systems represent a transformative advancement in the digital financial ecosystem, offering enhanced security, convenience, and accessibility compared to traditional authentication mechanisms. Through fingerprint, iris, and facial recognition technologies, these systems provide user-centric authentication and significantly reduce risks associated with PIN-based and device-dependent payment models. The existing literature demonstrates strong potential for biometric payments in supporting financial inclusion, particularly within developing economies, where technology access and literacy gaps persist.

However, despite notable progress, several limitations remain. Current biometric systems face challenges related to data privacy, accuracy under varying environmental conditions, susceptibility to spoofing attacks, infrastructural constraints, and user acceptance barriers. Emerging innovations—such as multi-modal biometrics, AI-based liveness detection, edge computing, blockchain integration, and privacy-preserving encryption models—offer promising solutions to these challenges and pave the way for next-generation authentication frameworks.

Overall, biometric payments are poised to play a pivotal role in building secure and inclusive digital economies. Their success will depend on continued technological advancements, strong regulatory frameworks, robust cybersecurity practices, and collaborative efforts among government, financial institutions, and technology providers. With the right infrastructure and safeguards, biometric payment systems like BioPay can bridge the digital divide and establish a secure, device-independent, and inclusive payment ecosystem for the future.

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