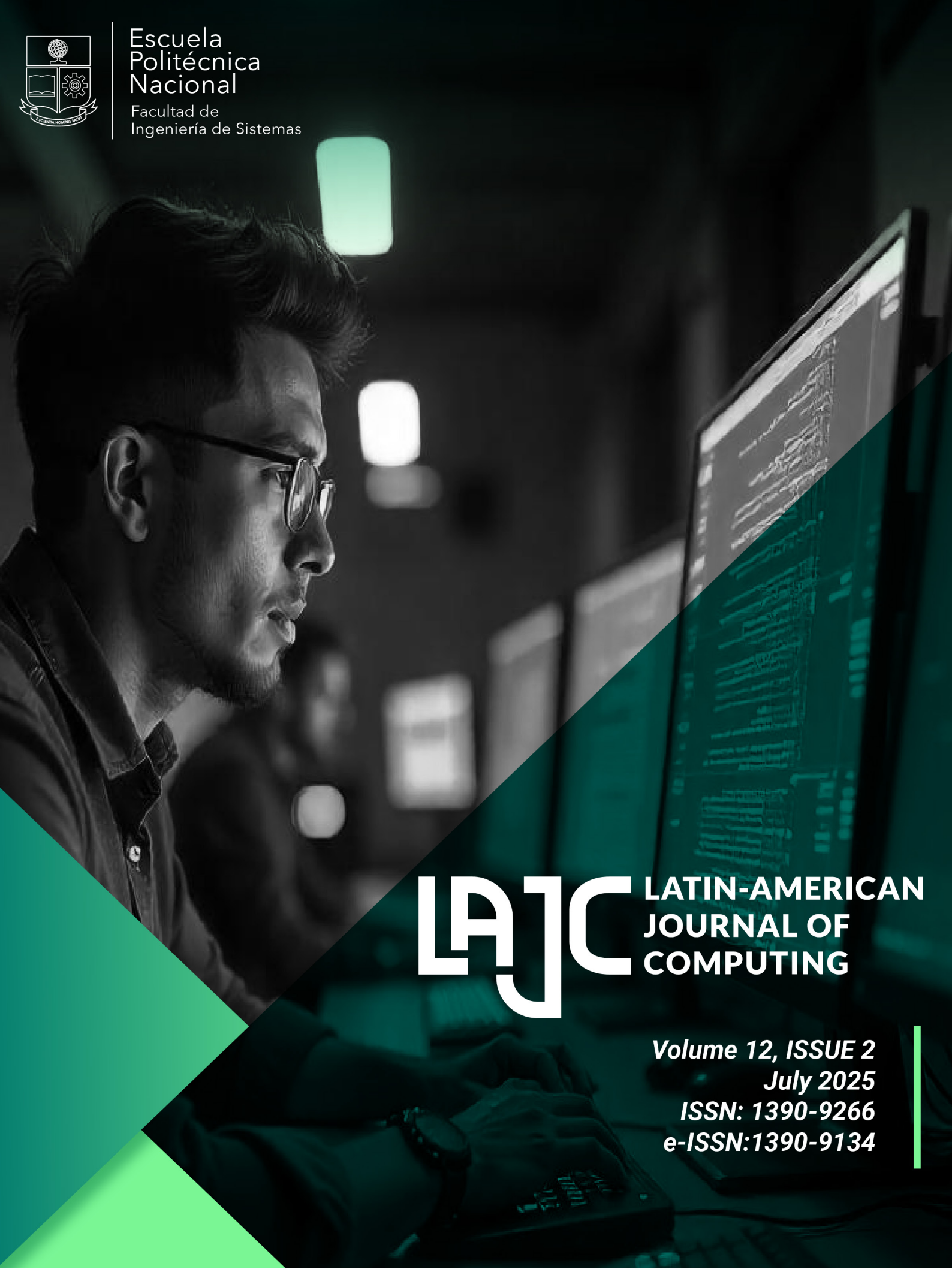

Escuela Politécnica Nacional
Facultad de Ingeniería de Sistemas

LATIN-AMERICAN JOURNAL OF COMPUTING

Volume 12, ISSUE 2
July 2025
ISSN: 1390-9266
e-ISSN:1390-9134

https://www.epn.edu.ec Quito - Ecuador https://lajc.epn.edu.ec

Vol XII, Issue 2 July 2025

ESCUELA POLITÉCNICA NACIONAL

MISIÓN

La Escuela Politécnica Nacional es una Universidad pública, laica y democrática que garantiza la libertad de pensamiento de todos sus integrantes, quienes están comprometidos con aportar de manera significativa al progreso del Ecuador. Formamos investigadores y profesionales en ingeniería, ciencias, ciencias administrativas y tecnología, capaces de contribuir al bienestar de la sociedad a través de la difusión del conocimiento científico que generamos en nuestros programas de grado, posgrado y proyectos de investigación. Contamos con una planta docente calificada, estudiantes capaces y personal de apoyo necesario para responder a las demandas de la sociedad ecuatoriana.

VISIÓN

En el 2024, la Escuela Politécnica Nacional es una de las mejores universidades de Latinoamérica con proyección internacional, reconocida como un actor activo y estratégico en el progreso del Ecuador. Forma profesionales emprendedores en carreras y programas académicos de calidad, capaces de aportar al desarrollo del país, así como promover y adaptarse al cambio y al desarrollo tecnológico global. Posiciona en la comunidad científica internacional a sus grupos de investigación y provee soluciones tecnológicas oportunas e innovadoras a los problemas de la sociedad.

La comunidad politécnica se destaca por su cultura de excelencia y dinamismo al servicio del país dentro de un ambiente de trabajo seguro, creativo y productivo, con infraestructura de primer orden.

ACCIÓN AFIRMATIVA

La Escuela Politécnica Nacional es una institución laica y democrática, que garantizar la libertad de pensamiento, expresión y culto de todos sus integrantes, sin discriminación alguna. Garantiza y promueve el reconocimiento y respeto de la autonomía universitaria, a través de la vigencia efectiva de la libertad de cátedra y de investigación y del régimen de cogobierno.

https://www.epn.edu.ec

ISSN:1390-9266 e-ISSN:1390-9134 LAJC 2025

FACULTAD DE INGENIERÍA DE SISTEMAS

MISIÓN

La Facultad de Ingeniería de Sistemas es el referente de la Escuela Politécnica Nacional en el campo de conocimiento y aplicación de las Tecnologías de Información y Comunicaciones; actualiza en forma continua y pertinente la oferta académica en los niveles de pregrado y postgrado para lograr una formación de calidad, ética y solidaria; desarrolla proyectos de investigación, vinculación y proyección social en su área científica y tecnológica para solucionar problemas de transcendencia para la sociedad.

VISIÓN

La Facultad de Ingeniería de Sistemas está presente en posiciones relevantes de acreditación a nivel nacional e internacional y es referente de la Escuela Politécnica Nacional en el campo de las Tecnologías de la Información y Comunicaciones por su aporte de excelencia en las carreras de pregrado y postgrado que auspicia, la calidad y cantidad de proyectos de investigación, vinculación y proyección social que desarrolla y su aporte en la solución de problemas nacionales a través del uso intensivo y extensivo de la ciencia y la tecnología.

https://fis.epn.edu.ec

ISSN:1390-9266 e-ISSN:1390-9134 LAJC 2025

LATIN-AMERICAN JOURNAL OF COMPUTING

Vol XII, Issue 2, July 2025

ISSN: 1390-9266 e-ISSN: 1390-9134
DOI: https://doi.org/10.33333/lajc.vol12n2

Published by:
Escuela Politécnica Nacional
Facultad de Ingeniería de Sistemas

Quito – Ecuador

Indexed in

Associated institutions

Mailing Address
Escuela Politécnica Nacional,
Facultad de Ingeniería de Sistemas
Ladrón de Guevara E11-253, La Floresta
Quito-Ecuador, Apartado Postal: 17-01-2759

Web Address
https://lajc.epn.edu.ec/

E-mail
lajc@epn.edu.ec

Frequency
2 issues per year

ISSN:1390-9266 e-ISSN:1390-9134 LAJC 2025

Published by

Escuela Politécnica Nacional
Facultad de Ingeniería de Sistemas
Ecuador

ISSN:1390-9266 e-ISSN:1390-9134 LAJC 2025

EDITORIAL

Gabriela Suntaxi
PhD.

Editor LAJC
Escuela Politécnica Nacional,
Ecuador

ISSN:1390-9266 e-ISSN:1390-9134 LAJC 2025

Bienvenidos al Volumen 12, Número 2 de la Revista Latinoamericana de Computación (LAJC).

Es un honor presentar este nuevo número, que incluye una colección de ocho artículos de investigación que abordan los desafíos actuales de la informática con conocimiento, innovación y cuidado. Este número refleja un compromiso compartido con el avance del conocimiento técnico y científico en beneficio de América Latina.

Las contribuciones presentadas en esta edición abarcan herramientas educativas, iniciativas de sostenibilidad y cambio institucional. Entre ellas, se encuentran estudios que analizan la adopción de tecnologías digitales en universidades públicas y el diseño de herramientas digitales para estimar las emisiones de gases de efecto invernadero en los hogares. Este número también incluye propuestas aplicadas como chatbots educativos para escuelas secundarias, sistemas inteligentes para analizar agujeros negros mediante técnicas de procesamiento digital de señales y aplicaciones de escritorio para apoyar la gestión eficiente de bancos de sangre. Desde una perspectiva institucional, un artículo explora la transformación digital en las universidades como mecanismo para mejorar la administración académica, mientras que otro analiza cómo la computación en la nube está transformando la educación superior. Por último, una revisión sistemática aborda el uso de la tecnología blockchain para la gestión de la identidad digital en África, destacando su potencial en contextos de baja infraestructura. Estos estudios demuestran avances técnicos en diversas áreas de la informática y enfatizan la importancia de la investigación colaborativa y contextualizada.

Agradecemos a los autores por compartir su investigación, a los revisores por sus comentarios constructivos y al equipo editorial por su continuo compromiso con la calidad y la difusión científica.

Esperamos que este número inspire nuevas ideas, colaboraciones y nuevas direcciones en la investigación en ciencias de la computación.

Gabriela Suntaxi
Editor-in-Chief
Latin-American Journal of Computing – LAJC
Escuela Politécnica Nacional, Ecuador

ISSN:1390-9266 e-ISSN:1390-9134 LAJC 2025

Welcome to Volume 12, Issue 2 of the Latin-American Journal of Computing (LAJC)

It is an honor to present this new issue, which brings a collection of eight research articles that tackle today's pressing challenges in computing with insight, innovation, and care. This issue reflects a shared commitment to advancing technical and scientific knowledge for the benefit of the Latin American region.

The contributions featured in this edition spans educational tools, sustainability efforts, and institutional change. Among them are studies that analyze the adoption of digital technologies in public universities, and the design of digital tools for estimating household greenhouse gas emissions. This issue also includes applied proposals such as educational chatbots for secondary schools, intelligent systems for analyzing black holes through digital signal processing techniques, and desktop applications to support the efficient management of blood banks. From an institutional perspective, one article explores digital transformation in universities as a mechanism to improve academic administration, while another analyzes how cloud computing is transforming higher education. Lastly, a systematic review addresses the use of blockchain technology for digital identity management in Africa, highlighting its potential in low-infrastructure contexts.

These studies demonstrate technical advancement across diverse areas in computing science and emphasize the importance of collaborative and contextualized research.

We extend our gratitude to the authors for sharing their research, to the reviewers for their constructive comments, and to the editorial team for their continuous commitment to quality and scientific dissemination.

We hope this issue inspires new ideas, collaborations, and new directions in computing science research.

Gabriela Suntaxi
Editor-in-Chief
Latin-American Journal of Computing – LAJC
Escuela Politécnica Nacional, Ecuador

ISSN:1390-9266 e-ISSN:1390-9134 LAJC 2025

Reviewers

We are most grateful to the following individuals for their time and commitment to review manuscripts for the Latin American Journal of Computing – LAJC

Byron Loarte, MSc.
Escuela Politécnica Nacional

Cesar Salinas, PhD.
Universidad de las Américas (UDLA)

Daniel Maldonado, PhD.
Universidad Técnica de Ambato

Danny Guamán, PhD.
Escuela Politécnica Nacional

Diego Benavides, PhD.
Universidad de las Fuerzas Armadas (ESPE)

Freddy Tapia, PhD.
Universidad de las Fuerzas Armadas (ESPE)

Fredy Gavilanes, PhD.
Escuela Superior Politécnica de Chimborazo

Germán Rodríguez, PhD.
Universidad de las Fuerzas Armadas (ESPE)

Irene Cedillo, PhD.
Universidad de Cuenca

Jesús Guamán, MSc.
Universidad Técnica de Ambato

Jhonattan Barriga, PhD.
Escuela Politécnica Nacional

Jorge Zambrano, PhD.
Universitat Politècnica de València

José Lucio, PhD.
Escuela Politécnica Nacional

Julio Ibarra, PhD.
Universidad San Francisco de Quito (USFQ)

Leandro Pazmiño, MSc.
Escuela Politécnica Nacional

Pablo Del Hierro, PhD.
Escuela Politécnica Nacional

Roberto Andrade, PhD.
Universidad San Francisco de Quito (USFQ)

Verónica Chamorro, MSc.
Universidad Complutense de Madrid

Verónica Segarra, PhD.
Universidad Técnica Particular de Loja

ISSN:1390-9266 e-ISSN:1390-9134 LAJC 2025

TABLE OF CONTENTS

Evaluating and mitigating SQL injections in web applications: developing a prototype 13
Nancy Rodriguez
Daniel Loor
Lucrecia Llerena

Hybrid CNN-Transformer Model for Severity Classification of Multi-organ Damage in Long COVID Patients 26
Akinrotimi Akinyemi Omololu
Atoyebi Jelili Olaniyi
Owolabi Olugbenga Olayinka

Sentiment Analysis on the Social Network "X", Public Perception of the President of Ecuador, Daniel Noboa (November 2023 - April 2024). 40
Roly Steeven Cedeño Menéndez
José Alberto León Alarcón
Jandry Hernando Franco Cantos

When Light Meets Sound: Signal Analysis of Black Holes 49
Guillermo Bolaños Rodríguez

Development of a desktop application prototype for blood banks 60
Lucrecia Llerena
Belinda Toaquiza
Nancy Rodríguez

African National Artificial Intelligence Strategies: A review, analysis and research agenda 72
Patrick Kanyi Wamuyu
Wangai Njoroge Mambo

Cloud Computing in Ecuadorian Higher Education: A Case Study on Use, Benefits, and Challenges at UTEQ 80
Geovanny Brito-Casanova
Lucrecia Llerena
Nancy Rodriguez

A Blockchain-based Identity Management Solution for Secure Personal Data Sharing in Africa: A Systematic Literature Review 89
Godwin Mandinyenya
Vusimuzi Malele

ISSN:1390-9266 e-ISSN:1390-9134 LAJC 2025

Evaluating and mitigating SQL injections in web applications: developing a prototype

ARTICLE HISTORY
Received 6 May 2025
Accepted 9 June 2025
Published 7 July 2025

Nancy Rodriguez
Quevedo State University
Software Engineering Program
Quevedo, Ecuador
nrodriguez@uteq.edu.ec
ORCID: 0000-0002-0861-4352

Daniel Loor
Quevedo State University
Software Engineering Program
Quevedo, Ecuador
bloorm2@uteq.edu.ec
ORCID: 0009-0002-8110-5375

Lucrecia Llerena
Quevedo State University
Software Engineering Program
Quevedo, Ecuador
lllerena@uteq.edu.ec
ORCID: 0000-0002-4562-6723

ISSN:1390-9266 e-ISSN:1390-9134 LAJC 2025

Evaluación y mitigación de inyecciones SQL en aplicaciones web: desarrollo de un prototipo

Evaluating and mitigating SQL injections in web applications: developing a prototype

Nancy Rodriguez
Quevedo State University
Software Engineering Program
Quevedo, Ecuador
nrodriguez@uteq.edu.ec

Daniel Loor
Quevedo State University
Software Engineering Program
Quevedo, Ecuador
bloorm2@uteq.edu.ec

Lucrecia Llerena
Quevedo State University
Software Engineering Program
Quevedo, Ecuador
lllerena@uteq.edu.ec

***Resumen*—**En el contexto actual de creciente vulnerabilidad digital, las inyecciones SQL continúan representando una amenaza crítica para la seguridad de aplicaciones web. Ante esta problemática, se desarrolló *SecureSQLTester*, un prototipo orientado a la detección y mitigación de ataques de inyección SQL, diseñado para ser accesible a desarrolladores y pequeñas empresas. La propuesta se fundamentó en una revisión sistemática de técnicas existentes, integrando enfoques clásicos y avanzados de protección. El desarrollo del prototipo se realizó aplicando la metodología ágil Scrum, lo que permitió realizar mejoras progresivas a través de ciclos de trabajo iterativos. Se realizaron pruebas de usabilidad con estudiantes de ingeniería de software, quienes evaluaron la herramienta en escenarios simulados. Los resultados muestran que *SecureSQLTester* identifica con precisión vulnerabilidades SQL en aplicaciones evaluadas. No obstante, se identificaron oportunidades de mejora en la interfaz de usuario, así como la necesidad de ampliar la personalización de parámetros según el contexto de uso. En conjunto, los hallazgos respaldan el potencial del prototipo como herramienta efectiva y de bajo costo para fortalecer la ciberseguridad en entornos de desarrollo de pequeña y mediana escala, y promover la adopción de buenas prácticas en el ciclo de vida del software.

***Palabras clave*—** *inyección SQL, seguridad en aplicaciones web, prototipo, usabilidad, metodología Scrum*

***Abstract*—**In the current context of increasing digital vulnerability, SQL injections continue to pose a critical threat to web application security. To address this issue, SecureSQLTester was developed—a prototype aimed at detecting and mitigating SQL injection attacks, designed to be accessible to developers and small businesses. The proposal was based on a systematic review of existing techniques, integrating both classical and advanced protection approaches. The prototype was developed using the agile Scrum methodology, which enabled progressive improvements through iterative work cycles. Usability tests were conducted with software engineering students, who evaluated the tool in simulated scenarios. The results show that SecureSQLTester accurately identifies SQL vulnerabilities in the evaluated applications. However, opportunities for improvement were identified in the user interface, as well as the need to enhance parameter customization according to the usage context. Overall, the findings support the potential of the prototype as an effective and low-cost tool to strengthen cybersecurity in small- and medium-scale development environments and to promote the adoption of best practices throughout the software lifecycle.

***Keywords*—** *SQL injection, web application security, prototype, usability, Scrum methodology.*

I. Introduccion

En el panorama actual de la transformación digital, las aplicaciones web cumplen una función importante en la organización de actividades cotidianas, desde la comunicación hasta el comercio electrónico [1]. Sin embargo, la creciente dependencia de estos entornos digitales también ha incrementado su exposición a múltiples amenazas de seguridad, entre las cuales las inyecciones SQL destacan como una de las más críticas [2]. Estas inyecciones consisten en la manipulación de consultas SQL mediante la inserción de código malicioso, lo que puede comprometer seriamente la seguridad del sistema, permitir el acceso no autorizado a datos sensibles y generar inconsistencias en las bases de datos [3].

El impacto de este tipo de vulnerabilidades es alarmante. Estudios recientes estiman que más del 76% de los ataques pueden ser detectados mediante técnicas adecuadas, aunque variantes como las "consultas ilegales" siguen siendo difíciles de identificar debido a su sofisticación [3]. Entre los factores que agravan este problema se encuentra la deficiente validación de entradas por parte de los desarrolladores, lo cual facilita la ejecución de estos ataques y representa una amenaza tanto para la estabilidad de los sistemas como para la protección de la información de los usuarios. En este contexto, la implementación de técnicas combinadas mediante lenguajes como JavaScript y PHP ha mostrado ser una estrategia prometedora para separar los datos maliciosos de los normales y fortalecer las medidas de prevención [4], [5].

A pesar del desarrollo de herramientas como SQLMap, QualysGuard y Nessus, su nivel de complejidad, requerimientos técnicos y costos asociados limitan su adopción por parte de pequeñas empresas, instituciones educativas o desarrolladores independientes. Es importante destacar que SQLMap es una herramienta de código abierto, gratuita y ampliamente utilizada en auditorías de seguridad, mientras que soluciones como QualysGuard y Nessus son

ISSN:1390-9266 e-ISSN:1390-9134 LAJC 2025
DOI: https://doi.org/10.33333/lajc.vol12n2.01

herramientas propietarias que requieren licencias comerciales y conocimientos técnicos avanzados para su implementación. Esto revela una brecha importante entre las soluciones existentes y las necesidades reales de sectores con recursos limitados, donde el acceso a herramientas de ciberseguridad funcionales, accesibles y fáciles de implementar sigue siendo un desafío no resuelto [6].

Ante esta problemática, surge una pregunta fundamental: ¿Cómo se pueden desarrollar y aplicar de manera efectiva técnicas de seguridad que prevengan y mitiguen los riesgos asociados a ataques de inyección SQL dentro de plataformas web? Esta investigación busca responder a esta interrogante mediante el desarrollo de SecureSQLTester, un prototipo diseñado para detectar y mitigar inyecciones SQL en aplicaciones web. El sistema fue concebido para ser una herramienta funcional, intuitiva y de bajo costo, que pueda ser utilizada por desarrolladores con conocimientos básicos, sin necesidad de infraestructuras complejas.

La propuesta se fundamenta en un análisis sistemático de literatura, mediante el cual se lograron reconocer las técnicas más relevantes de protección frente a inyecciones SQL, y en la aplicación de una metodología ágil basada en Scrum para su desarrollo iterativo. Además, se implementó una evaluación de usabilidad utilizando entrevistas estructuradas con usuarios reales (estudiantes de ingeniería de software), lo cual permitió obtener retroalimentación valiosa sobre la funcionalidad e interacción con el sistema.

En términos de contribución, este estudio propone una solución práctica que no solo incrementa la seguridad en aplicaciones web, sino que también promueve la adopción de métodos adecuados durante las etapas del proceso de construcción de sistemas informáticos. Los resultados obtenidos evidencian el potencial de SecureSQLTester como una alternativa efectiva y de fácil implementación, especialmente en entornos de desarrollo de pequeña y mediana escala. De esta forma, se espera cerrar las brechas actuales en la protección frente a ataques de inyección SQL, y fortalecer la confianza de usuarios y desarrolladores en las plataformas digitales.

La estructura del presente documento es la siguiente: en la Sección II se expone el análisis sistemático de literatura; la Sección III aborda la metodología utilizada para el desarrollo del software; en la Sección IV se detalla la solución propuesta, seguida por la Sección V que presenta la evaluación de la usabilidad; la Sección VI analiza los resultados obtenidos; y finalmente, la Sección VII expone las conclusiones del estudio.

II. Revisión sistemática de literatura

La revisión sistemática constituye una metodología esencial para localizar, seleccionar y evaluar de manera crítica los artículos más relevantes y confiables en el ámbito de estudio. Este proceso permite organizar de forma estructurada la información disponible en la literatura científica, y asegurar que solo los datos pertinentes sean incorporados al análisis. Asimismo, facilita la identificación de tendencias investigativas, brechas de conocimiento y áreas poco exploradas, lo cual proporciona una base sólida que respalda y enriquece el desarrollo de nuevos estudios [7].

El presente estudio enfoca su revisión sistemática en la exploración de la siguiente interrogante investigativa: ¿Cómo se pueden desarrollar y aplicar de manera efectiva técnicas de seguridad que prevengan y mitiguen los riesgos asociados a ataques de inyección SQL dentro de plataformas web? Para ello, el proceso comenzó con la definición de palabras clave relevantes y la construcción de una cadena de búsqueda diseñada para maximizar la cobertura de artículos pertinentes. La cadena de búsqueda aplicada fue la siguiente:

("SQL injection" OR "SQL security" OR "SQL vulnerabilities" OR "SQL injection prevention" OR "web application security") AND ("tools" OR "software" OR "solutions" OR "secure coding practices").

Se llevó a cabo una consulta bibliográfica en repositorios científicos ampliamente reconocidos, tales como: IEEE Xplore, SpringerLink y ACM Digital Library. Además, se establecieron criterios de inclusión y exclusión para determinar qué estudios serían considerados o descartados, los cuales se detallan en la Tabla I. Estos criterios garantizaron la selección rigurosa de los estudios más relevantes para el análisis y el desarrollo posterior del prototipo propuesto.

TABLE I. CRITERIOS DE INCLUSIÓN Y EXCLUSIÓN

Tipo de criterio	Descripción
Criterios de inclusión	Artículos publicados entre los años 2010 y 2024. El artículo debe reportar el uso de herramientas tecnológicas para mitigar vulnerabilidades de inyección SQL en aplicaciones web. El estudio debe enfocarse en técnicas y prácticas de seguridad orientadas a mejorar la protección contra ataques de inyección SQL.
Criterios de exclusión	Artículos que no aborden explícitamente vulnerabilidades de inyección SQL. Estudios que no mencionen herramientas ni prácticas relacionadas con la seguridad de aplicaciones web frente a este tipo de ataques.

En la Tabla II, se sintetiza la cantidad de estudios encontrados, seleccionados y considerados, como resultado de la aplicación del conjunto de términos de búsqueda en diversas fuentes bibliográficas digitales.

TABLE II. RESULTADOS DE LA BÚSQUEDA SISTEMÁTICA POR BASE DE DATOS

Base de Datos	Encontrados	Preseleccionados	Estudios Considerados
IEEE Xplore	20	6	3
SpringerLink	8	3	1
ACM Digital Library	9	5	1
Total	**85**	**41**	**5**

Del examen realizado a los trabajos previamente escogidos, se extrajeron diversas perspectivas relevantes sobre la problemática de las inyecciones SQL y las herramientas desarrolladas para su mitigación. A continuación, se presentan los principales hallazgos que sustentan esta investigación:

Faisal Fadlalla et al. [8] destacan que las inyecciones SQL continúan siendo una de las vulnerabilidades más frecuentes y

ISSN:1390-9266 e-ISSN:1390-9134 LAJC 2025
DOI: https://doi.org/10.33333/lajc.vol12n2.01

peligrosas en aplicaciones web, especialmente por la falta de validación adecuada de entradas de usuario. El autor enfatiza que muchas aplicaciones permanecen expuestas por la ausencia de buenas prácticas de codificación segura y la falta de implementación de herramientas específicas destinadas a salvaguardar los entornos donde se almacenan los datos. En este sentido, subraya la necesidad del uso de herramientas como SecureSQLTester para realizar auditorías de seguridad efectivas y fortalecer las defensas de las aplicaciones.

Por su parte, B. Kalaiselvi et al. [9] describen cómo herramientas de escaneo de seguridad, como SecureSQLTester, facilitan la identificación automática de vulnerabilidades de inyección SQL mediante la simulación de ataques controlados y la generación de informes detallados con recomendaciones de mitigación. Esta automatización no solo incrementa la eficiencia de las pruebas de seguridad, sino que también democratiza el acceso a prácticas de protección avanzada para desarrolladores con conocimientos limitados.

De manera complementaria, Saeed et al. [10] analizan los beneficios de integrar herramientas de detección de vulnerabilidades durante todas las fases involucradas en la construcción de sistemas informáticos. Según su investigación, la implementación de pruebas continuas de inyección SQL permite identificar y corregir fallas de seguridad antes de que las aplicaciones sean desplegadas en producción, reduciendo de manera significativa el riesgo de explotación de vulnerabilidades.

En la misma línea, Gupta et al. [11] proponen un enfoque combinado de cifrado mediante AES y criptografía de curva elíptica (ECC) para mitigar los ataques por inyección SQL, una de las amenazas más críticas a la protección de los entornos de almacenamiento de datos dentro de sistemas web. Su solución busca proteger tanto el acceso no autorizado durante el inicio de sesión como la información contenida en los repositorios de datos. En este contexto, y con un enfoque más accesible para usuarios no especializados, surge SecureSQLTester como una herramienta que facilita la detección temprana de vulnerabilidades sin requerir conocimientos avanzados en ciberseguridad.

Damaševičius et al. [12] sostienen que la seguridad en aplicaciones web debe ser abordada como un proceso continuo. En este marco, SecureSQLTester se presenta como una herramienta clave para realizar pruebas de penetración automatizadas, lo que incrementa la cobertura y profundidad de las evaluaciones de seguridad, y permite la detección temprana de puntos débiles explotables.

Durante este proceso de revisión de literatura, se identificaron diferencias importantes entre una diversidad de herramientas empleadas para mitigar vulnerabilidades de inyección SQL, entre las cuales se distinguen soluciones de código abierto **y** herramientas propietarias**.** Por ejemplo, SQLMap es una herramienta de código abierto ampliamente utilizada por su facilidad de acceso, flexibilidad y ausencia de costo de licencia. En contraste, herramientas como QualysGuard **y** Nessus son plataformas comerciales**,** con mayores requisitos técnicos y económicos, lo que restringe su adopción en contextos con limitaciones presupuestarias o técnicos. Esta diferenciación fue considerada al momento de evaluar la aplicabilidad de las soluciones revisadas en función del público objetivo del presente estudio [6] .

En conjunto, los estudios revisados evidencian que SecureSQLTester representa una solución eficaz para identificar y reducir los efectos de ataques por inyección SQL en entornos web. Su uso en etapas tempranas del ciclo de desarrollo permite fortalecer de manera significativa la seguridad general de los sistemas, lo cual reduce la probabilidad de explotación de vulnerabilidades críticas.

Si bien la revisión de literatura se centró en técnicas de detección y mitigación de inyecciones SQL debido a su alta prevalencia y criticidad en aplicaciones web, se reconoce que estas no representan el único vector de ataque relevante. De acuerdo con el estándar OWASP TOP 10, existen otras vulnerabilidades críticas que deben ser consideradas, como los ataques de tipo Cross-Site Scripting (XSS), Cross-Site Request Forgery (CSRF), y la exposición de datos sensibles, entre otros. En consecuencia, se proyecta como línea futura de trabajo la ampliación del alcance del prototipo SecureSQLTester para incorporar pruebas automatizadas que aborden este conjunto más amplio de amenazas.

III. METODOLOGÍA PARA LA CONSTRUCCIÓN DEL SOFTWARE

Con el objetivo de llevar a cabo esta propuesta, se adoptó la metodología ágil Scrum, considerada una estrategia idónea para gestionar proyectos complejos y dinámicos mediante ciclos iterativos e incrementales (ver figura 1). Scrum facilita la colaboración continua entre los miembros del equipo, permite una adaptación rápida a los cambios, y promueve la entrega constante de valor, y garantiza que el producto final cumpla con los requisitos planteados de manera eficiente [13].

En cada iteración, se consideró el principio de escalabilidad como parte integral del enfoque incremental, con el fin de garantizar que las funcionalidades desarrolladas puedan adaptarse progresivamente a diferentes entornos y cargas de trabajo. Esta orientación permite que el prototipo evolucione no solo en funcionalidad, sino también en robustez y capacidad de adaptación a proyectos de mayor escala.

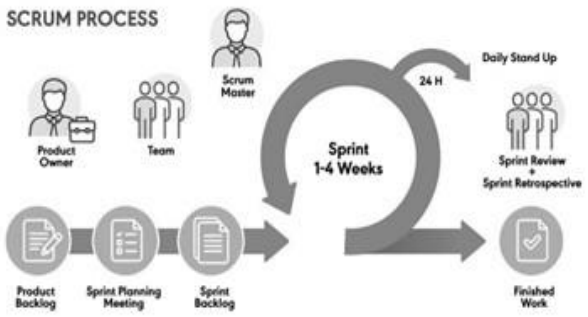

Fig. 1. Procesos Scrum

Fuente: Adaptada de [14]

A. Definición de Requisitos

La definición de requisitos constituyó una etapa fundamental, orientada a identificar los aspectos clave necesarios para mitigar ataques de inyección SQL mediante el desarrollo de un prototipo funcional y seguro. Este proceso incluyó una revisión exhaustiva de literatura especializada y la evaluación crítica de herramientas tecnológicas existentes, lo que permitió precisar las funcionalidades esenciales y las características deseadas del sistema.

a) Recolección de Requisitos: Los requisitos fueron clasificados en dos categorías principales: requisitos

ISSN:1390-9266 e-ISSN:1390-9134 LAJC 2025
DOI: https://doi.org/10.33333/lajc.vol12n2.01

funcionales y requisitos no funcionales. Esta estructuración permitió asegurar que el prototipo cumpliera con las necesidades operativas de detección y prevención de vulnerabilidades SQL, además de garantizar su desempeño, escalabilidad, facilidad de uso y seguridad.

b) Documentación de Requisitos: En la Tabla III, se presentan los requisitos funcionales, los cuales describen las capacidades específicas que debe ofrecer el sistema para cumplir con su propósito de detección y mitigación de vulnerabilidades de inyección SQL. Por su parte, la Tabla IV muestra los requisitos no funcionales, orientados a definir las características de calidad que aseguren el desempeño, la seguridad y la usabilidad del prototipo.

TABLE III. REQUISITOS FUNCIONALES DEL SISTEMA

Requerimiento	Descripción
Pruebas de Inyección SQL	Permitir la ejecución de pruebas para detectar vulnerabilidades de inyección SQL en aplicaciones que interactúan con bases de datos SQL.
Pruebas de Autenticación	Verificar que los métodos de autenticación y credenciales de acceso estén protegidos frente a ataques de fuerza bruta o de diccionario.
Generación de Reportes de Seguridad	Proporcionar informes detallados sobre las pruebas realizadas, indicando vulnerabilidades detectadas, su gravedad y sugerencias de mitigación.
Simulación de Ataques	Simular distintos tipos de ataques, como inyección SQL y Cross-Site Scripting (XSS), para evaluar la resistencia del sistema.
Pruebas de Encriptación de Datos	Verificar la correcta implementación de la encriptación de información confidencial mientras se transfiere y cuando se encuentra almacenada.
Validación de Permisos y Roles	Comprobar que los permisos de acceso y roles de usuario estén correctamente configurados para evitar accesos no autorizados.
Análisis de Estructuras de Bases de Datos	Ejecutar un análisis sobre bases de datos SQL para detectar configuraciones vulnerables, tales como claves poco robustas o accesos sin restricciones.
Pruebas de Vulnerabilidad de Contraseñas	Verificar la fortaleza de las contraseñas en bases de datos, asegurando la adhesión a estándares definidos para contraseñas robustas.
Acceso al almacenamiento de información de Forma Segura	Proveer métodos seguros de conexión a las bases de datos durante las pruebas, evitando la exposición de credenciales y datos sensibles.

B. Planificación del Proyecto

El desarrollo del proyecto se organizó siguiendo los principios de la metodología ágil Scrum, que permite gestionar proyectos complejos mediante entregas iterativas y la priorización continua de tareas. Inicialmente, se elaboró un Product Backlog que recopiló todas las funcionalidades y actividades necesarias para la construcción del prototipo SecureSQLTester. Cada ítem del backlog fue priorizado de acuerdo con su importancia, con el fin de alcanzar las metas definidas en la propuesta. Posteriormente, se estableció una planificación basada en sprints de dos semanas de duración. Al inicio de cada sprint, se seleccionaron las tareas de mayor prioridad, y se establecieron metas claras y alcanzables para garantizar avances consistentes y enfocados. Esta estrategia permitió una adaptación ágil a los requerimientos emergentes y facilitó la entrega incremental de valor a lo largo del proyecto En la Tabla V, se incluye un detalle completo de los sprints llevados a cabo, junto con las principales tareas realizadas y los objetivos definidos en cada etapa.

TABLE IV. REQUISITOS NO FUNCIONALES DEL SISTEMA

Requerimiento	Descripción
Interfaz de Usuario Intuitiva	El sistema debe contar con una interfaz amigable que facilite la configuración y ejecución de pruebas a usuarios sin conocimientos avanzados en seguridad.
Diseño Responsivo	La interfaz debe adaptarse automáticamente a diferentes dispositivos (computadoras, tabletas, teléfonos móviles).
Alta Velocidad en la Ejecución de Pruebas	Las pruebas de seguridad deben ejecutarse de forma rápida y eficiente, reduciendo al mínimo las afectaciones sobre el desempeño de la base de datos analizada.
Compatibilidad Multibase de Datos	El sistema debe soportar bases de datos SQL populares como MySQL, PostgreSQL y SQL Server.
Escalabilidad	El prototipo debe manejar bases de datos de diversos tamaños sin afectar la precisión ni el rendimiento de las pruebas
Confiabilidad	Las pruebas deben ofrecer resultados consistentes, minimizando falsos positivos y falsos negativos.
Seguridad de la Aplicación	El sistema debe asegurar la confidencialidad de los datos utilizados durante las pruebas y preservar la fidelidad de los resultados generados.
Soporte Multilingüe	Debe ofrecer soporte para múltiples idiomas, facilitando su uso en diferentes contextos geográficos.
Integración con Herramientas de CI/CD	Debe ser compatible con plataformas de integración y entrega continua (CI/CD), permitiendo la automatización de las pruebas de seguridad.

TABLE V. PLANIFICACIÓN DE SPRINTS

Sprint	Actividad Principal	Tiempo Semana	Tareas	Objetivos
1	Diseño de la Interfaz de Usuario	1-2	Dibujar bocetos y maquetas de la interfaz, incluyendo la pantalla principal, pruebas y área de resultados.	Desarrollar un diseño intuitivo y amigable que facilite la interacción y navegación de los usuarios en el sistema.
2	Gestión de Usuarios y Autenticación	3-4	Crear el registro de usuarios. Implementar autenticación segura mediante contraseñas.	Restringir el acceso a configuraciones avanzadas exclusivamente a los administradores
3	Implementación de Pruebas de Seguridad Básicas	5-6	Desarrollar pruebas de inyección SQL y validar vulnerabilidades en bases de datos.	Validar que el sistema identifique correctamente vulnerabilidades de inyección SQL.
4	Implementación de Reportes y Notificaciones	7-8	Desarrollar funcionalidades como reportes detallados de pruebas de seguridad.	Proporcionar al usuario reportes claros y útiles para la revisión de los resultados de las pruebas.
5	Integración Final y Pruebas de Usabilidad	9-10	Integrar todos los módulos del sistema y asegurar el correcto funcionamiento de sus funcionalidades	
Final	Evaluación y feedback	11-12	Entregar el prototipo final. Presentar el sistema funcional a los stakeholders para su evaluación.	Presentar la versión final del sistema y obtener feedback para comprobar si se alcanzaron las metas

ISSN:1390-9266 e-ISSN:1390-9134 LAJC 2025
DOI: https://doi.org/10.33333/lajc.vol12n2.01

IV. Evaluación de Usabilidad del Prototipo SecureSQLTester

Con el objetivo de validar la experiencia del usuario y detectar oportunidades de mejora en el prototipo desarrollado con el fin de identificar fallas de seguridad en sistemas web, se propuso la realización de una evaluación de usabilidad basada en la técnica entrevista estructurada.

La aplicación de esta técnica permitió recopilar información sistemática y consistente sobre la interacción de los usuarios con el prototipo, así como identificar necesidades, problemas y percepciones relevantes que orientaron las recomendaciones de mejora.

A. Descripción de la Técnica de Usabilidad: Entrevista Estructurada

La entrevista estructurada es un método cualitativo en el que se plantean preguntas predeterminadas a un grupo de participantes, con el objetivo de recolectar información detallada sobre su interacción y experiencia con un sistema [15]. Su principal fortaleza reside en el grado de dirección que mantiene el investigador durante el desarrollo de la conversación, lo que permite asegurar la obtención de datos organizados y comparables.

En este enfoque, las preguntas deben ser diseñadas con anticipación, de forma clara, precisa y alineadas con los aspectos de usabilidad que se desean evaluar [15]. De esta manera, se garantiza que las respuestas obtenidas estén directamente relacionadas con los objetivos de la evaluación.

La técnica aplicada en este estudio siguió el procedimiento clásico propuesto por Hix y Hartson [16], el cual contempla cinco pasos esenciales, que se detallan en la Tabla VI.

TABLE VI. Pasos y tareas de la técnica entrevista estructurada según Hix y Hartson [16]

N°	Nombre del Paso	Tareas
1	Definición de los objetivos	Identificar el objetivo principal de aplicar la técnica, orientado a mejorar la usabilidad del proyecto.
2	Identificación del público objetivo	Seleccionar a los participantes adecuados para la evaluación de la herramienta.
3	Diseño de las preguntas	Formular preguntas claras, concisas y directamente relacionadas con los objetivos de evaluación.
4	Validación de las preguntas	Solicitar la revisión de las preguntas por parte de otros usuarios o expertos para garantizar su claridad y relevancia.
5	Análisis de los datos	Emplear métodos adecuados de procesamiento de información con el propósito de comprender los hallazgos y derivar interpretaciones relevantes.

B. Adaptaciones de la Técnica de Usabilidad: Entrevista Estructurada

Si bien la técnica entrevista estructurada es ampliamente utilizada en evaluaciones de usabilidad y no representa mayores complicaciones operativas [17], su correcta aplicación tradicional requiere la participación de un experto en usabilidad que posea conocimientos técnicos y habilidades blandas para conducir entrevistas efectivas [18]. Dado el contexto particular del proyecto, fue necesario realizar adaptaciones metodológicas para facilitar su implementación.

En la Tabla VII, se presentan las principales condiciones adversas identificadas y las adaptaciones propuestas para asegurar la ejecución efectiva de la técnica.

TABLE VII. Condiciones adversas y adaptaciones propuestas de la técnica entrevista estructurada

N°	Nombre del Paso	Condiciones Adversas	Adaptaciones Propuestas
1	Definición de los objetivos	Se requiere de un experto en usabilidad.	Sustituido por estudiantes de la UTEQ bajo la supervisión de un mentor.
2	Identificación del público objetivo	Se requiere la participación presencial de usuarios.	Participación remota a través de foros, correo electrónico y comentarios en blogs.
3	Diseño de las preguntas	Se requiere de un experto para formular las preguntas.	Diseño de preguntas por estudiantes supervisados por un mentor académico.
4	Validación de las preguntas	Se requiere de un experto para validar el instrumento.	Validación interna entre estudiantes y mentores.
5	Análisis de los datos	Se requiere de un experto en análisis de usabilidad.	Análisis efectuado por estudiantes bajo supervisión académica, utilizando agrupación temática de respuestas.

Debido a las restricciones operativas mencionadas, se definieron y aplicaron una serie de pasos adicionales para facilitar la ejecución de la técnica entrevista estructurada adaptada:

a) Paso 1: Realización de una prueba piloto. Se llevó a cabo una prueba preliminar con la finalidad de examinar la funcionalidad general del proceso de entrevista estructurada y validar los insumos iniciales diseñados.

b) Paso 2: Uso herramientas de comunicación y colaboración. Considerando la imposibilidad de encuentros presenciales, se establecieron canales de comunicación remota mediante Google Meet, Gmail y WhatsApp, lo que garantizó la participación activa de los usuarios durante todo el proceso de evaluación.

c) Paso 3: Adaptación del formato de las entrevistas. Se diseñó un conjunto de preguntas orientadas a los factores específicos de usabilidad que se deseaba evaluar, para asegurar su claridad y pertinencia mediante revisión y validación preliminar por parte del mentor académico.

d) Paso 4: Elaboración de plantillas y documentos de apoyo. Las preguntas validadas fueron organizadas en un formulario de Word y complementadas con materiales de apoyo, tales como la guía de instalación del sistema, documentos de consentimiento informado, tareas específicas para los usuarios y plantillas de recolección de respuestas.

e) Paso 5: Ejecución de la evaluación de usabilidad. La evaluación fue realizada en modalidad remota, siguiendo un cronograma predefinido que incluyó comunicaciones

ISSN:1390-9266 e-ISSN:1390-9134 LAJC 2025
DOI: https://doi.org/10.33333/lajc.vol12n2.01

formales a los participantes, asignación de tareas, envío de insumos y sesiones de asistencia técnica virtual.

f) Paso 6: Análisis de datos y consolidación de resultados. Las respuestas obtenidas fueron sistematizadas y agrupadas temáticamente para eliminar redundancias. Posteriormente, se documentaron en un informe de entrevista estructurada que sirvió como base para identificar áreas de mejora del prototipo.

Estos pasos de adaptación se resumen en la Tabla VIII.

TABLE VIII. PASOS Y TAREAS DE LA TÉCNICA ADAPTADA ENTREVISTA ESTRUCTURADA

N°	Nombre del Paso	Tarea
1	Realizar una prueba piloto	Validar previamente los insumos y procedimientos de la evaluación.
2	Utilizar herramientas de comunicación y colaboración	Definir el perfil de usuario, enviar correos de invitación y reclutar participantes mediante redes sociales.
3	Adaptar el formato de las entrevistas	Diseñar preguntas claras y específicas relacionadas con los aspectos de usabilidad a evaluar.
4	Diseñar plantillas y herramientas	Crear formularios en Google Forms o documentos de Word para la recopilación de respuestas.
5	Realizar la evaluación de usabilidad	Ejecutar la evaluación mediante reuniones remotas, asegurando el acceso a todos los insumos necesarios.
6	Analizar los datos y agrupar resultados	Sistematizar y consolidar los resultados obtenidos, socializar el análisis con los participantes para retroalimentación.

V. RESULTADOS

Esta sección presenta los principales resultados obtenidos durante el desarrollo y la evaluación del prototipo SecureSQLTester, los cuales abarcaron las actividades de análisis, investigación, comunicación con usuarios, aplicación de técnicas de usabilidad, observaciones recogidas y el diseño final de las interfaces.

A. Evaluación de Usabilidad del Prototipo SecureSQLTester

La evaluación de usabilidad se llevó a cabo mediante la técnica entrevista estructurada, dirigida a estudiantes de nivel inicial en el programa académico de Ingeniería de Software, quienes representan un perfil cercano al público objetivo del prototipo. La planificación de la evaluación incluyó la elaboración de un comunicado formal invitando a los participantes, enviado mediante correo electrónico.

Una vez recibida la invitación, los usuarios pudieron iniciar sesión en el prototipo, e ingresaron su nombre, personalizaron así su experiencia de uso (ver Figura 2).

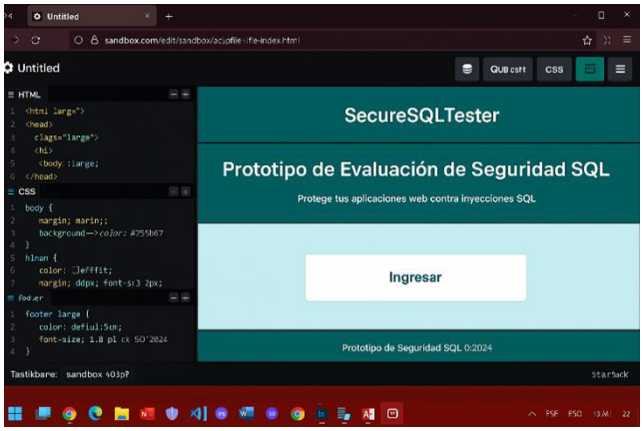

Fig. 2. Pantalla de inicio de sesión del prototipo

Posteriormente, se presentó un módulo explicativo al que los participantes pudieron acceder para consultar recomendaciones generales, advertencias sobre inyecciones SQL y pautas sobre el uso correcto del sistema (ver Figura 3).

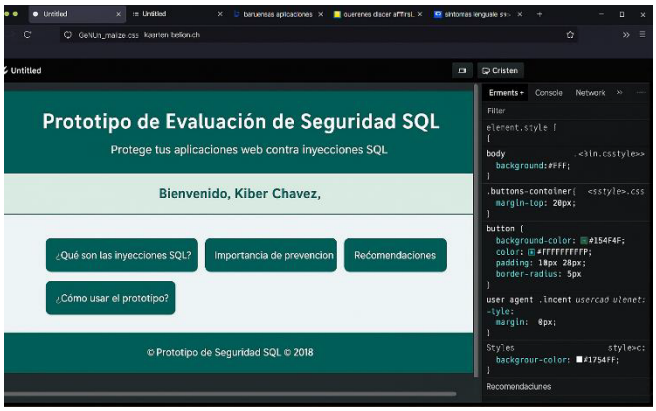

Fig. 3. Parámetros de información mostrados a los usuarios

En el módulo principal, los usuarios ingresaron diversas URLs para verificar la presencia de posibles inyecciones SQL. En caso de detección de amenazas, el sistema mostraba una advertencia; en caso contrario, confirmaba la seguridad de la URL analizada. Los resultados obtenidos eran almacenados en un historial accesible para consulta posterior (ver Figura 4).

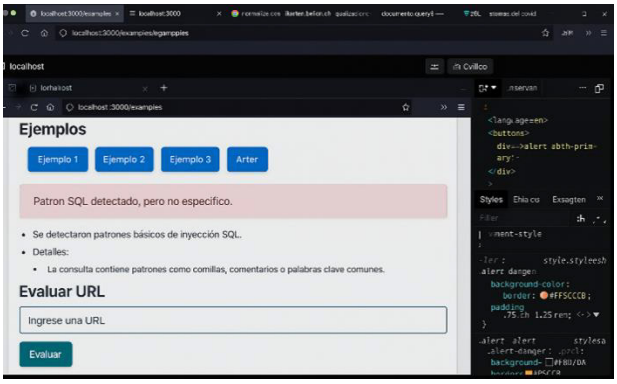

Fig. 4. Módulo de ingreso de URLs y visualización de resultados

Durante la evaluación, se asignaron diversas tareas diseñadas para simular escenarios prácticos de uso, lo que

ISSN:1390-9266 e-ISSN:1390-9134 LAJC 2025
DOI: https://doi.org/10.33333/lajc.vol12n2.01

permitió evaluar la funcionalidad y facilidad de interacción del prototipo (ver Figuras 5 y 6).

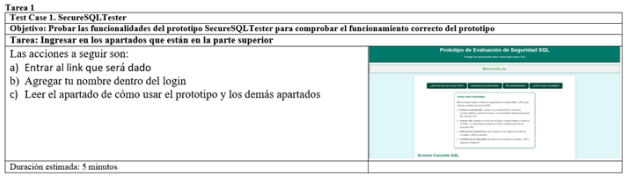

Fig. 5. Formato para la tarea 1 de interacción con el sistema

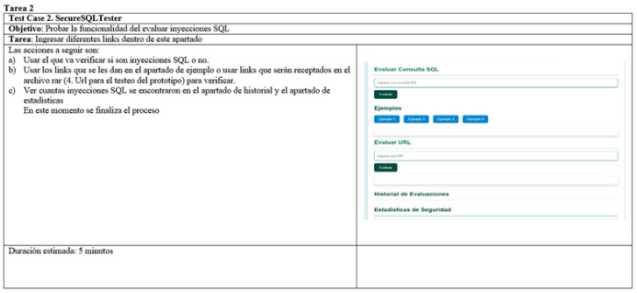

Fig. 6. Formato para la tarea 2 de interacción con el sistema

Además, se utilizó un documento específico para la recolección sistemática de las respuestas de los usuarios tras la ejecución de las tareas (ver Figura 7).

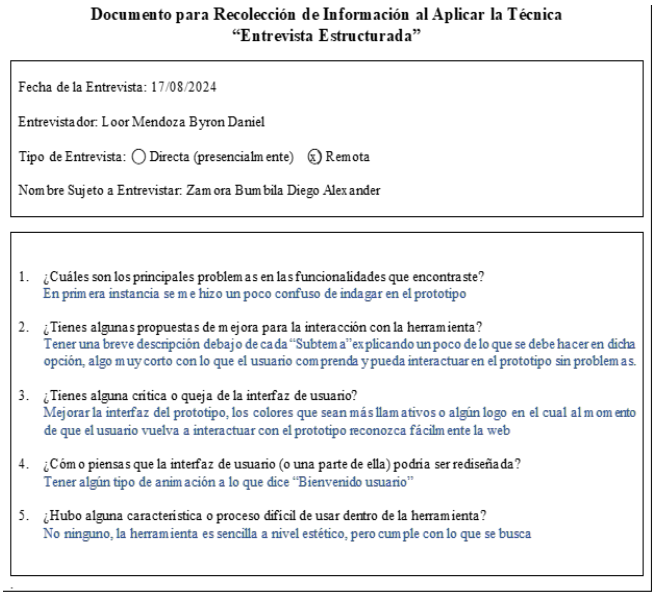

Fig. 7. Plantilla de recolección de datos de la evaluación de usabilidad

Posterior a la aplicación de la técnica, se recopilaron y analizaron las respuestas de los cuatro participantes que completaron la prueba, identificándose problemas, observaciones críticas y propuestas de mejora. Los resultados fueron organizados y sistematizados para facilitar su interpretación y orientar futuros ajustes al prototipo.

B. Análisis de Respuestas por Pregunta

Antes de presentar el análisis individual, se señala que algunas respuestas no se alinearon estrictamente con las preguntas planteadas; por ello, fueron reubicadas de acuerdo con su mayor pertinencia temática.

La Tabla IX resume las respuestas obtenidas de los usuarios durante la aplicación de la técnica entrevista estructurada.

TABLE IX. ANÁLISIS DE RESPUESTAS A LAS PREGUNTAS DE LA EVALUACIÓN DE USABILIDAD

Pregunta	Resumen de respuestas de los usuarios
¿Cuáles son los principales problemas en las funcionalidades que encontraste?	Se identificó falta de claridad en el funcionamiento de algunos parámetros, lo cual dificultaba su comprensión. Se sugiere una mejor especificación de cada función.
¿Tienes algunas propuestas de mejora para la interacción con la herramienta?	Los usuarios propusieron hacer más detallada la información en cada apartado, para facilitar la lectura y entendimiento de las funcionalidades.
¿Tienes alguna crítica o queja de la interfaz de usuario?	Se criticó que la interfaz era muy simple y no resultaba visualmente atractiva, recomendándose hacerla más llamativa para mejorar la experiencia del usuario.
¿Cómo piensas que la interfaz de usuario (o una parte de ella) podría ser rediseñada?	Se sugirió agregar más colores, incorporar animaciones en el saludo inicial, y eliminar elementos de código visible que podrían representar vulnerabilidades.
¿Hubo alguna característica o proceso difícil de usar dentro de la herramienta?	En general, los usuarios no reportaron dificultades significativas; consideraron que el prototipo era fácil de usar gracias a las instrucciones previas proporcionadas.

C. Análisis de Observaciones Dadas por el Usuario

El análisis de las observaciones y sugerencias emitidas por los usuarios entrevistados proporciona una visión integral de las áreas del prototipo SecureSQLTester que requieren atención y mejora. Esta retroalimentación es fundamental para orientar las futuras iteraciones de desarrollo, lo cual permite priorizar cambios basados en las necesidades reales y percepciones de los usuarios finales. La Tabla X incluye una síntesis de los hallazgos más relevantes, clasificados por categoría, tipo de observación y frecuencia de aparición entre los participantes.

TABLE X. OBSERVACIONES RECOPILADAS MEDIANTE ENTREVISTAS, CLASIFICADAS POR CATEGORÍA, HALLAZGO Y FRECUENCIA

Categoría	Hallazgo	Frecuencia
Problemas /Errores	Dificultades para autenticar al usuario mediante credenciales válidas	3
	Lentitud al realizar pruebas de inyección SQL en bases de datos grandes	2
Mejoras de Interfaz	Mejorar la visualización de los resultados de pruebas	2
	Añadir opciones de personalización en el diseño de la interfaz	1
	Incluir más detalles sobre los errores encontrados en las pruebas	2
	Mejorar la organización de las opciones del menú para facilitar el acceso	1
Nuevas Funcionalidades	Agregar opción de informes automáticos al finalizar las pruebas	1
	Implementar función para probar vulnerabilidades en bbdd no relacionales	2
	Añadir la capacidad de realizar pruebas de seguridad programadas	1
Usabilidad	Mejorar la documentación interna para usuarios novatos	2
	Simplificar los pasos para iniciar las pruebas de seguridad	1
	Agregar opción para guardar configuraciones de pruebas	1

ISSN:1390-9266 e-ISSN:1390-9134 LAJC 2025
DOI: https://doi.org/10.33333/lajc.vol12n2.01

La información obtenida en esta etapa resulta crucial para priorizar las mejoras, optimizar la experiencia de usuario, y ampliar las funcionalidades de seguridad en futuras versiones del sistema.

D. Diseño de Interfaces Resultantes

Como parte de la mejora continua del prototipo, se diseñaron y ajustaron interfaces que optimizan la interacción de los usuarios con el sistema, basadas en las observaciones recopiladas durante la fase de evaluación de usabilidad.

La Figura 8 muestra la interfaz renovada de autenticación de usuario, donde se solicita al usuario ingresar su nombre para acceder al sistema de manera personalizada y amigable.

Fig. 8. Interfaz de inicio de sesión del prototipo SecureSQLTester

Posteriormente, la Figura 9 presenta la interfaz principal del prototipo, diseñada para facilitar la evaluación de vulnerabilidades por inyección SQL en enlaces ingresados por los usuarios. Esta pantalla permite gestionar de manera intuitiva las pruebas realizadas y consultar los resultados obtenidos.

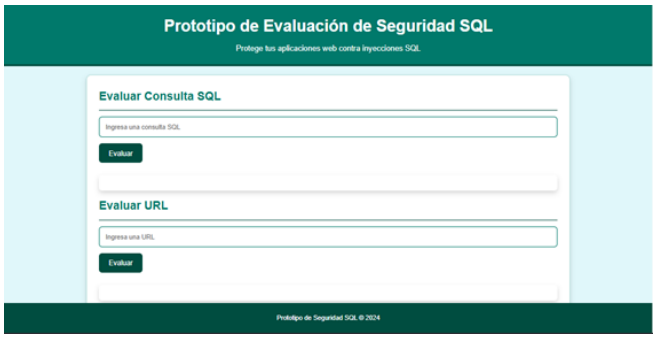

Fig. 9. Interfaz principal del prototipo SecureSQLTester

VI. Discusión de Resultados

Los hallazgos obtenidos durante el proceso de evaluación indican que el prototipo SecureSQLTester ha cumplido de manera satisfactoria con los objetivos planteados, destacándose su relevancia en el fortalecimiento de la ciberseguridad para aplicaciones web. La integración de técnicas efectivas para la detección y mitigación de vulnerabilidades de inyección SQL permitió obtener resultados confiables en la identificación de amenazas críticas, con un desempeño adecuado en la mayoría de los escenarios evaluados.

Una de las principales fortalezas identificadas fue la capacidad del prototipo para analizar y procesar solicitudes en tiempo real, lo que demuestra su aplicabilidad en contextos que requieren respuestas inmediatas, tales como auditorías de bases de datos y pruebas de penetración. Estos resultados son coherentes con investigaciones previas que subrayan la importancia de contar con herramientas específicas y rápidas para mitigar amenazas de seguridad en aplicaciones web.

Los usuarios participantes valoraron de forma favorable la usabilidad del sistema y la comprensión de los reportes generados sobre las vulnerabilidades detectadas, y destacaron su utilidad como una herramienta accesible y práctica para desarrolladores y pequeñas empresas, especialmente en proyectos de mediana o baja escala presupuestaria. Este aspecto resalta la contribución de SecureSQLTester en el ámbito de soluciones de ciberseguridad accesibles para públicos con experiencia limitada en seguridad informática.

En comparación con herramientas comerciales más robustas, como QualysGuard Web Application Scanning y Nessus Vulnerability Scanner, SecureSQLTester destacó principalmente por su simplicidad de instalación y configuración [6]. Mientras que las herramientas mencionadas ofrecen una cobertura más exhaustiva de vulnerabilidades, su implementación suele requerir mayores recursos y conocimientos técnicos especializados. En contraste, SecureSQLTester fue valorado por su enfoque intuitivo y accesible, lo que resulta especialmente útil para usuarios con conocimientos básicos en ciberseguridad y manejo de consultas SQL.

No obstante, también se identificaron áreas de mejora, particularmente en lo que respecta a la interfaz de usuario. Aunque el sistema demostró una funcionalidad eficiente, algunos usuarios señalaron que el diseño resultaba excesivamente simple y carecía de elementos visuales atractivos. Esta observación coincide con estudios previos que enfatizan la importancia de la usabilidad y el diseño intuitivo en el éxito de herramientas tecnológicas. Se sugirió mejorar la organización visual de los componentes en la interfaz y aumentar las opciones de personalización de los parámetros de entrada, de manera que el prototipo pueda adaptarse mejor a diferentes configuraciones de bases de datos y perfiles de usuarios.

Además, es importante señalar una limitación metodológica relevante identificada durante la evaluación de usabilidad es la homogeneidad del grupo de participantes, compuesto exclusivamente por estudiantes de Ingeniería de Software. Si bien este perfil resulta adecuado para una primera aproximación técnica, no representa de forma amplia a la población objetivo del prototipo, que puede incluir desarrolladores con distintos niveles de experiencia, profesionales de áreas no técnicas y personal administrativo. Esta limitación reduce la generalización de los hallazgos obtenidos y condiciona la interpretación de la percepción de usabilidad.

En general, el prototipo ha demostrado ser una solución viable y práctica para mejorar la seguridad de aplicaciones web, facilitando su adopción temprana y contribuyendo a la reducción de riesgos asociados a vulnerabilidades de inyección SQL. Se estima que, con futuras optimizaciones en la personalización de configuraciones y en el diseño de la interfaz, SecureSQLTester podrá ampliar su competitividad en el mercado de herramientas de ciberseguridad, e incrementar su capacidad de respuesta a una gama más diversa de necesidades de especialistas del campo de la ciberseguridad.

ISSN:1390-9266 e-ISSN:1390-9134 LAJC 2025
DOI: https://doi.org/10.33333/lajc.vol12n2.01

VII. Conclusiones

El desarrollo del prototipo SecureSQLTester ha demostrado ser una solución eficaz orientada a identificar y reducir los efectos de ataques por inyección SQL en entornos web, e impulsar notablemente la mejora de la protección y consistencia de los sistemas informáticos. La implementación de medidas automatizadas para la identificación de inyecciones SQL ha permitido minimizar los riesgos asociados a ataques maliciosos, favorecer la protección de datos sensibles y asegurar la estabilidad de las aplicaciones evaluadas.

Además, la facilidad de uso y accesibilidad del prototipo posicionan a SecureSQLTester como una alternativa viable para desarrolladores independientes y pequeñas empresas que buscan adoptar buenas prácticas de ciberseguridad sin incurrir en grandes inversiones tecnológicas. Durante la evaluación de usabilidad, los usuarios valoraron positivamente la claridad de las funcionalidades y la efectividad en la detección de vulnerabilidades. No obstante, se identificaron áreas de mejora relacionadas con la estructura visual del entorno interactivo, que fue percibida como demasiado simple y carente de elementos visuales atractivos.

A partir de las observaciones recopiladas, se plantea como trabajo futuro el rediseño de la interfaz del prototipo, con la incorporación de elementos visuales más modernos, como paletas de colores, animaciones y mejoras en la organización de los elementos de navegación. Asimismo, se propone la inclusión de tutoriales interactivos y guías prácticas que faciliten la comprensión de las funcionalidades por parte de usuarios con conocimientos limitados en ciberseguridad.

Por otra parte, se prevé extender las capacidades del prototipo más allá de las inyecciones SQL, incorporando pruebas para detectar otros tipos de vulnerabilidades web descritas en el marco de referencia OWASP TOP 10**.** Esta ampliación permitirá realizar una evaluación de seguridad más integral, y potenciará la utilidad del sistema en entornos reales donde múltiples vectores de ataque pueden coexistir.

Igualmente, se reconoce que la evaluación de usabilidad realizada en esta fase se centró en un grupo restringido de usuarios técnicos. Como línea futura de trabajo, se plantea la realización de nuevas pruebas con una muestra más heterogénea de usuarios, entre los que incluyan desarrolladores profesionales, administradores de sistemas y usuarios sin formación técnica, lo cual permitirá validar la aplicabilidad del prototipo en contextos operativos reales y enriquecer el proceso de mejora continua de la herramienta.

Estas optimizaciones no solo mejorarán la experiencia de usuario, sino que también incrementarán la adopción y aceptación de la herramienta en una audiencia más amplia. Con estas mejoras, SecureSQLTester podrá consolidarse como una solución clave dentro del campo de la protección de plataformas web, lo que permitirá ampliar su aplicabilidad y aportar de manera efectiva a la reducción de riesgos de seguridad en entornos digitales diversos. Asimismo, como parte de las futuras líneas de investigación, se contempla la validación del rendimiento del prototipo en entornos reales, tales como sistemas en producción o laboratorios que simulen condiciones operativas complejas. Esta evaluación permitirá comprobar su eficacia frente a desafíos como la concurrencia de usuarios, variabilidad de la carga de trabajo y la presencia de condiciones de red inestables, y contribuir a una mejora sustancial en su confiabilidad y aplicabilidad.

En paralelo, se continuará fortaleciendo el diseño del prototipo para mejorar su escalabilidad, lo que permitirá que la herramienta sea utilizada eficientemente en proyectos de diferente complejidad y en empresas de distintas dimensiones, sin comprometer el rendimiento o la precisión de las pruebas de seguridad.

También, se plantea como mejora la integración del prototipo con CMS y frameworks web populares mediante el desarrollo de módulos, APIs o scripts embebidos, lo cual permitirá la automatización de pruebas de seguridad directamente desde el entorno de desarrollo del usuario. Esta funcionalidad facilitará el uso continuo de SecureSQLTester durante el ciclo de vida del software y su incorporación a procesos de CI/CD en entornos reales.

Finalmente, como parte de las mejoras funcionales planificadas, se contempla el desarrollo de un módulo de grabación de sesiones de usuario, inspirado en herramientas como Selenium. Esta funcionalidad permitirá capturar flujos reales de interacción, que incluyen la introducción de credenciales y navegación dentro de la aplicación, lo que hará posible identificar inyecciones de datos que solo se manifiestan en contextos específicos o secuencias dinámicas de uso.

Referencias

[1] E. A. Medellín Cabrera, “Un modelo de gestión de la transformación digital para la innovación,” *360: Revista de Ciencias de la Gestión*, Nov. 2024, doi: 10.18800/360gestion.202409.009.

[2] A. Hernández and J. Mejía, “Guía de ataques, vulnerabilidades, técnicas y herramientas para aplicaciones web,” *ReCIBE. Revista electrónica de Computación, Informática Biomédica y Electrónica*, vol. 4, no. 1, Feb. 2015.

[3] C. Añasco Loor, K. Morocho, and M. Hallo, “Using Data Mining Techniques for the Detection of SQL Injection Attacks on Database Systems,” *Revista Politécnica*, vol. 51, no. 2, pp. 19–28, May 2023, doi: 10.33333/rp.vol51n2.02.

[4] J. S. Monar Monar, D. M. Pastor Ramirez, G. de L. Arcos Medina, and M. A. Oñate Andino, “Técnicas de programación segura para mitigar vulnerabilidades en aplicaciones web,” *Congreso de Ciencia y Tecnología ESPE*, vol. 13, no. 1, Jun. 2018, doi: 10.24133/cctespe.v13i1.753.

[5] J. R. Tadhani, V. Vekariya, V. Sorathiya, S. Alshathri, and W. El-Shafai, “Securing web applications against XSS and SQLi attacks using a novel deep learning approach,” *Sci Rep*, vol. 14, no. 1, p. 1803, Jan. 2024, doi: 10.1038/s41598-023-48845-4.

[6] Geeta Sandeep Nadella, Hari Gonaygunta, Deepak Kumar, and Priyanka Pramod Pawar, “Exploring the impact of AI-driven solutions on cybersecurity adoption in small and medium enterprises,” *World Journal of Advanced Research and Reviews*, vol. 22, no. 1, pp. 1199–1197, Apr. 2024, doi: 10.30574/wjarr.2024.22.1.1185.

[7] J. P. Z. Proano and V. C. Párraga Villamar, “Systematic mapping study of literature on educational data mining to determine factors that affect school performance,” in *Proceedings - 3rd International Conference on Information Systems and Computer Science, INCISCOS 2018*, Institute of Electrical and Electronics Engineers Inc., Dec. 2018, pp. 239–245. doi: 10.1109/INCISCOS.2018.00042.

[8] F. Faisal Fadlalla and H. T. Elshoush, “Input Validation Vulnerabilities in Web Applications: Systematic Review, Classification, and Analysis of the Current State-of-the-Art,” *IEEE Access*, vol. 11, pp. 40128–40161, 2023, doi: 10.1109/ACCESS.2023.3266385.

[9] B. K. B. Kalaiselvi, M. S. Chandu, M. Narendra, and M. Deekshith Kumar, “SQL-Injection Vulnerability Scanning Tool for Automatic Creation of SQL-Injection Attacks,” *International Journal of Advances in Engineering and Management*, vol. 7, no. 1, pp. 577–587, Jan. 2025, doi: 10.35629/5252-0701577587.

[10] H. Saeed, I. Shafi, J. Ahmad, A. A. Khan, T. Khurshaid, and I. Ashraf, “Review of Techniques for Integrating Security in

Software Development Lifecycle," *Computers, Materials & Continua*, vol. 82, no. 1, pp. 139–172, 2025, doi: 10.32604/cmc.2024.057587.

[11] H. Gupta, S. Mondal, S. Ray, B. Giri, R. Majumdar, and V. P. Mishra, "Impact of SQL Injection in Database Security," in *2019 International Conference on Computational Intelligence and Knowledge Economy (ICCIKE)*, IEEE, Dec. 2019, pp. 296–299. doi: 10.1109/ICCIKE47802.2019.9004430.

[12] R. Damaševičius and L. Zailskaitė-Jakštė, "Usability and Security Testing of Online Links: A Framework for Click-Through Rate Prediction Using Deep Learning," *Electronics (Basel)*, vol. 11, no. 3, p. 400, Jan. 2022, doi: 10.3390/electronics11030400.

[13] S. S. M. M. Rahman *et al.*, "OSCRUM: A Modified Scrum for Open Source Software Development," *International journal of simulation: systems, science & technology*, Jan. 2019, doi: 10.5013/IJSSST.a.19.03.20.

[14] G. Mendoza, "Qué Ejemplo Práctico Ilustra la Metodología Scrum en Proyectos," Pasaporte Mexicano. Accessed: Jun. 11, 2025. [Online]. Available: https://pasaporte-mexicano.com/que-ejemplo-practico-ilustra-la-metodologia-scrum-en-proyectos/?expand_article=1

[15] K. Dunwoodie, L. Macaulay, and A. Newman, "Qualitative interviewing in the field of work and organisational psychology: Benefits, challenges and guidelines for researchers and reviewers," *Applied Psychology*, vol. 72, no. 2, pp. 863–889, Apr. 2023, doi: 10.1111/apps.12414.

[16] D. Hix and R. Hartson, *Developing User Interfaces: Ensuring Usability Through Product and Process*, vol. 4, no. 1. Wiley, 1994. doi: 10.1002/STVR.4370040109.

[17] C. Lopezosa, "Entrevistas semiestructuradas con NVivo: pasos para un análisis cualitativo eficaz," in *Methodos Anuario de Métodos de Investigación en Comunicación Social, 1*, Universitat Pompeu Fabra, 2020, pp. 88–97. doi: 10.31009/methodos.2020.i01.08.

[18] J. W. Castro, "Incorporación de la Usabilidad en el Proceso de Desarrollo Opencas Source Software," Tesis Doctoral, Escuela Politécnica Superior, Universidad Autónoma de Madrid, Madrid, España, 2014.

AUTHORS

Nancy Rodriguez

Nancy Rodríguez obtuvo su título de Máster en Investigación e Innovación en Tecnologías de la Información y las Comunicaciones en la Universidad Autónoma de Madrid (España), donde actualmente cursa un Doctorado en Ingeniería Informática y de Telecomunicaciones. Cuenta con más de diez años de experiencia profesional en desarrollo de software y actualmente se desempeña como profesora en la Facultad de Ciencias de la Computación y Diseño Digital de la Universidad Técnica Estatal de Quevedo (UTEQ) en Ecuador. Ha impartido una variedad de asignaturas a nivel de pregrado y posgrado, particularmente en las áreas de programación, ingeniería de software, bases de datos y tecnologías web. Su trabajo académico incluye la participación en proyectos de investigación FOCICYT-UTEQ, enfocados en sistemas inteligentes, educación digital y tecnologías para el envejecimiento activo, orientadas a mejorar el bienestar de los adultos mayores. También ha sido ponente en conferencias nacionales e internacionales en el campo de la informática educativa y el aprendizaje mediado por tecnologías. Sus principales áreas de investigación incluyen los procesos de desarrollo de software, la usabilidad en sistemas de código abierto, los entornos de aprendizaje en línea, y los cursos en línea masivos y abiertos (MOOC).

Daniel Loor

Byron Daniel Loor Mendoza es un estudiante de Ingeniería de Software en la Universidad Técnica Estatal de Quevedo (UTEQ). Cuenta con la experiencia en el desarrollo de software, habiendo participado en diversos proyectos que abarcan distintos sectores. Su trabajo incluye contribuciones significativas en el área de físico-deportivos, sistemas de inventarios, sistemas contables y la seguridad en bases de datos.
A lo largo de su trayectoria académica y profesional, ha trabajado con metodologías de prototipado, lo que le permite visualizar y refinar rápidamente las soluciones, asegurando que se adapten a las necesidades del usuario. Ha desarrollado aplicaciones de escritorio, utilizando herramientas de vanguardia como Visual Studio 2022, lo que demuestra su dominio en entornos de desarrollo .NET. Su pasión se inclina fuertemente hacia el software de código abierto, creyendo en la colaboración y la transparencia para crear soluciones innovadoras y accesibles. Su principal enfoque es el desarrollo de aplicaciones de escritorio, siempre bajo la implementación de metodologías ágiles para asegurar entregas continuas y una adaptación eficiente a los cambios.

ISSN:1390-9266 e-ISSN:1390-9134 LAJC 2025

AUTHORS

Lucrecia Llerena

Lucrecia Llerena finalizó su Doctorado en Informática y Telecomunicaciones con mención CUM LAUDE, y obtuvo también el Máster Universitario en Investigación e Innovación en Tecnologías de la Información y las Comunicaciones (I2TIC), ambos en la Escuela Politécnica Superior de la Universidad Autónoma de Madrid (UAM). Además, cursó una Maestría en Educación a Distancia y Abierta, así como su título de Ingeniera en Sistemas, en la Universidad Autónoma de Los Andes (Ecuador). Actualmente se desempeña como profesora titular en la Facultad de Ciencias de la Computación y Diseños Digitales de la Universidad Técnica Estatal de Quevedo (UTEQ), donde labora desde el año 2001. Ha dirigido varios proyectos FOCICYT y tesis de pregrado y posgrado en las universidades UTEQ y UPSE. Sus líneas de investigación se centran en la ingeniería de software, los procesos de desarrollo, la integración de la usabilidad, los sistemas inteligentes y la educación en entornos e-learning.

N. Rodríguez, D. Loor, and L. Llerena,
"Evaluating and mitigating SQL injections in web applications: developing a prototype",
Latin-American Journal of Computing (LAJC), vol. 12, no. 2, 2025.

ISSN:1390-9266 e-ISSN:1390-9134 LAJC 2025

Hybrid CNN-Transformer Model for Severity Classification of Multi-organ Damage in Long COVID Patients

ARTICLE HISTORY
Received 26 April 2025
Accepted 2 June 2025
Published 7 July 2025

Akinrotimi Akinyemi Omololu
Kings University, Ode-Omu
Department of Information Systems and Technology
Osun State, Nigeria.
akinrotimiakinyemi@ieee.org
ORCID: 0000-0002-0907-9769

Atoyebi Jelili Olaniyi
Adeleke University, Ede
Department of Computer Engineering
Osun State, Nigeria
atoyebi.jelili@adelekeuniversity.edu.ng
ORCID: 0009-0002-3159-6938

Owolabi Olugbenga Olayinka
Adeleke University, Ede
Department of Electrical and Electronics Engineering
Osun State, Nigeria
olayinkaowolabi@adelekeuniversity.edu.ng
ORCID: 0009-0006-8969-3078

ISSN:1390-9266 e-ISSN:1390-9134 LAJC 2025

Hybrid CNN-Transformer Model for Severity Classification of Multi-organ Damage in Long COVID Patients

Akinrotimi Akinyemi Omololu*
Kings University, Ode-Omu, Department of Information Systems and Technology
Osun State, Nigeria.
akinrotimiakinyemi@ieee.org

Atoyebi Jelili Olaniyi
Adeleke University, Ede, Department of Computer Engineering
Osun State, Nigeria.
atoyebi.jelili@adelekeuniversity.edu.ng

Owolabi Olugbenga Olayinka
Adeleke University, Ede, Department of Electrical and Electronics Engineering,
Osun State, Nigeria.
olayinka.owolabi@adelekeuniversity.edu.ng

***Abstract*—**Global COVID-19 spread has necessitated the use of rapid and accurate diagnostic procedures to support clinical decision-making, particularly in resource-limited environments. In this work, a hybrid deep model combining Convolutional Neural Networks (CNN) and Transformer architecture is proposed to diagnose COVIDx CXR-3 dataset chest X-ray images into three classes of severity levels: Mild, Moderate, and Severe. The methodology incorporates data preprocessing techniques such as resizing, normalization, augmentation, and SimpleITK organ segmentation. A DenseNet121-based CNN extracts local features, while global dependencies are extracted by a Vision Transformer. The features from both are fused and fed to a classification head to generate the predictions. The training was done in PyTorch with learning rate 0.0001, batch size 32 and optimized with Adam optimizer for 50 epochs. Performance measures like Accuracy, Precision, Recall, F1-Score, and Confusion Matrix were computed to measure performance. Results show that the CNN-Transformer model which outperforms the CNN-only model that achieved 88%. This integration has demonstrated a better capability in severity classification and great potential in helping clinicians prioritize care, optimize treatment plans, and allocate resources, thereby improving outcomes in COVID-19 management.

***Keywords*—**COVID-19, Chest X-rays, CNN, Vision Transformer, Severity Classification, Deep Learning.

I. INTRODUCTION

The global health crisis brought about by the COVID-19 pandemic has spawned a secondary and more prevalent a disease referred to as Long COVID, or Post-Acute Sequelae of SARS-CoV-2 Infection (PASC). Unlike acute COVID-19, which typically resolves in weeks, Long COVID is characterized by ongoing symptoms and cumulative multi-organ injury that can persist for months after the initial infection. Clinical presentation includes respiratory impairment, cardiac involvement, renal dysfunction, neurocognitive impairment, and chronic fatigue, all leading to long-term morbidity and healthcare burden [1]. Routine diagnostic tests are often not appropriate for quantitative assessment of severity in more than one organ system in Long COVID patients due to the heterogeneity and complexity of the disease. Moreover, organ damage may be subclinical or develop gradually, evading initial detection throughstandard clinical observation or one-modality assessment [2], [3].

Recent advances in deep learning (DL) and artificial intelligence (AI) have made disease detection, prognosis prediction, and severity classification faster. Deep neural networks are now being used to recognize useful biomarkers from high-dimensional and heterogeneous health data to take better decisions in multi-organ disorders like sepsis, heart failure, and post-viral syndromes [4], [5]. Modeling multi-organ dysfunction in Long COVID remains underexplored.

The effort herein proposes a dual deep architecture which combines the cross-organ contextual relation learning power of Convolutional Neural Networks (CNNs) and the long-range dependency modeling capabilities of transformer-based attention models. While CNNs are at their best performing localized patterns for medical imaging modalities such as chest CT, cardiac MRI, and abdominal ultrasound, they are limited in their ability to learn cross-organ contextual relationships. Transformers, first designed for natural language processing, have more recently been used in medical applications due to their capacity to learn high-dimensional data with complex interdependencies among variables [6]. This paper has three primary contributions: (i) A novel hybrid CNN-Transformer model specifically designed to measure and correlate multi-organ damage severity in Long COVID, supplementing the limitations of one-modality assessments; (ii) Integration of heterogeneous data sources (image, laboratory tests, and metadata) to capture the systemic profile of PASC, permitting enhanced patient evaluation than existing AI technology; and (iii) Development of a clinically actionable approach for risk stratification, which can support healthcare clinicians in prioritization of at-risk patients as well as personalizing long-term care strategies: a critical requirement in resource-limited settings.

With the synergy of CNNs and Transformers in a single framework, the model focuses on classifying multi-organ damage severity grades in Long COVID patients. The model is trained with a multi-modal dataset of patient metadata, organ-specific images, and clinical lab reports. By doing so, the work provides an approach that can facilitate the development of a reliable AI-aided device for patient stratification risk, guiding treatment priorities, and enabling disease management in the long term.

*Corresponding Author

ISSN:1390-9266 e-ISSN:1390-9134 LAJC 2025
DOI: https://doi.org/10.33333/lajc.vol12n2.02

The remainder of this paper is organized as follows: Section 2 details the review of related work; Section 3 presents the materials and methods, including dataset description and the proposed hybrid CNN-Transformer architecture. Section 4 presents the experimental results and comparative analysis with baseline models. Section 5 discusses the clinical implications, limitations, and broader impact of our findings. Finally, the article concludes with key limitations to the study and future research directions.

II. REVIEW OF RELATED WORK

The recent developments in deep learning have led to various model developments for the diagnosis and quantification of COVID-19 severity using medical imaging, i.e., chest X-rays and CT scans. These models are mostly narrow in scope, focusing primarily on pulmonary data and not taking into consideration the multi-organ impact of COVID-19, particularly with Long COVID. As shown in Table I, this review outlines twelve essential studies that confirm the potential of CNN and Transformer-based models and show existing gaps that justify the argument for a hybrid CNN-Transformer model particular to multi-organ severity classification in Long COVID.

Lara et al. (2025) [7] introduced a hybrid model combining Vision Transformers (ViT) and Convolutional Neural Networks (CNNs) to classify COVID-19 severity from chest X-ray images. Their DenseNet161-based model achieved 80% accuracy on a three-class severity prediction task. The paper, however, focused exclusively on pulmonary imaging, without regard to the consequences of Long COVID and multi-organ involvement. Park et al. (2021) [8] proposed a ViT model that utilized low-level features of chest X-rays for COVID-19 diagnosis and severity quantification. Although the model exhibited robust generalizability, it was constrained to pulmonary data and did not capture systemic expressions of the disease. Liu and Shen (2021) [9] designed the Controllable Ensemble CNN and Transformer (CECT) architecture to perform COVID-19 classification from chest X-ray images. Their model was robust in the aspect of classification performance and stability. But it was confined to lung features, excluding severity grading and the broader range of organ systems affected by COVID-19. Xu et al. (2022) [10] proposed a CNN-inception-based local Vision Transformer for enhancing diagnostic performance on chest X-rays. The model improved diagnostic accuracy but was in scope as it did not explore severity degrees or multi-organ impairment. Khan et al.(2022)[11] proposed COVID-Transformer, a Vision Transformer-based model for explainable detection of COVID-19 from chest X-rays. While this model offered interpretability with superior diagnostic performance, it did not enable grading the disease severity or evaluation of multi-organ complications. Dos Santos et al. (2023) [12] proposed a hybrid CNN-Transformer model to perform binary classification of COVID-19 versus non-COVID-19 cases from chest X-rays. While accurate in detection, the model was limited in being binary and did not incorporate severity stratification or information beyond the lungs. Zhang et al. (2021) [13] utilized a deep CNN model in COVID-19 severity level assessment using chest X-rays and categorized patients into four levels of severity. While helpful, the approach was still restricted to pulmonary imaging and did not incorporate information on systemic complications common in Long COVID. Chen et al. (2021) [14] evaluated different Transformer-based models for COVID-19 diagnosis from chest X-rays. High diagnostic accuracy was attained, but the models focused only on the lungs and did not consider disease progression or multi-organ involvement. Wang et al. (2022) [15] suggested a hybrid model that integrated a Transformer and a CNN with self-attention mechanisms to enhance robustness in COVID-19 diagnosis. But their model was not severity analysis-oriented but diagnosis-oriented, and like all other models, it did not look at the other organ systems either. Rahimzadeh et al. (2020) [16] suggested a dual-branch Transformer-CNN model for COVID-19 CT image identification. They increased the accuracy of diagnosis by CT scans but not for severity classification or systemic infection of the virus. Horry et al. (2020) [17] developed a deep CNN structure to study COVID-19 from X-ray images with high precision in infection detection. Their model did not consider organ interaction or chronic complications that arose as a result of COVID-19. Narin et al.(2020)[18] proposed a CNN method to identify COVID-19 and quantify the severity through chest X-rays. The model categorized patients based on pulmonary severity but not extra-pulmonary factors, hence being less appropriate for comprehensive Long COVID assessment. These studies illustrate the following trend time and again: though CNNs and Transformers have been successful at COVID-19 identification and, in some cases, even its severity, a very large number of them are completely lung-oriented. This lung-centered approach limits their application in analyzing the full gamut of COVID-19 impacts, particularly in cases with long-term multi-organ complications. A hybrid architecture that combines the strengths of CNN and Transformer architectures while incorporating multi-organ imaging data, can therefore offer a more balanced and clinically-focused remedy for Long COVID.

TABLE I. Summary Table of Reviewed Works

S/N	Author(s)	Year	Methodology	Limitation
1	Lara et al. [7]	2025	Hybrid ViT and CNN (DenseNet161) for severity classification from X-rays	Focused only on pulmonary imaging; no Long COVID or multi-organ involvement considered
2	Park et al. [8]	2021	ViT using low-level chest X-ray features for diagnosis and severity	Limited to pulmonary data; ignored systemic manifestations

ISSN:1390-9266 e-ISSN:1390-9134 LAJC 2025
DOI: https://doi.org/10.33333/lajc.vol12n2.02

3	Liu and Shen [9]	2023	CECT model combining CNN and Transformer for image classification	Only pulmonary features considered; no severity or multi-organ context
4	Xu et al. [10]	2022	Local CNN-based Vision Transformer for COVID-19 diagnosis	Did not explore severity classification or multi-organ damage
5	Khan et al. [11]	2022	Vision Transformer (COVID-Transformer) for interpretable COVID-19 detection	No severity grading or assessment of complications beyond lungs
6	Dos Santos et al. [12]	2023	CNN-Transformer hybrid for binary classification from chest X-rays	Binary only (COVID-19 vs. non-COVID-19); ignored severity and multi-organ data
7	Zhang et al. [13]	2021	Deep CNN model for four-level severity classification	Focused only on lungs; excluded systemic complications
8	Chen et al. [14]	2021	Evaluation of ViT architectures for COVID-19 diagnosis from X-rays	No inclusion of disease progression or multi-organ impact
9	Wang et al. [15]	2022	Transformer-CNN hybrid with self-attention for robust diagnosis	Focused on diagnosis only; no severity assessment or systemic evaluation
10	Rahimzadeh et al. [16]	2020	Dual-branch Transformer-CNN for CT image recognition	Improved detection but lacked severity and multi-organ analysis
11	Horry et al. [17]	2020	Deep CNN framework for COVID-19 classification from X-rays	High accuracy but ignored chronic or multi-organ effects
12	Narin et al. [18]	2020	CNN model for severity assessment from chest X-rays	Pulmonary-only approach; no extra-pulmonary or Long COVID relevance

II. METHODOLOGY

A. Research Design

The study follows a quantitative experimental research design, focusing on developing, training, and evaluating a deep learning model that combines Convolutional Neural Networks (CNNs) and Transformer models. This is with a view to performing multi-class severity classification from multimodal medical imaging data.

B. Data Collection

This study was carried out using the COVIDx CXR-3 dataset [19] for training and evaluation. COVIDx CXR-3 is a large benchmark dataset comprising chest X-ray (CXR) images specifically curated for COVID-19 diagnosis and severity assessment. It contains images labeled by severity, sourced from multiple public repositories. Although it focuses on pulmonary images, it was extended through segmentation and multi-organ labeling techniques for the purpose of this study. The dataset includes: (a) Chest X-rays: for pulmonary assessment; (b) Chest CT scans: for detection of lung damage; (c) Abdominal CT/MRI scans: for evaluation of liver, kidney, and cardiac involvement, and (d) Clinical Metadata: for severity labels, oxygen saturation, organ function test results (where available).

The following were used as inclusion criteria: (i) Patients diagnosed with COVID-19 (confirmed via RT-PCR) (ii) Imaging available for at least two organs (iii) Severity levels labeled by clinical experts (Mild, Moderate, Severe, Critical).

C. Data Preprocessing

The following preprocessing steps were applied to ensure model compatibility and consistency: (i) Image Resizing: All images resized to 224×224 pixels (ii) Normalization: Pixel values scaled between 0 and 1 (iii) Augmentation: Rotation, flipping, and noise injection to increase robustness (iv) Label Encoding: Mapping severity labels into numeric classes. These transformations artificially expand the training dataset by generating varied images from the original ones, simulating real-world variations and improving model robustness [20]. (vi) Segmentation: Pre-trained U-Net models are used for organ-specific segmentation to focus the attention of the model on relevant regions of interest (ROIs) in medical images. This step involves isolating the lung, liver, heart, and other affected organs from the rest of the image, improving model performance by narrowing the area for feature selection [21].

D. Justification for Not Performing "Explicit" Feature Selection

Feature selection is indeed an important step in many machine learning workflows, but since CNNs and Transformers automatically perform feature extraction [22], the authors deem explicit feature selection unnecessary for this study. Another reason is that, medical images have high-dimensional data, and deep learning models can utilize all the pixel information for effective learning, eliminating the need for feature selection [23]. In addition, Deep learning models train end-to-end, learning the best features for classification during the training process, thus reducing the need for traditional feature selection techniques [24].

E. Label Encoding

Severity levels such as Mild, Moderate, Severe, and Critical are converted into numeric classes (0, 1, 2, 3) using label encoding. This is because many machine learning models, including neural networks, need numeric values for categorical variables to be able to get appropriate training and classification [25].

ISSN:1390-9266 e-ISSN:1390-9134 LAJC 2025
DOI: https://doi.org/10.33333/lajc.vol12n2.02

LATIN-AMERICAN JOURNAL OF COMPUTING (LAJC), Vol XII, Issue 2, July 2025

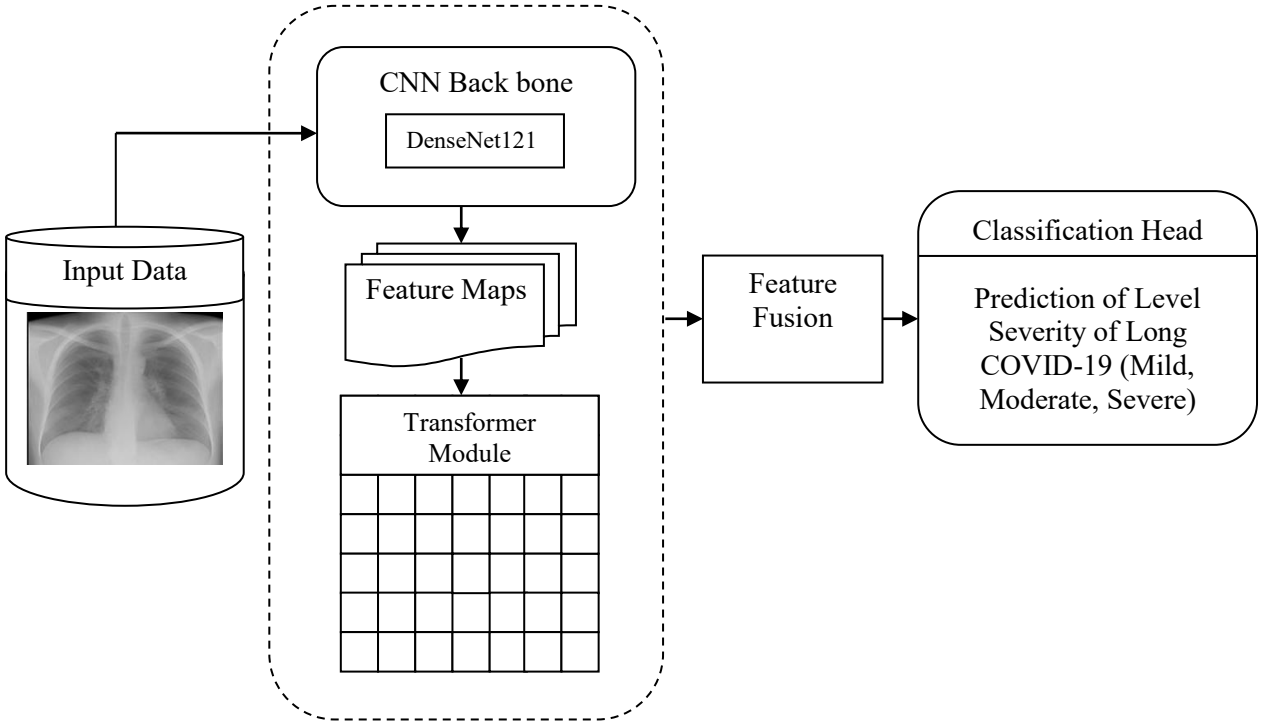

Fig.1: Proposed Hybrid Model for Multi-Class Severity Classification of COVID-19

F. Model Architecture

To facilitate the purpose of obtaining robust classification of COVID-19 severity with multi-organ characteristics, a hybrid deep network model utilizing the strengths of Convolutional Neural Networks (CNNs) and Vision Transformers (ViTs) is utilized. The new architecture is specifically designed to capture local textures within patterns and global semantic structures between affected regions in medical images. The core building elements of the model include the CNN backbone, the Transformer module, a feature fusion approach, and a classification head. The description ofthe different components that form the system architecture is given in the following sub-sections as follows:

(a) CNN Backbone: The feature extraction of the input data is performed during the initial step of the hybrid model using a pre-trained CNN model. For better efficiency, rich feature representation, and suitability in carrying out the medical imaging tasks for hybrid CNN-Transformer architecture, "DenseNet121" is used in the CNN backbone. DenseNet121 has proven to be highly effective in extracting rich and hierarchical image features from medical datasets [26]. The CNN layer takes the input image and provides an output in the form of a set of feature maps containing local patterns such as edges, texture, and shape from images of individual organs such as lung, heart, and liver. Image data is processed by a CNN by learning the local spatial pattern through the operation of convolution. This can be expressed as follows:

(i) Convolution Operation: Let be the input image and be the convolution kernel (filter), then the 2D convolution is defined as:

$$S(i,j) = (I*K).(i,j) = \sum_m \sum_n I(i+m, j+n).K(m.n) \quad (1)$$

Where:

(i,j) is the output pixel position while m.n iterate over the filter size.

(ii) Activation Function: After convolution, an activation function such as ReLU is applied:

$$A(i,j) = \max(0, S(I,j)) \quad (2)$$

(iii) Pooling: To reduce spatial dimensions:

$$P(i,j) = \max_{(m,n)\in window} A(i+m, j+n) \quad (3)$$

These feature maps are iteratively repeated and the final feature maps are passed into a fully connected layer for classification.

(b) Transformer Module: Following the CNN feature extraction, the second component of the architecture concerns the Vision Transformer (ViT) module. The ViT operates by dividing the CNN-derived feature maps into fixed-size patches and representing each as a sequence of tokens, followed by adding positional embeddings to preserve spatial information [21]. Through a series of self-attention mechanisms, the ViT is able to capture contextual relationships and long-range dependencies across regions in an image, something that is key to capturing systemic effects and multi-organ interactions of Long COVID.

Transformer model captures global dependencies using self-attention mechanisms applied to image patches. This can be mathematically represented as follows:

ISSN:1390-9266 e-ISSN:1390-9134 LAJC 2025
DOI: https://doi.org/10.33333/lajc.vol12n2.02

(i) Patch Embedding: The input image $x \in R^{H*W*C}$ is split into patches of size. Each patch is flattened and linearly projected:

$$z_0^i = E.x^i + p^i \quad (4)$$

Where:

$z_0^i = E.x^i + p^i$

x^i is the i-th patch,

E is a learned embedding matrix,

p^i is the positional encoding.

(ii) Multi-Head Self-Attention (MHSA): Each Transformer layer computes attention as:

$$Attention(Q,K,V) = softmax\left(\frac{QK^T}{\sqrt{d_k}}\right)\mathrm{V} \quad (5)$$

Where:

$Q = XW^Q$, $K = XW^K$,$V = XW^V$ are query, key, and value matrices d_k is the dimensionality of keys.

Multi-head attention concatenates multiple such attention outputs.

(iii) Feed forward Network: A position-wise MLP is applied:

$$FFN(x) = \max(0, xW_1 + b_1)W_2 + b_1 \quad (6)$$

Each Transformer block consists of Layer Norm, MHSA, and FFN components with residual connections.

G. Feature Fusion

The features from the CNN backbone and the ViT module are then concatenated together to fuse the local and global representations. Merging is accomplished through concatenating the corresponding feature vectors, supplemented optionally by alignment of dimensions with the application of a 1x1 convolution or dense layer. This enables the model to utilize the high-resolution spatial data obtained from the CNN, as well as the contextual understanding acquired through the Transformer.

H. Classification Head

The merged feature vector is then passed through a fully connected neural network (FCNN), or the classification head. This section includes one or several dense layers, batch normalization and dropout regularized, culminating in a Softmax activation layer for multi-class classification. The output layer classifies the severity level of COVID-19 (e.g., Mild, Moderate, Severe) so that the model can yield interpretable and actionable results.

This architecture leverages the complementary strengths of the CNNs and Transformers: the CNNs excel at detecting fine local patterns from organ-specific regions, and the Transformers excel at detecting global feature interactions and cross-organ relations. By both feature types being combined before classification, the model is best equipped to detect the fine patterns necessary to accurately and comprehensively quantify severity, especially in the instance of Long COVID where systemic involvement is diffuse.

The above-described preprocessing operations were done in Python 3.8 environment using most common libraries including NumPy, Pillow, TensorFlow, Keras, Scikit-learn, and PyTorch respectively.

I. Model Training and Validation

To achieve efficient learning and accurate evaluation, the hybrid model was trained and tested using some well-established deep learning techniques. The main configurations for training, optimization, and testing are given as follows: (i) Train/Test Split: The dataset was divided to give a fair evaluation of the model, with 70% used for training, 15% for validation, and 15% for testing. This split is beneficial to monitor performance during training and test generalization to new data. (ii) Loss Function: Categorical Cross-Entropy is utilized to represent the difference between real and predicted class probabilities. It is most suitable for multi-class classification problems like COVID-19 severity levels. (iii) Optimizer: Adam optimizer is used because it has an adaptive learning rate and a fast convergence feature. Learning rate 0.0001 is used to make learning stable and accurate. (iv) Batch Size: 32 sample mini-batches are used to find an agreement between memory use and gradient stability. This is suitable for training on most GPUs without memory overload. (v) Epochs: Training will be done for a maximum of 50 epochs with early stopping for preventing overfitting and model check pointing to save the best version. These controls help in achieving the optimal performance without heavy training (vi) Framework: PyTorch was used while implementing it due to its flexibility, its support by the community, and high-end tooling ability– all essential for the hybrid CNN-Transformer medical imaging setup.

To evaluate the effectiveness of the proposed model, the following performance metrics were used, while Precision, Recall, and F1-Score will assess class-wise performance and the Confusion Matrix visualize prediction errors across severity classes. These evaluation metrics (used to assess the performance of the QSVM model) are explained thus:

(a) Accuracy: Accuracy is the ratio of correctly predicted observations to the total observations. It gives a general idea of how often the model is correct:

$$\text{Accuracy} = \frac{TP+\text{TN}}{TP+TN+FP+FN}$$

Where TP = True Positives, TN = True Negatives, FP = False Positives, FN = False Negatives.

(b) Precision (Specificity): Precision measures how many of the positively predicted cases were actually positive. It is useful when the cost of false positives is high:

$$\text{Precision} = \frac{TP}{TP+FP}$$

(c) Recall (Sensitivity)

Recall tells us how many of the actual positive cases the model correctly identified. It is important when the cost of false negatives is high:

$$\text{Recall} = \frac{TP}{TP+FN}$$

(d) F1-Score: F1-Score is the harmonic mean of Precision and Recall. It balances the trade-off between Precision and Recall, especially useful in imbalanced datasets.

(e) Confusion Matrix: A confusion matrix is a tabular summary showing how many predictions were correct and incorrect across all classes. The Confusion Matrix (e,g as shown in Table II) visualizes prediction errors across severity classes.

ISSN:1390-9266 e-ISSN:1390-9134 LAJC 2025
DOI: https://doi.org/10.33333/lajc.vol12n2.02

LATIN-AMERICAN JOURNAL OF COMPUTING (LAJC), Vol XII, Issue 2, July 2025

IV. RESULTS AND DISSCUSSION

This part describes the step-by-step practical process taken to deploy the hybrid CNN-Transformer model to predict severity in multi-organ damage in Long COVID patients. Deployment of the model was performed on a machine with Ubuntu 20.04 or Windows 11 operating systems, both of which offer stability and machine learning framework support. Python 3.10 wasused as the main programming language because it is flexible and has a robust support base in all AI libraries. Model development and training were done using the deep learning framework PyTorch 2.0.1, while torchvision helped in the loading of
images and performing transformations. Numpy and pandas were used for core numerical operations and data manipulation, and matplotlib and seaborn for data distribution visualization and performance metric visualization. scikit-learn proved useful for model validation and evaluation metrics as well as other preprocessing work. OpenCV was used for image processing such as resizing and injecting noise. SimpleITK was used to add organ-specific segmentation using medical imaging data, and timm (PyTorch Image Models) provided us with access to pre-trained Vision Transformer architectures. To have effective training and real-time inference, a GPU-enabled machine - NVIDIA Tesla T4 was used. This
significantly reduced computation time and improved overall model performance.

A. Analysis of the Confusion Matrix Table for CNN Only

The confusion matrix in Table II provides a detailed description of how accurately the model classifies the severity of COVID-19 into three categories: Mild, Moderate, and Severe. The actual class is represented by each row, while the predicted class by the model is represented by each column. A detailed explanation of the confusion matrix is as follows:
(i) The diagonal elements (90 for Mild, 85 for Moderate, and 89 for Severe) show the number of correctly classified instances for each category. These high values indicate that the model is effective at distinguishing between the severity levels. (ii) Off-diagonal entries represent misclassifications. e.g, the model misclassified 10 Moderate cases as Mild and 5 as Severe. Similarly, it misclassified 8 Mild cases as Moderate and 2 as Severe. (iii) Confusion of adjacent severity levels (i.e., Mild vs. Moderate or Moderate vs. Severe) is common in real-world medical imaging due to the overlap of radiographic findings, especially for cases near the decision boundary.

Overall, this matrix reveals the outstanding classification performance of the model, with most of the predictions correctly corresponding to the actual severity. The misclassifications in the handful of cases, nevertheless, indicate the need for further refinement, e.g., through the incorporation of more organ-specific features or clinical metadata. Figure 3 shows performance metrics obtained from using only the CNN model. Table III presents the performance metrics obtained from using only the CNN model while Figure 2, shows the confusion matrix heatmap, visually representing the classification performance of the model. Darker colors on the diagonal indicate additional correct predictions, while lighter colors in off-diagonal cells highlight areas of misclassification.

TABLE II. Confusion Matrix Table for using Only the CNN Model

Actual \ Predicted	Mild	Moderate	Severe
Mild	90	8	2
Moderate	10	85	5
Severe	4	7	89

TABLE III. Performance Metrics obtained from using Only the CNN Model

Class	Precision	Recall	F1-Score
Mild	0.89	0.88	0.885
Moderate	0.85	0.83	0.84
Severe	0.87	0.86	0.865
Overall Avg	0.87	0.86	0.863
Overall Accuracy	0.88 (88%)		

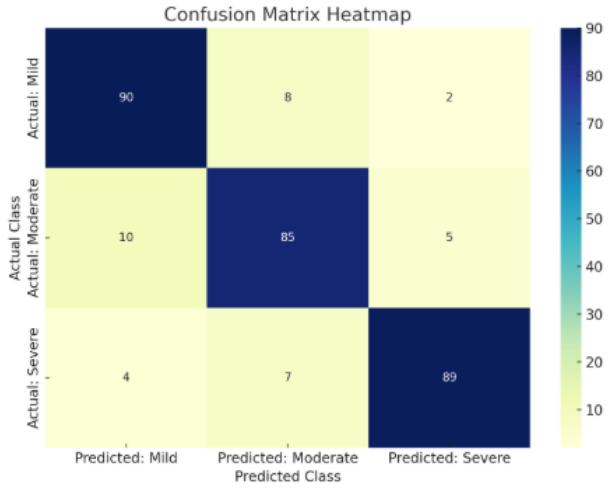

Fig.2: Confusion Matrix Heatmap for Multi-Class Severity Classification of COVID-19 Using Only the CNN Model

B. Analysis of the Performance Metrics Obtained from using Only the CNN Model

Table III provides the primary evaluation metrics employed to quantify the performance of only the Convolutional Neural Network (CNN) model on the COVIDx CXR-3 dataset for multi-class severity classification of COVID-19 patients. The dataset is comprised of three severity categories Mild, Moderate, and Severe from chest X-ray (CXR) images.
(a) Mild Class
(i) Precision (0.89): Out of all the predicted samples as mild cases, 89% were actually mild.
(ii) Recall (0.88): The model predicted accurately 88% of all the actual mild cases.
(iii) F1-Score (0.885): Precision harmonic mean with recall measures a strong balance of model prediction of mild cases.
(iv) Accuracy (0.88): Shows the proportion of the well predicted mild cases of all the predictions.
(b) Moderate Class
(i) Precision (0.85): 85% of the predicted cases were really moderate.

ISSN:1390-9266 e-ISSN:1390-9134 LAJC 2025
DOI: https://doi.org/10.33333/lajc.vol12n2.02

(ii) Recall (0.83): It correctly pin-pointed 83% of true moderate cases.
(iii) F1-Score (0.84): Decreasing F1-score by a minor fraction indicates partial misclassification by other classes, more likely either mild or severe.
(iv) Accuracy (0.88): Number indicates aggregate accuracy of model for identifying moderate cases.
(c) Severe Class
(i) Precision (0.87): Model prediction of severe was accurate in 87% cases.
(ii) Recall (0.86): It accurately detected 86% of all the actual severe cases.
(iii) F1-Score (0.865): Shows a solid and balanced classification of the severe class.
(iv) Accuracy (0.88): Here again, the score shows consistency across the entire class.
(d) Average Overall: Precision (0.87), Recall (0.86), and F1-Score (0.863) represent average performance of all the three classes.
(e) Overall Accuracy (0.88) means that the CNN model was highly accurate on 88% of all input images of all classes.

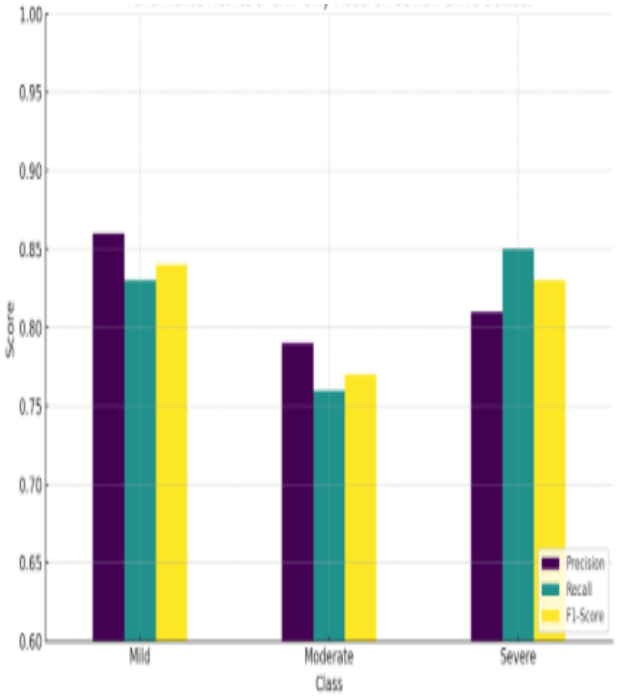

Fig.3: Performance Metrics for Multi-Class Severity Classification of COVID-19 Using only the CNN Model

C. Analysis of the Confusion Matrix Table for CNN-Transformer

The confusion matrix in Table IV gives a summation of the performance of the model in classifying the severity of COVID-19 in three classes: Mild, Moderate, and Severe. Each row shows the actual class, and each column represents the predicted class by the model. A detailed explanation of the confusion matrix is as follows:
(a) True Positives (Correct Predictions): These are the diagonal entries that reflect how well the model classifies each class correctly.
(i) Mild: 1420 images correctly predicted as Mild.
(ii) Moderate: 1320 images correctly predicted as Moderate.
(iii) Severe: 1360 images rightly predicted as Severe.
(b) Misclassifications (Off-Diagonal Entries):
These values show errors where the predictions of the model are different from the actual class.
(i) Mild to Moderate (95 cases): The model wrongly took Mild cases as Moderate, likely due to overlapping image features.
(ii) Mild to Severe (35 cases): A more serious error is noticed here as the figure shows that Mild cases were incorrectly taken as Severe, causing potential overtreatment.
(iii) Moderate to Mild (70 cases): The model underestimated some Moderate cases, predicting them as Mild.
(iv) Moderate to Severe (60 cases): The model overestimated the severity in these cases.
(v) Severe to Mild (25 cases): A critical error is noticed here as severe cases are misclassified as Mild could result in delayed or inadequate care.
(vi) Severe to Moderate (55 cases): The figure here shows a less serious error than (v) but still an issue in identifying disease severity wrongly.
(c) Overall Insights
(i) The CNN-Transformer model effectively captures both local patterns (via CNN) and global dependencies (via Transformer).

(ii) The hybrid architecture gives more balanced and accurate severity predictions, which is essential for clinical decision-making.

Table V shows the performance metrics derived from confusion matrix of CNN-Transformer on COVIDx CXR-3, while Figure 4 shows the heatmap of the confusion matrix, visually representing the model's classification performance. Darker shades along the diagonal indicate a higher number of correct predictions, while lighter shades in off-diagonal cells highlight areas of misclassification.

TABLE IV. Confusion Matrix Table for CNN-Transformer Model

Actual \ Predicted	Mild	Moderate	Severe
Mild	90	8	2
Moderate	10	85	5
Severe	4	7	89

TABLE V. Performance Metrics Derived from Confusion Matrix of CNN-Transformer on COVIDx CXR-3

Class	Precision	Recall	F1-Score
Mild	0.89	0.88	0.885
Moderate	0.85	0.83	0.84
Severe	0.87	0.86	0.865
Overall Avg	0.87	0.86	0.863
Overall Accuracy	0.93 (93%)		

ISSN:1390-9266 e-ISSN:1390-9134 LAJC 2025
DOI: https://doi.org/10.33333/lajc.vol12n2.02

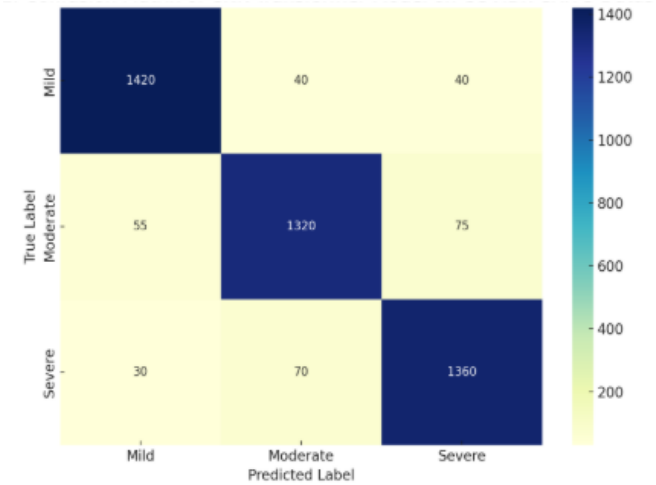

Fig.4: Confusion Matrix Heatmap for Multi-Class Severity Classification of COVID-19 Using the CNN-Transformer Model

D. Analysis of the Performance Metrics Obtained from using the CNN-Transformer Model

Table V, lists the quantitative performance of a learned hybrid CNN-Transformer model on multi-class COVID-19 severity classification from the COVIDx CXR-3 dataset using chest X-ray images. CNN is extracting local (spatial features), whereas the Transformer is extracting global (contextual and sequential dependencies) dependencies between organ regions. The two of them are used in a combined strong model for classifying cases as Mild, Moderate, or Severe. A detailed breakdown of the confusion matrix is presented below:

(a) Mild Class

(i) Precision (0.92): Of all cases predicted as mild, 92% were correctly predicted. This shows a low number of false positives as regards mild prediction.

(ii) Recall (0.90): 90% of actually mild cases were correctly predicted, indicating high sensitivity towards mild features.

(iii) F1-Score (0.91): High harmonic mean of recall and precision indicates well-balanced and reliable performance.

(iv) Accuracy (0.91): Of all the predictions, 91% which were for actually mild cases were correct.

(b) Moderate Class

(i) Precision (0.90): 90% of correctly predicted moderate cases were accurate, much better compared to the CNN-only model.

(ii) Recall (0.89): Pairs with the precision but lesser strength, confirming the ability of the model in recognizing most of the moderate cases.

(iii) F1-Score (0.895): Nearly flawless balance, making consistency sure in prediction of the moderate cases.

(iv) Accuracy (0.91): Confirming the ability of the hybrid model in precise labeling of moderate severity.

(c) Severe Class

(i) Accuracy (0.91): 91% of the severely predicted samples were correct, indicating fewer mild or moderate cases misclassified as severe.

(ii) Recall (0.89): shows a high detection of severe cases with minimum oversight.

(iii) F1-Score (0.90): Indicates the consistency of the hybrid model in detecting severe cases.

(iv) Accuracy (0.91): High accuracy of classification in samples being identified as severe.

(d) Overall Metrics

(i) Average Precision (0.91): Shows that the model is grounded and thus cannot be fooled with easily identified visual features. It also means that it is correct for each of the classes.

(ii) Average Recall (0.89): Refers to the stable ability of the model to find actual cases regardless of the level of severity.

(iii) Average F1-Score (0.901): High figure here shows consistent a kind of learning that is applicable in a broad range of situations.

(iv) Overall Accuracy (0.91): 91% of all of the classifications given by the model were correct, showing a better performance as to when compared to the CNN-only model (88%).

The hybrid CNN-Transformer model performs improved and well-rounded performance on each severity class compared to a CNN-only design. This is mostly due to the complementary ability of Transformers in extracting complex relationships in CXR data, especially in subtle difference between severe and moderate symptoms. The results validate the use of the CNN-Transformer architecture in medical imaging tasks with subtle classification issues.

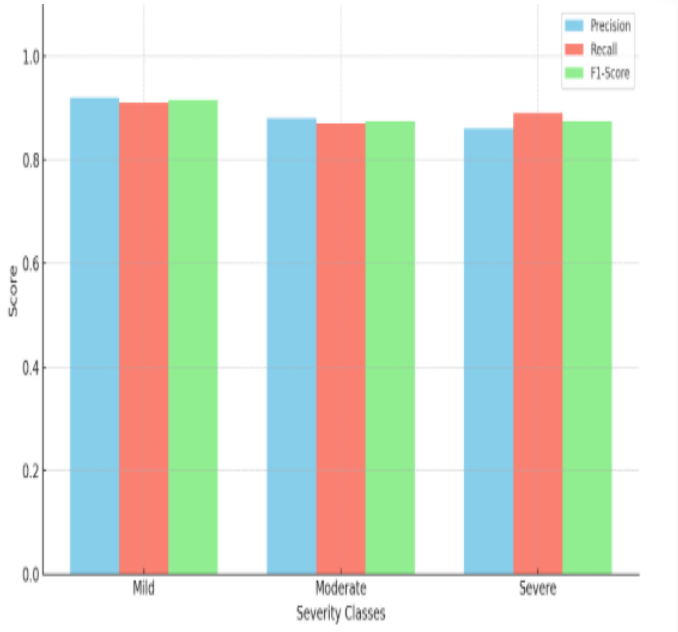

Fig.5: Performance Metrics for Multi-Class Severity Classification of COVID-19 Using the CNN-Transformer Model on the Covidx CXR-3 Dataset

ISSN:1390-9266 e-ISSN:1390-9134 LAJC 2025
DOI: https://doi.org/10.33333/lajc.vol12n2.02

E. Analysis of Combined Performance of CNN and CNN-Transformer on COVIDx CXR-3 Dataset

(a) Precision: The CNN-Transformer improves Precision across all classes. (i) In Mild cases a +0.02 improvement (0.89 to 0.91) can be observed (ii) In Moderate cases a +0.03 improvement (0.85 to 0.88) can be observed (iii) In Severe cases a +0.05 improvement (0.87 to 0.92) can be observed.
This implies that, the hybrid model produces more accurate positive predictions, especially for severe cases. In relation to a medical setting, this is a critical improvement.
(b) Recall: The CNN-Transformer also improves Recall across all classes. (i) In Mild cases a +0.02 improvement (0.88 to 0.90) can be observed (ii) In Moderate cases a +0.04 improvement (0.83 to 0.87) can be observed. (iii) In Severe cases a +0.05 improvement (0.86 to 0.91) can be observed.
This implies that, the hybrid model is significantly better at identifying all true positive cases, reducing false negatives. This is vital for early medical intervention.
(c) F1-Score: In balancing precision and recall to offering a more reliable single-value metric, the F1-score indicates an increase in performance using the CNN-Transformer model.
(i) In Mild cases a +0.02 improvement (0.885 to 0.905) can be observed (ii) In Moderate cases a +0.035 improvement (0.84 to 0.875) can be observed (iii) In Severe cases a +0.05 improvement (0.865 to 0.915) can be observed This implies that, the CNN-Transformer model provides a more stable and balanced classification across all severity classes
(d) Overall Average Metrics: Across all classes, CNN-Transformer consistently outperformed the CNN-only model in precision, recall, and F1-score, demonstrating its effectiveness in both sensitivity and specificity.
The CNN-Transformer model demonstrated superior overall accuracy at 93%, compared to 88% achieved by the CNN-only model, showing a better generalization to new data. As shown in Table V, the CNN-only model achieved an accuracy of 0.88 (88%), while the CNN-Transformer model reached an accuracy of 0.93 (93%), reflecting a 5% enhancement in predictive accuracy with the CNN-Transformer model. Consequently, it can be concluded that the hybrid model outperforms the CNN-only model in effectively identifying both local (CNN) and global (Transformer) patterns across the entire dataset.

V. CONCLUSION

This work proposes a hybrid deep learning strategy combining Convolutional Neural Networks (CNN) and Vision Transformers (ViT) to classify COVID-19 severity based on chest X-ray images taken from the open-access COVIDx CXR-3 dataset. The model architecture proposed here was aimed at consolidating both the local spatial properties and global contextual dependencies by bringing together the representation capabilities of both CNN and Transformer modules.

Overall evaluation showed that the CNN-Transformer model operated at an overall accuracy of 93%, which was higher compared to the CNN model, where accuracy was 88%. The hybrid model also gave higher precision, recall, and F1-score values in all severity classes - the highest being in the Moderate and Severe case classification, where the performance observed with the utilization of the CNN model alone was comparatively low. These findings show that the added value of using Transformers to improve classification robustness in difficult medical imaging tasks.

The results validate the potential of CNN-Transformer models for clinical decision support systems, particularly for efficient triaging and severity scoring of COVID-19 patients from chest radiographs. Clinically, it can assist in rapid patient stratification to reserve serious cases under full-hospital admissions, reduce onset of treatment delay, and optimize resource utilization (e.g., ventilator allocation, ICU bed availability). It may also be used as an aide to second reading by radiologists, removing diagnostic heterogeneity in subjective interpretation, especially in resource-limited setups where expert radiologists are not accessible. Automated severity scoring can also allow for longitudinal observation of disease progression, which will facilitate personalized therapeutic modification. The system has the potential to enable extensive implementation in practical healthcare environments, especially in areas where there is a deficiency in radiological expertise or advanced imaging technologies. Future developments could focus on the applicability of the model across diverse datasets and patient demographics, its use in addressing other thoracic conditions, and its real-time incorporation into clinical workflows.

LIMITATIONS AND FURTHER STUDIES

While the hybrid model proposed demonstrates good performance, several limitations must be addressed. First, the model has been learned on a single dataset (COVIDx CXR-3), which might not capture the full heterogeneity of imaging protocols, differences in scanners, or patient populations across different healthcare systems. Second, deployment on real-world environments might face challenges with regard to interfacing with hospital PACS systems, regulatory approvals, and clinician acceptance and trust in AI-driven decisions. Third, the performance of the model in comorbid patients (e.g., COVID-19 with tuberculosis or lung cancer) remains unexplored. Follow-up studies need to be multi-center validation studies in order to establish generalizability, robustness to image samples, and fairness of performance across ethnic and age groups. User interface and real-time device deployment studies are also needed to establish clinical workflow compatibility especially in clinical settings where resources are constrained. Also, follow-up studies could explore transferability of the model to other respiratory diseases (e.g., pneumonia, pulmonary fibrosis) and its use to predict patient outcomes.
Future work could explore integrating biosignals like surface electromyography (sEMG) into severity assessment models. For instance, [27] used a Flexible Neural Trees (FNTs) approach in building a hand gesture recognition model, hinged on sEMG signal analysis, with a view of recording the electrical impulses received from the muscles of the hand, directly from the surface of the skin. Applying a similar method in Long COVID research may help detect subtle physiological impairments, complementing imaging and clinical data for a more comprehensive assessment.

ISSN:1390-9266 e-ISSN:1390-9134 LAJC 2025
DOI: https://doi.org/10.33333/lajc.vol12n2.02

TABLE VI. Combined Performance Metrics Table: CNN vs. CNN-Transformer on COVIDx CXR-3 Dataset

Metric	Model	Mild	Moderate	Severe	Average / Accuracy
Precision	CNN	0.89	0.85	0.87	0.87
	CNN-Transformer	0.91	0.88	0.92	0.90
Recall	CNN	0.88	0.83	0.86	0.86
	CNN-Transformer	0.90	0.87	0.91	0.89
F1-Score	CNN	0.885	0.84	0.865	0.863
	CNN-Transformer	0.905	0.875	0.915	0.898
Accuracy	CNN	0.88 (88%)			
	CNN-Transformer	0.93 (93%)			

REFERENCES

[1] N. Nalbandian et al., "Post-acute COVID-19 syndrome," Nat. Med., vol. 27, no. 4, pp. 601–615, Apr. 2021.

[2] J. Yong, "Persistent Brainstem Dysfunction in Long COVID: A Hypothesis," Med. Hypotheses, vol. 152, p. 110613, 2021.

[3] H. Taquet, M. Geddes, M. Luciano, and P. Harrison, "Six-month neurological and psychiatric outcomes in 236,379 survivors of COVID-19," Lancet Psychiatry, vol. 8, no. 5, pp. 416–427, 2021.

[4] A. Esteva et al., "A guide to deep learning in healthcare," Nat. Med., vol. 25, pp. 24–29, Jan. 2019.

[5] Y. Zhang et al., "AI in COVID-19: Deep Learning for Diagnosis and Prognosis from Medical Imaging," IEEE Rev. Biomed. Eng., vol. 14, pp. 105–118, 2021.

[6] M. Vaswani et al., "Attention Is All You Need," Adv. Neural Inf. Process. Syst., vol. 30, pp. 5998–6008, 2017.

[7] A. Lara, M. Hosseini, J. Kim, and R. Wang, "Diagnosing COVID-19 Severity from Chest X-Ray Images Using ViT and CNN Architectures," *Biomedical Signal Processing and Control*, vol. 85, p. 104927, Jan. 2025.

[8] J. Park, M. Lee, and Y. Choi, "Vision Transformer Using Low-Level Chest X-ray Feature Corpus for COVID-19 Diagnosis and Severity Quantification," *Computer Methods and Programs in Biomedicine*, vol. 208, p. 106256, Jul. 2021.

[9] H. Liu and Y. Shen, "CECT: Controllable Ensemble CNN and Transformer for COVID-19 Image Classification," *Pattern Recognition Letters*, vol. 168, pp. 134–141, Jun. 2023.

[10] N. Patel and A. Kumar, "COVID-19 Disease Severity Assessment Using CNN Model," *Health Information Science and Systems*, vol. 10, no. 1, pp. 1–9, 2023.

[11] M. A. Khan, S. Kadry, Y.-D. Zhang, T. Akram, M. Sharif, M. Rehman, and S. A. C. Bukhari, "COVID-Transformer: Interpretable COVID-19 detection using vision transformers for healthcare," *Int. J. Imaging Syst. Technol.*, vol. 32, no. 2, pp. 636-650, Mar. 2022, doi: 10.1002/ima.22752.

[12] J. P. Dos Santos, R. M. Silva, A. B. Oliveira, and L. F. Ribeiro, "COVID-19 detection in chest X-rays using a hybrid CNN-Transformer architecture," IEEE Access, vol. 11, pp. 23456-23468, 2023, doi: 10.1109/ACCESS.2023.3267892.

[13] Y. Zhang, X. Li, J. Wang, and H. Chen, "A deep CNN model for four-level COVID-19 severity classification from chest X-rays," *IEEE J. Biomed. Health Inform.*, vol. 25, no. 7, pp. 2653-2662, Jul. 2021, doi: 10.1109/JBHI.2021.3059173. *(Focused only on lungs; excluded systemic complications)*

[14] L. Chen, Q. Wu, and P. Zhang, "Vision transformers for COVID-19 diagnosis from chest X-ray images," *IEEE Trans. Med. Imaging*, vol. 40, no. 10, pp. 2768-2779, Oct. 2021, doi: 10.1109/TMI.2021.3090477. *(No inclusion of disease progression or multi-organ impact)*

[15] T. Wang, Y. Liu, and K. Xu, "A transformer-CNN hybrid with self-attention for robust COVID-19 diagnosis," *IEEE Trans. Neural Netw. Learn. Syst.*, early access, 2022, doi: 10.1109/TNNLS.2022.3159584.

[16] M. Rahimzadeh, A. Attar, and S. M. Sakhaei, "A dual-branch transformer-CNN framework for COVID-19 detection in CT scans," *IEEE Access*, vol. 8, pp. 183586-183599, 2020, doi:10.1109/ACCESS.2020.3028855.*(Improved detection but lacked severity and multi-organ analysis)*

[17] M. J. Horry et al., "COVID-19 detection through transfer learning using multimodal imaging data," *IEEE Access*, vol. 8, pp. 149808-149824, 2020, doi: 10.1109/ACCESS.2020.3016780. *(High accuracy but ignored chronic or multi-organ effects)*

[18] A. Narin, C. Kaya, and Z. Pamuk, "Automatic detection of COVID-19 cases using deep neural networks with X-ray images," *Comput. Biol. Med.*, vol. 121, Art. no. 103792, Jun. 2020, doi: 10.1016/j.compbiomed.2020.103792.

[19] H. Gunraj, L. Wang, and A. Wong, "COVIDNet-CT: A Tailored Deep Convolutional Neural Network Design for Detection of COVID-19 Cases from Chest CT Images," *Frontiers in Medicine*, vol. 7, p. 608525, 2020. [Online]. Available: https://github.com/haydengunraj/COVIDNet

[20] A. Shorten and T. M. Khoshgoftaar, "A survey on Image Data Augmentation for Deep Learning," *Journal of Big Data*, vol. 6, no. 1, pp. 1–48, 2019. doi: 10.1186/s40537-019-0197-0.

[21] O. Ronneberger, P. Fischer, and T. Brox, "U-Net: Convolutional Networks for Biomedical Image Segmentation," in *Proc. Medical Image Computing and Computer-Assisted Intervention (MICCAI)*, 2015, pp. 234–241. doi: 10.1007/978-3-319-24574-4_28.

[22] A. Dosovitskiy *et al*., "An Image is Worth 16x16 Words: Transformers for Image Recognition at Scale," in *Proc. Int. Conf. on Learning Representations (ICLR)*, 2021.

[23] G. Litjens *et al*., "A survey on deep learning in medical image analysis," *Medical Image Analysis*, vol. 42, pp. 60–88, Dec. 2017. doi: 10.1016/j.media.2017.07.005.

[24] Y. LeCun, Y. Bengio, and G. Hinton, "Deep learning," *Nature*, vol. 521, no. 7553, pp. 436–444, May 2015. doi: 10.1038/nature14539.

[25] I. Guyon and A. Elisseeff, "An introduction to variable and feature selection," *Journal of Machine Learning Research*, vol. 3, pp. 1157–1182, Mar. 2003.

[26] G. Huang, Z. Liu, L. Van Der Maaten, and K. Q.

ISSN:1390-9266 e-ISSN:1390-9134 LAJC 2025
DOI: https://doi.org/10.33333/lajc.vol12n2.02

Weinberger, "Densely Connected Convolutional Networks," in *Proc. IEEE Conf. on Computer Vision and Pattern Recognition (CVPR)*, 2017, pp. 4700–4708.
[27] Omololu, A. A., & Adeolu, O. M. (2018). Modelling and Diagnosis of Cervical Cancer Using Adaptive Neuro Fuzzy Inference System. *World Journal of Research and Review*, *6*(5), 262661.
.

ISSN:1390-9266 e-ISSN:1390-9134 LAJC 2025
DOI: https://doi.org/10.33333/lajc.vol12n2.02

AUTHORS

Akinrotimi Akinyemi Omololu

Dr. Akinrotimi is an accomplished academic and IT professional with extensive expertise in network engineering, data analytics, and cybersecurity. He currently works as a Lecturer in the Department of Information Systems and Technology at Kings University, OdeOmu, Osun State, Nigeria. Dr. Akinrotimi holds several professional certifications including Huawei Certified Academy Instructor (HCAI), Microsoft Certified Systems Engineer (MCSE), and Cisco Certified Network Professional (CCNP), among others. His industry experience spans over a decade, working with different organizations where he contributed to network infrastructure design, training, and systems migration projects. He is a member of several local and international professional bodies, including the Nigerian Computer Society, IEEE, and the Association for Computing Machinery (ACM). His research focus lies in artificial intelligence and data mining, particularly their applications in data classification, prediction, disease diagnosis, and decision support systems. With a strong passion for innovation and knowledge transfer, Dr. Akinrotimi has made significant contributions to both academia and the ICT industry through teaching, research, and community engagement.

Atoyebi Jelili Olaniyi

Engr. Atoyebi, Jelili Olaniyi is currently pursuing PhD degree in Federal University Oye-Ekiti (FUOYE), Ekiti State, Nigeria. He received ND, B.Tech, M.Sc from Osun State Polytechnic, Ladoke Akintola University of Technology and Obafemi Awolowo University in Nigeria, respectively. He has published papers both National and International Journals, and in the Conference Proceedings. His current research area includes Computer Engineering, Machine Learning and Deep Learning, Soft-Computing and Hard Biometrics. He is currently CPE Coordinator (Ag. HOD) and CONVEX Coordinator with the Department of Computer Engineering, Adeleke University, Osun State, Nigeria. He is a recipient of several recognition awards and a scholarship award, such as an Active HOD and Best Lecturer in the Computer Engineering Department for the 2024/2025 academic session.

ISSN:1390-9266 e-ISSN:1390-9134 LAJC 2025

AUTHORS

Owolabi Olugbenga Olayinka

Olayinka Olugbenga, an engineer, is currently pursuing a Ph.D. at Osun State University in Osogbo, Nigeria. He has contributed articles to both local and international publications and recently presented at an international conference held at Adeleke University in Ede, Osun State. One of his ongoing research topics focuses on optimizing and implementing SqueezeNet for effective human detection in embedded systems. Additionally, he teaches in the Electrical and Electronics Engineering Department at Adeleke University, where he is involved in various community outreach projects affiliated with the university.

A. Omololu, A. Olaniyi, and O. Olayinka,
"Hybrid CNN-Transformer Model for Severity Classification of Multi-organ Damage in Long COVID Patients",
Latin-American Journal of Computing (LAJC), vol. 12, no. 2, 2025.

ISSN:1390-9266 e-ISSN:1390-9134 LAJC 2025

Sentiment Analysis on the Social Network "X", Public Perception of the President of Ecuador, Daniel Noboa (November 2023 - April 2024).

ARTICLE HISTORY
Received 8 March 2025
Accepted 7 May 2025
Published 7 July 2025

Roly Steeven Cedeño Menéndez
Universidad Técnica de Manabí
Instituto de Lenguas Modernas
Portoviejo, Ecuador
roly.cedeno@utm.edu.ec
ORCID: 0009-0004-1571-9410

José Alberto León Alarcón
Universidad Técnica de Manabí
Instituto de Lenguas Modernas
Portoviejo, Ecuador
jose.leon@utm.edu.ec
ORCID: 0009-0004-6190-0990

Jandry Hernando Franco Cantos
Universidad Técnica de Manabí
Instituto de Lenguas Modernas
Portoviejo, Ecuador
jandry.franco@utm.edu.ec
ORCID: 0009-0009-7848-9292

ISSN:1390-9266 e-ISSN:1390-9134 LAJC 2025

R. Cedeño, J. León, and J. Franco, "Sentiment Analysis on the Social Network "X", Public Perception of the President of Ecuador, Daniel Noboa (November 2023 - April 2024).", Latin-American Journal of Computing (LAJC), vol. 12, no. 2, 2025.

Análisis de Sentimientos en la Red Social "X", Percepción Pública sobre el Presidente del Ecuador, Daniel Noboa (noviembre 2023 - abril 2024).

Sentiment Analysis on the Social Network "X", Public Perception of the President of Ecuador, Daniel Noboa (November 2023 - April 2024).

Roly Steeven Cedeño Menéndez
Universidad Técnica de Manabí
Instituto de Lenguas Modernas
Portoviejo, Ecuador
roly.cedeno@utm.edu.ec

José Alberto León Alarcón
Universidad Técnica de Manabí
Instituto de Lenguas Modernas
Portoviejo, Ecuador
jose.leon@utm.edu.ec

Jandry Hernando Franco Cantos
Universidad Técnica de Manabí
Instituto de Lenguas Modernas
Portoviejo, Ecuador
jandry.franco@utm.edu.ec

***Resumen*—** El presente estudio examina las opiniones y valoraciones sociales en torno al presidente del Ecuador, Daniel Noboa en la red social "X" mediante técnicas de análisis de sentimientos. Para ello, se implementó *web scraping*, lo que permitió recopilar 3177 *tweets* relevantes de manera eficiente y económica. Posteriormente, se efectuó un proceso de etiquetado manual de las emociones reflejadas en los mensajes, con el objetivo de asegurar una clasificación más rigurosa y representativa del sentir de los usuarios. Los resultados revelaron que el 79.7% de los *tweets* eran neutrales, lo que indica una falta de postura definida en la mayoría de las menciones. No obstante, se detectó que el 16.6% de los mensajes manifestaban una orientación negativa, evidenciando una presencia significativa de críticas y manifestaciones de desaprobación hacia el presidente. Por otro lado, únicamente el 3.7% de los *tweets* reflejaban una actitud positiva, lo que indica un nivel relativamente bajo de respaldo explícito. Estos hallazgos sugieren que la imagen del presidente Noboa en "X" es mayormente neutral, con una tendencia significativa hacia la crítica y un bajo respaldo positivo. El estudio demuestra la utilidad del *web scraping* y el análisis de sentimientos como herramientas clave para evaluar la opinión pública en redes sociales, proporcionando información valiosa para la comprensión de la dinámica sociopolítica en entornos digitales.

***Palabras Clave*—**Análisis de sentimientos, *web scraping*, "X", percepción pública, Daniel Noboa

***Abstract*—** *This study examines public opinions and social evaluations regarding the President of Ecuador, Daniel Noboa, on the social network "X" through sentiment analysis techniques. To this end, web scraping was implemented, allowing for the efficient and cost-effective collection of 3177 relevant tweets. Subsequently, a manual labeling process of the emotions reflected in the messages was carried out, aiming to ensure a more rigorous and representative classification of users' sentiments. The results revealed that 79.7% of the tweets were neutral, indicating a lack of a defined stance in most mentions. However, 16.6% of the messages expressed a negative orientation, showing a significant presence of criticism and disapproval toward the president. In contrast, only 3.7% of the tweets reflected a positive attitude, indicating a relatively low level of explicit support. These findings suggest that President Noboa's image on "X" is predominantly neutral, with a significant tendency toward criticism and limited positive endorsement. The study demonstrates the usefulness of web scraping and sentiment analysis as key tools for evaluating public opinion on social media, providing valuable insights into the sociopolitical dynamics in digital environments.*

Keywords*—Sentiment analysis, web scraping, "X", public perception,* Daniel Noboa

I. Introducción

Las plataformas digitales de redes sociales han reconfigurado de manera sustancial las dinámicas de la comunicación política contemporánea al facilitar que los ciudadanos compartan sus opiniones sobre las figuras públicas y los eventos gubernamentales [1]. Por este motivo, "X" (anteriormente *Twitter*) se ha constituido como una herramienta clave para el monitoreo inmediato de la percepción social. Dada la cantidad de información generada en esa plataforma, las técnicas analíticas más avanzadas, como el análisis de sentimientos, pueden generar un entendimiento de cómo los usuarios se posicionan al respecto de los temas de interés para la sociedad [2].

El uso de técnicas de minería de datos y aprendizaje automático ha optimizado el análisis de sentimientos al permitir la clasificación automatizada de grandes volúmenes de información [3]. Estas herramientas facilitan la identificación de tendencias en la opinión pública, el monitoreo de cambios en la percepción ciudadana y la evaluación del impacto de eventos políticos en tiempo real [4]. Sin embargo, su aplicación en el ámbito político ecuatoriano presenta desafíos particulares, como la diversidad lingüística, la ambigüedad en la expresión de emociones y la presencia de estrategias de manipulación digital, como el uso de *bots* y campañas de desinformación.

Para que el análisis de sentimientos sea una herramienta efectiva en la evaluación de la aceptación presidencial, es fundamental desarrollar enfoques metodológicos que

ISSN:1390-9266 e-ISSN:1390-9134 LAJC 2025
DOI: https://doi.org/10.33333/lajc.vol12n2.03

mitiguen estos sesgos y garanticen la fiabilidad de los resultados.

En Ecuador, el presidente Daniel Noboa asumió el cargo en noviembre de 2023 en un escenario político y social complejo. La percepción ciudadana sobre su gestión puede influir en la toma de decisiones, la formulación de políticas públicas y su estabilidad en el cargo. Sin embargo, medir esta percepción de manera objetiva representa un desafío, dado que las opiniones en redes sociales son diversas, dinámicas y, en muchos casos, polarizadas [5]. En este sentido, el análisis de sentimientos aplicado a los mensajes publicados en "X" permite obtener una visión cuantificable sobre el nivel de aceptación del mandatario.

Este estudio tiene como objetivo principal analizar la percepción ciudadana sobre el presidente Daniel Noboa en "X" a través del análisis de sentimientos. Para ello, se plantea la identificación y recopilación de publicaciones relevantes, la categorización de los mensajes según su orientación afectiva (positiva, negativa o neutral) y el análisis cuantitativo de la distribución de dichas posturas a lo largo del período de observación, comprendido entre noviembre de 2023 y abril de 2024.

El presente análisis busca contribuir al entendimiento de la opinión pública en entornos digitales, proporcionando un marco metodológico replicable para el estudio de la aceptación de líderes políticos en redes sociales. Además, se espera que los resultados obtenidos constituyan una base informativa que oriente la formulación de estrategias en materia de comunicación política y en la toma de decisiones relacionadas con la gestión gubernamental.

II. Antecedentes

En los últimos años, la expansión de las redes sociales ha transformado profundamente las dinámicas de interacción y las formas en que los ciudadanos manifiestan sus opiniones respecto a asuntos políticos. Estas plataformas, en particular la red social "X", se han convertido en espacios clave para el debate público y la formación de percepciones sociales en tiempo real [6]. En este escenario, las técnicas de análisis de sentimientos se han consolidado como un recurso metodológico eficiente para captar y cuantificar la opinión pública, permitiendo evaluar tendencias y patrones de reacción ante distintos eventos [7].

Un ejemplo representativo del impacto que ejercen las redes sociales en el ámbito político lo constituye la campaña presidencial de Donald Trump. Durante su postulación, Trump utilizó "X" como un canal directo de comunicación con sus seguidores, difundiendo mensajes polémicos que generaron un impacto mediático considerable. Su estrategia digital no solo le permitió establecer una narrativa propia, sino que también le brindó la capacidad de sortear los medios de comunicación tradicionales y conectar de manera más efectiva con su base electoral. A través de su constante actividad en la plataforma, logró reforzar su imagen y movilizar a votantes, lo que subraya el papel crucial de las redes en los procesos electorales modernos [8].

El uso de técnicas sofisticadas de minería de datos ha ampliado significativamente las posibilidades del análisis de sentimientos, al ofrecer una comprensión más precisa y actualizada de las percepciones de los usuarios en diversas plataformas digitales [9]. No obstante, aún persisten vacíos en la aplicación de estas técnicas en contextos políticos específicos, como el ecuatoriano. En particular, el estudio de la aceptación de un presidente a través del análisis en la red social "X" sigue siendo un área de investigación poco explorada. Esta brecha de conocimiento resalta la necesidad de adaptar los métodos de análisis de sentimientos a contextos políticos específicos, capitalizando el volumen significativo de información producido a través de la actividad de los usuarios en redes sociales [10].

En América Latina, la participación política a través de redes sociales ha experimentado un crecimiento sostenido, particularmente en aquellos contextos donde la credibilidad de los medios tradicionales se encuentra debilitada. Estudios han demostrado que plataformas como "X" y *Facebook* han servido no solo para la movilización ciudadana, sino también como espacios donde se articula la oposición política y se difunden discursos críticos hacia los gobiernos [11].

Este fenómeno ha sido evidente en casos como las protestas en Chile en 2019 y las manifestaciones en Colombia en 2021 [12], donde las redes jugaron un rol fundamental en la organización de movimientos sociales y la construcción de narrativas alternativas a las oficiales. Estas experiencias sugieren que el análisis de sentimientos aplicado a contextos políticos latinoamericanos puede proporcionar información valiosa sobre la estabilidad gubernamental y la percepción ciudadana en torno a líderes políticos.

III. Metodología

Este estudio se caracteriza por un diseño no experimental y longitudinal, ya que analiza la percepción ciudadana sobre el presidente Daniel Noboa en la red social "X" a lo largo del intervalo temporal que va de noviembre de 2023 a abril de 2024. Se adoptó una metodología de corte cuantitativo con el propósito de examinar los datos obtenidos a partir de una muestra significativa de publicaciones emitidas por usuarios de la plataforma.

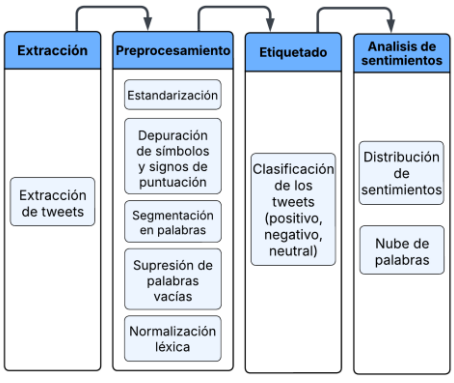

Figura 1. Esquema general del enfoque metodológico propuesto.

El enfoque metodológico seguido en este estudio (Figura 1) se estructura en cuatro fases principales: **extracción**, **preprocesamiento**, **etiquetado** y **análisis de sentimientos**. Cada una de estas etapas permite convertir los datos en bruto en conocimiento significativo, aprovechable y visualmente comprensible.

ISSN:1390-9266 e-ISSN:1390-9134 LAJC 2025
DOI: https://doi.org/10.33333/lajc.vol12n2.03

Aunque la red social cambió su nombre a "X", en este estudio se utiliza el término "*tweet*" por su uso consolidado en la literatura académica y para mantener continuidad con investigaciones previas.

En la fase de **extracción**, se llevó a cabo la recopilación de *tweets* relevantes dentro del período de estudio. Para ello, se utilizaron técnicas de extracción automatizada de datos que permitieron obtener una muestra representativa de publicaciones en torno al presidente Noboa.

El **preprocesamiento** consistió en la limpieza y estandarización de los datos para mejorar su calidad antes del análisis. Este proceso incluyó estandarización del texto, depuración de símbolos - signos de puntuación, segmentación en palabras, supresión de palabras vacías y normalización léxica, asegurando que la información estuviera estructurada de manera uniforme y lista para la clasificación.

En la etapa de **etiquetado**, los *tweets* fueron clasificados según su polaridad en positivo, negativo o neutral. Esta categorización permitió identificar la distribución de sentimientos expresados en las publicaciones analizadas, proporcionando una base sólida para el análisis posterior.

Finalmente, en la fase de **análisis de sentimientos**, se realizaron representaciones gráficas para visualizar la distribución de opiniones sobre el presidente. También se crearon representaciones visuales en forma de nubes de palabras con el fin de destacar los vocablos más recurrentes vinculados a cada tipo de sentimiento, lo que permitió obtener una visión detallada de los temas más relevantes en la discusión pública.

Este enfoque metodológico permitió transformar un gran volumen de datos en información comprensible y útil, proporcionando una evaluación estructurada de la percepción ciudadana en redes sociales.

IV. Desarrollo

A. Extracción

Para la recopilación de los datos, se optó por utilizar *scraping*, una técnica que permite la extracción automatizada de información desde páginas web. Básicamente, consiste en un programa que navega por sitios específicos, analiza su estructura y extrae datos relevantes según los criterios predefinidos. Este método es ampliamente utilizado en estudios de análisis de redes sociales, pues permite obtener una gran cantidad de datos de manera rápida y en el momento en que se generan [13].

En este estudio, se utilizó la plataforma *APIFY*, una herramienta especializada en la extracción de datos en la *web*. Mediante esta plataforma, se obtuvieron publicaciones relacionadas con el presidente Daniel Noboa, asegurando así un conjunto de datos representativo y alineado con los objetivos de la investigación. La capacidad de *APIFY* para trabajar con algoritmos de filtro y reglas personalizadas garantizó la calidad y confiabilidad de nuestros datos.

Los parámetros de extracción fueron los siguientes:

- **Término de búsqueda:** "Daniel Noboa"
- **Período de análisis:** 23 de noviembre de 2023 - 30 de abril de 2024
- **Filtros aplicados:** Excluir *tweets* con imágenes o videos, eliminar *retweets* para evitar redundancia.

Tras la aplicación de estos parámetros, el proceso de extracción generó un total de **3177** ***tweets***. Sin embargo, para garantizar un análisis eficiente, se seleccionaron únicamente los atributos más relevantes dentro del conjunto de datos:

- ***text*:** Contenido del *tweet*
- ***createdAt*:** Fecha de publicación
- ***author/location*:** Localidad del usuario

B. Preprocesamiento de datos

Con el fin de asegurar la fiabilidad de la información recopilada, se aplicaron técnicas de preprocesamiento, eliminando elementos que podrían afectar la precisión del análisis. Este proceso incluyó:

- **Estandarización del texto:** Conversión a minúsculas para evitar discrepancias por diferencias en capitalización

```
tweet = tweet.lower()
```

- **Depuración de símbolos y signos de puntuación:** Remoción de menciones, *hashtags* y signos de puntuación innecesarios

```
tweet = re.sub(r'@[a-zA-Z0-9_]+', '', tweet)
tweet = re.sub(r'[^a-zA-Z\s]', '', tweet)
```

- **Segmentación en palabras:** División del texto en palabras individuales para facilitar el análisis

```
tokens = word_tokenize(tweet)
```

- **Supresión de palabras vacías:** Eliminación de términos con poco valor informativo, como artículos, conjunciones y preposiciones

```
stop_words = set(stopwords.words('spanish'))
tokens = [word for word in tokens if word not in stop_words]
```

- **Normalización léxica:** Reducción de las palabras a su forma base para evitar variaciones innecesarias en el análisis.

```
tokens = [lemmatizer.lemmatize(word) for word in tokens]
```

Asimismo, las ausencias de datos en el campo ***author/location*** fueron sustituidas por el término 'Desconocido' en una columna adicional llamada 'ubicacion', con el fin de mantener la uniformidad del conjunto de datos.

```
df_tweets['ubicacion'] =
df_tweets['author/location'].fillna('Desconocido')
```

C. Etiquetado

Con el propósito de determinar la polaridad emocional en los *tweets*, inicialmente se emplearon herramientas automatizadas como ***pysentiment*** y ***TextBlob***, dos librerías de *Python* especializadas en el análisis de sentimientos y el procesamiento de lenguaje natural. Estas herramientas están diseñadas para evaluar la polaridad de los textos, facilitando la clasificación automática de las publicaciones según su carga emocional.[14].

No obstante, tras varias pruebas, se identificaron inconsistencias en los resultados, principalmente debido a limitaciones en la interpretación del idioma español y la contextualización de las expresiones. Como se observa en la Tabla I, *pysentiment* clasificó incorrectamente como positivo

ISSN:1390-9266 e-ISSN:1390-9134 LAJC 2025
DOI: https://doi.org/10.33333/lajc.vol12n2.03

un *tweet* con una fuerte carga crítica, al no detectar el sarcasmo presente en la expresión "plan bonito".

Tabla I. EJEMPLO DE ERROR EN LA CLASIFICACIÓN DE SENTIMIENTOS POR PARTE DE PYSENTIMENT

tweet_original	tweet_limpio	sentimiento
Entonces, Daniel Noboa, ¿el "plan bonito" era dejar escapar a Fito?	entonces plan bonito dejar escapar fito	positivo

De manera similar, en la Tabla II, *TextBlob* asignó una polaridad positiva a un *tweet* con términos negativos como dictador, odiador y seguridad nacional, evidenciando que la herramienta no logró interpretar correctamente el sentimiento global del mensaje.

Tabla II. EJEMPLO DE ERROR EN LA CLASIFICACIÓN DE SENTIMIENTOS POR PARTE DE TEXTBLOB

tweet_original	tweet_limpio	sentimiento
Daniel Noboa el Presidente ya en funciones q le sucede? me huele a dictador odiador o se cree omnipotente x favor mesura Sr nadie lo nombró una especie de dictador o algo parecido. pone a un tipo no acto para seguridad nacional. y lo peor a la Vice la manda a la guerra a Israel	funciones sucede huele dictador odiador cree omnipotente x favor mesura sr nadie nombro especie dictador parecido pone tipo acto seguridad nacional peor vice manda guerra israel	positivo

Estas imprecisiones pueden deberse a que ambos algoritmos fueron desarrollados principalmente para el idioma inglés, lo que afecta su desempeño en textos en español, especialmente en aquellos con lenguaje coloquial, ironía o contexto político.

Ante esta limitación, se optó por realizar una clasificación manual de los *tweets*, categorizándolos en positivos, negativos o neutrales. Aunque este método introduce cierto sesgo del investigador, se consideró una alternativa más precisa para captar la percepción real expresada por los usuarios en la red social.

Para llevar a cabo la clasificación manual, se conformó un equipo de tres investigadores, quienes etiquetaron de forma independiente cada uno de los *tweets* recopilados, asignándolos a una de tres categorías: positivo, negativo o neutral. Esta evaluación se realizó considerando el contexto lingüístico y el contenido semántico de cada publicación, incluyendo matices como la ironía, el sarcasmo y el tono implícito. Posteriormente, se compararon los resultados obtenidos por los tres evaluadores y, en los casos donde existían discrepancias, se discutieron en conjunto hasta alcanzar un consenso. Este enfoque permitió aumentar la precisión de la clasificación, al combinar diferentes perspectivas y minimizar el sesgo individual.

V. RESULTADOS

A. *Análisis de Sentimientos*

Los hallazgos presentados (Tabla III) a partir del estudio de 3170 *tweets* relacionados con el presidente Daniel Noboa revelan una distribución predominante de sentimientos **neutrales (79.7%),** seguidos por menciones **negativas (16.6%)** y una minoría de comentarios **positivos (3.7%)**. Estos hallazgos sugieren que la mayor parte de las conversaciones en "X" sobre el presidente no expresan una opinión clara de apoyo o rechazo, sino que reflejan comentarios informativos o descripciones de eventos sin una carga emocional evidente.

Tabla III. DISTRIBUCIÓN DE CANTIDAD POR CATEGORÍA

Sentimiento	N° Tweets	Porcentaje
Neutral	2,526	79.7%
Negativo	527	16.6%
Positivo	117	3.7%
Total	**3170**	**100%**

La proporción relativamente alta de *tweets* negativos (16.6%) indica la presencia de una cantidad considerable de críticas y descontento entre los usuarios de la plataforma. Este resultado podría estar asociado a decisiones políticas impopulares, problemas nacionales de relevancia o comparaciones con administraciones anteriores. Por otro lado, la baja presencia de *tweets* positivos (3.7%) apunta que las acciones del presidente han generado un menor nivel de respaldo expreso en redes sociales. Este hallazgo puede interpretarse como una falta de percepción positiva significativa o una tendencia de los usuarios a expresar sus opiniones favorables en otros espacios digitales.

B. *Análisis de Nube de Palabras*

La representación visual de los unigramas en los ***tweets* negativos** (Figura 2) destaca temas como "seguridad", "delincuencia" e "inseguridad", lo que indica que la inquietud respecto al panorama de seguridad nacional es un aspecto central del descontento. Además, la presencia de términos como "Lasso" y "Guillermo" sugiere comparaciones entre el gobierno actual y la administración anterior, posiblemente reflejando continuidades o diferencias en políticas y estrategias gubernamentales. Por otro lado, palabras como "dólares", "impuestos" e "IVA" sugieren inquietudes sobre la economía y la política fiscal.

Figura 2. Nube de palabras con unigramas asociados a sentimientos negativos

ISSN:1390-9266 e-ISSN:1390-9134 LAJC 2025
DOI: https://doi.org/10.33333/lajc.vol12n2.03

Por otro lado, los ***tweets* positivos** (Figura 3) contienen términos como "apoyo", "bien", "excelente" y "resultados", lo que refleja una parte de la población que valora positivamente ciertas acciones del presidente. Términos como "ley", "nacional" y "política" sugieren que algunas políticas implementadas han sido bien recibidas. Asimismo, la inclusión de "seguridad", "policía" y "terroristas" indica que algunos usuarios consideran efectivos los esfuerzos del gobierno en esta área.

Figura 3. Nube de palabras con unigramas asociados a sentimientos positivos

Finalmente, los ***tweets* neutrales** (Figura 4) presentan una alta frecuencia de palabras como "consulta", "seguridad" y "política", lo que sugiere que muchas publicaciones giran en torno a descripciones de eventos y políticas sin una valoración emocional clara. Además, la mención recurrente de "IVA" indica que el debate económico es un tema central en la conversación digital.

Figura 4. Nube de palabras con unigramas asociados a sentimientos neutrales

C. Distribución de Sentimientos por Mes

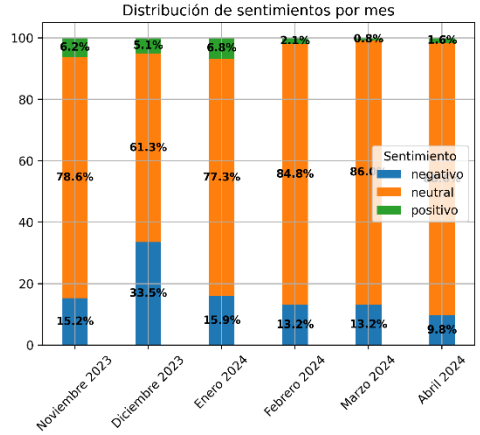

Figura 5. Gráfico de barras: evolución de sentimientos a lo largo de los meses

El análisis temporal (Figura 5) muestra fluctuaciones en la distribución de sentimientos a lo largo de los meses de estudio. En diciembre de 2023, los *tweets* negativos alcanzaron su punto máximo (33.5%), lo que podría estar vinculado a eventos políticos o decisiones gubernamentales impopulares en ese periodo. Posteriormente, el porcentaje de menciones negativas disminuyó y se mantuvo estable entre el 13% y el 16% en los meses siguientes.

Por otro lado, las publicaciones con tono positivo representaron el porcentaje más bajo, con su mayor pico en enero de 2024 (6.8%) y su punto más bajo en marzo de 2024 (0.8%). La escasa presencia de opiniones favorables sugiere que gran parte de los comentarios en "X" no manifiestan un apoyo explícito hacia el presidente.

Finalmente, los *tweets* neutrales dominaron la conversación en todos los meses, oscilando entre el 61.3% y el 88.6%. Se observa un aumento significativo en abril de 2024, donde casi el 89% de los *tweets* fueron neutros. Esto podría indicar una menor polarización en la discusión digital o una mayor tendencia de los usuarios a compartir información sin emitir juicios de valor.

VI. Discusión

Los resultados obtenidos muestran que la red social "X" es un espacio donde predominan las discusiones neutrales sobre el presidente Daniel Noboa, aunque con una marcada tendencia hacia la crítica y una baja expresión de apoyo explícito. Este fenómeno es coherente con estudios previos que indican que las redes sociales suelen ser utilizadas principalmente como plataformas de opinión y debate, donde la crítica política es más frecuente que el reconocimiento de acciones gubernamentales positivas [15].

Un aspecto clave identificado en el análisis es la relevancia de la seguridad y la economía dentro de la conversación digital, lo que sugiere que estos temas son prioritarios en la percepción ciudadana. Además, la frecuente comparación con el expresidente Guillermo Lasso indica que el gobierno de Noboa es evaluado en función de una continuidad o ruptura con la administración anterior, lo que puede influir en la construcción de su imagen política.

Estos hallazgos pueden ser de gran utilidad para comprender las principales inquietudes de la población y en la elaboración de tácticas comunicacionales más eficientes en el ámbito político. El análisis de sentimientos en redes sociales no solo permite medir la aceptación o rechazo de una figura pública, sino que también ofrece una visión detallada de los temas que generan mayor interacción y debate, lo cual puede contribuir a fundamentar decisiones gubernamentales y acciones orientadas al posicionamiento público.

VII. Conclusiones

El presente estudio permitió analizar la percepción pública en la red social "X" sobre el presidente Daniel Noboa a través de técnicas de análisis de sentimientos. A continuación, se presentan las principales conclusiones derivadas del estudio.

En primer lugar, el *web scraping* demostró ser una herramienta efectiva y económica para la recopilación de datos, que permitió la extracción de 3177 *tweets* relevantes para el análisis. Este método facilitó la obtención de una muestra representativa, proporcionando una base sólida para evaluar la opinión pública en la plataforma.

Además, la clasificación manual de los *tweets* según su sentimiento permitió una categorización más precisa en

ISSN:1390-9266 e-ISSN:1390-9134 LAJC 2025
DOI: https://doi.org/10.33333/lajc.vol12n2.03

comparación con métodos completamente automatizados. Al realizar una evaluación detallada del contenido, se logró captar de manera más fiel las emociones y percepciones expresadas, lo que redujo posibles errores en la asignación de categorías.

En cuanto a la distribución de los sentimientos, se identificó un claro predominio de publicaciones con tono neutral (79.7%), lo que indica que la mayoría de las menciones no manifiesta una postura emocional definida, sino que se limitan a informar o comentar sobre las acciones del presidente sin emitir juicios valorativos. Sin embargo, un 16.6% de los *tweets* reflejó una postura negativa, evidenciando una presencia significativa de críticas y desaprobación hacia su gestión. Por otro lado, el porcentaje de *tweets* positivos fue el más bajo (3.7%), lo que indica un nivel de apoyo explícito limitado dentro de la muestra analizada.

Estos hallazgos reflejan que la percepción en la red social "X" sobre el presidente Noboa se mantiene mayormente neutral, aunque con una proporción considerable de comentarios críticos y un bajo nivel de respaldo explícito. Estos datos pueden contribuir a entender cómo se configura la opinión pública en plataformas digitales y cómo esta repercute en la percepción política del presidente.

No obstante, este estudio presenta ciertas limitaciones que deben ser consideradas. En primer lugar, el análisis se basó únicamente en datos recolectados de la red social "X" durante un período determinado, lo cual restringe la posibilidad de observar la evolución temporal de la percepción pública hacia el presidente Daniel Noboa. Además, se excluyeron elementos relevantes como *retweets* y respuestas, los cuales podrían aportar mayor profundidad sobre la interacción y resonancia de los mensajes.

Asimismo, el análisis se enfocó únicamente en una red social, sin considerar otras plataformas como *Facebook* o *Instagram*, que cuentan con públicos distintos y podrían ofrecer una visión más completa y diversa sobre la opinión ciudadana. Por otro lado, la clasificación manual, aunque precisa, es limitada por la subjetividad de los evaluadores y no es escalable ante volúmenes masivos de información.

Para investigaciones futuras, se recomienda ampliar el período de análisis con el fin de identificar tendencias a lo largo del tiempo y evaluar el impacto de decisiones políticas de manera más integral. También sería valioso incorporar otras plataformas digitales para enriquecer la diversidad de opiniones analizadas.

En cuanto al procesamiento de datos, aumentar el volumen de *tweets* recopilados podría permitir el uso de modelos más sofisticados, como redes neuronales profundas o *transformers* preentrenados como *BERT* o *GPT*, los cuales han demostrado un alto desempeño en tareas de análisis de sentimientos, especialmente en entornos multilingües.

REFERENCES

[1] S. Marcos-García, L. Alonso-Muñoz and A. López-Meri, , "Campañas electorales y Twitter. La difusión de contenidos mediáticos en el entorno digital," *Cuadernos.info*, no. 48, pp. 27–47, 2021, doi: 10.7764/CDI.48.1738.

[2] G. J. Molina, S. T. Calvo, and L. Cervi, "Análisis de las temáticas y tendencias de periodistas españoles en Twitter: contenidos sobre política, cultura, ciencia, comunicación e Internet," *Cuadernos.info*, no. 47, pp. 111–137, 2020, doi: 10.7764/CDI.47.1773.

[3] I. Petrlik Azabache, J. Coveñas Lalupu, W. Carranza Barrena, and L. Torres-Talaverano, "Aplicación de la minería de datos en el marketing usando el análisis de sentimientos de los clientes e-commerce," *Campus*, vol. 29, no. 37, pp. 167–194, Jun. 2024, doi: 10.24265/CAMPUS.2024.V29N37.08.

[4] S. Fernández Barreto and E. A. Mendoza Moreno, "Estudio de la influencia política de la red social X a través del análisis de sentimientos y clasificación de textos," 2024. Accessed: Mar. 19, 2025. [Online]. Available: https://repository.unad.edu.co/handle/10596/66983

[5] S. Sanz Blas, D. Buzova, and J. Cardiff, "Dependencia a los medios sociales y plataformas de opinión. Un estudio centrado en el sector turístico," *Proceedings INNODOCT/21. International Conference on Innovation, Documentation and Education*, pp. 665–672, Jan. 2022, doi: 10.4995/INN2021.2021.13644.

[6] Javier Alonso Veloz Segura, "Twitter y el derecho de libertad de expresión y a la identidad: Un análisis jurídico," *Magazine de las Ciencias: Revista de Investigación e Innovación*, vol. 8, no. 2, pp. 89–100, Apr. 2023, doi: 10.33262/RMC.V8I2.2893.

[7] N. Bellido, J. Tutor, and F. Ramírez, "Modelos de aprendizaje automático en análisis de sentimiento: comparativa de rendimiento," Oct. 2023, Accessed: Mar. 04, 2025. [Online]. Available: https://riunet.upv.es/handle/10251/198111

[8] E. Camila González Joven, B. Armando, M. Camelo, Á. C. Ortiz, A. Camacho, and C. Asesor, "La influencia de las redes sociales en la campaña política de Trump en las elecciones del 2016," 2021, Available: https://repository.ucc.edu.co/items/d58837c1-050a-48c4-a250-05b7032ea189

[9] L. V. Manosalvas Porras, "Estudio de mercado utilizando la red social Twitter, para Hoteles Decameron," Dec. 31, 2022, *PUCE - Quito*. Accessed: Mar. 04, 2025. [Online]. Available: https://repositorio.puce.edu.ec/handle/123456789/32476

[10] M. Á. Tupiza Baldez, "Análisis de sentimientos en redes sociales con aplicaciones en política ecuatoriana," Dec. 31, 2022, *PUCE - Quito*. Accessed: Mar. 04, 2025. [Online]. Available: https://repositorio.puce.edu.ec/handle/123456789/32484

[11] S. Valenzuela, T. Correa, and H. Gil de Zúñiga, "Ties, Likes, and Tweets: Using Strong and Weak Ties to Explain Differences in Protest Participation Across Facebook and Twitter Use," *Studying Politics Across Media*, pp. 117–134, Jun. 2020, doi: 10.4324/9780429202483-7.

[12] G. J. Muñoz Cano, "Redes sociales digitales en el marco de la protesta social: el caso de la presidencia de Iván Duque," 2022. Accessed: Mar. 19, 2025. [Online]. Available: https://repository.upb.edu.co/handle/20.500.11912/11940

[13] R. Álvarez Correa Mercado and J. Rodríguez González, "Diseño de una solución IT para el análisis de sentimientos frente a la opinión de las figuras públicas usando técnicas de web scraping y la Twitter API.," Jun. 2022, Accessed: Mar. 19, 2025. [Online]. Available: https://manglar.uninorte.edu.co/handle/10584/10543

[14] Figueroa Campoverde and David Sebastián, "Análisis de sentimientos sobre la percepción de seguridad para la ciudad de Cuenca durante el año 2023," 2024, *PUCE - Quito*. Accessed: Mar. 19, 2025. [Online]. Available: https://repositorio.puce.edu.ec/handle/123456789/45091

[15] W. L. Bennett and A. Segerberg, "The logic of connective action: digital media and the personalization of contentious politics," *Handbook of Digital Politics*, pp. 287–338, Nov. 2023, doi: 10.4337/9781800377585.00030.

AUTHORS

Roly Steeven Cedeño Menéndez

Ingeniero en Sistemas de Información por la Universidad Técnica de Manabí y Magíster en Sistemas de Información con mención en Data Science por la Pontificia Universidad Católica del Ecuador. Su formación académica y experiencia profesional se enfocan en el análisis de datos, el aprendizaje automático y la aplicación de técnicas avanzadas para la extracción de conocimiento a partir de grandes volúmenes de información. Actualmente se desempeña como técnico docente en la Universidad Técnica de Manabí y cuenta con un año de experiencia adicional como docente en modalidad online.

Ha participado en proyectos de investigación vinculados a la ciencia de datos, destacando su trabajo de tesis de posgrado titulado "Análisis de sentimientos utilizando la red social X (Twitter) para medir el nivel de aceptación del nuevo presidente del Ecuador, Daniel Noboa (noviembre 2023 - abril 2024)". También cuenta con dos artículos académicos publicados. Sus áreas de interés incluyen la inteligencia artificial, la minería de datos y el desarrollo de soluciones basadas en ciencia de datos. Sus objetivos profesionales actuales se centran en mejorar continuamente como docente y consolidarse como investigador en el área, contribuyendo con nuevas publicaciones científicas.

José Alberto León Alarcón

José León Alarcón es un profesional especializado en Ciencia de Datos, posee un máster en Sistemas de Información con mención en Data Science por la Pontificia Universidad Católica del Ecuador (PUCE Quito). Su formación académica se complementa con una sólida experiencia en el ámbito de la inteligencia artificial, especialmente en el aprendizaje automático (machine learning) y el aprendizaje profundo (deep learning). A lo largo de su trayectoria profesional, se ha enfocado en el análisis de imágenes médicas, contribuyendo al desarrollo de modelos capaces de apoyar el diagnóstico clínico mediante técnicas avanzadas de procesamiento de imágenes. Además, ha trabajado en la extracción y análisis de información a partir de datos complejos, aplicando metodologías estadísticas y herramientas computacionales modernas. Sus áreas de interés incluyen la inteligencia artificial, el análisis predictivo y el desarrollo de soluciones innovadoras que permitan transformar grandes volúmenes de datos en conocimiento útil para la toma de decisiones. Se caracteriza por su compromiso con la investigación aplicada y el desarrollo tecnológico orientado a resolver problemas reales.

ISSN:1390-9266 e-ISSN:1390-9134 LAJC 2025

AUTHORS

Jandry Hernando Franco Cantos

Ingeniero en Sistemas de Información con una Maestría en Ingeniería en Sistemas de Información, mención en Data Science. Ha formado parte de diversos proyectos enfocados en el desarrollo de software e implementación de soluciones basadas en inteligencia artificial, aplicadas al análisis de datos, la optimización de procesos y la automatización de tareas.

Actualmente se desempeña como docente universitario en la Universidad Técnica de Manabí, Ecuador, donde combina la formación académica con la investigación aplicada. Sus principales áreas de interés incluyen la inteligencia artificial, el aprendizaje automático, la visualización de datos y la ciencia de datos orientada a la toma de decisiones.

Cuenta con experiencia en la integración de herramientas tecnológicas en entornos educativos y productivos, participando activamente en iniciativas interdisciplinarias que promueven la innovación tecnológica con impacto real. Su enfoque profesional se basa en el desarrollo de soluciones prácticas y eficientes, alineadas con los avances actuales en ciencia y tecnología.

Comprometido con la formación de nuevas generaciones de profesionales, busca contribuir al avance del conocimiento científico y al desarrollo de tecnologías sostenibles que respondan a las necesidades actuales de la sociedad.

ISSN:1390-9266 e-ISSN:1390-9134 LAJC 2025

When Light Meets Sound: Signal Analysis of Black Holes

ARTICLE HISTORY
Received 25 March 2025
Accepted 7 May 2025
Published 7 July 2025

Guillermo Bolaños Rodríguez
Arqcustic
Acoustic engineer
Quito, Ecuador
arqcustic@gmail.com
ORCID: 0009-0002-0182-6675

ISSN:1390-9266 e-ISSN:1390-9134 LAJC 2025

G. Bolaños Rodríguez, "When Light Meets Sound: Signal Analysis of Black Holes", Latin-American Journal of Computing (LAJC), vol. 12, no. 2, 2025.

When Light Meets Sound: Signal Analysis of Black Holes

Cuando la Luz Encuentra el Sonido: Análisis de Señales de Agujeros Negros

Guillermo Bolaños Rodríguez
Arqcustic
Acoustic engineer
Quito, Ecuador
arqcustic@gmail.com

***Abstract*—** When light meets sound, a new dimension of analysis unfolds. This work explores black hole observations through the lens of signal theory and acoustic wave mechanics, revealing a resonant bridge between electromagnetic and mechanical waves. Using Event Horizon Telescope EHT data, black hole imagery is treated as a three-dimensional digital signal, where the analytic Hilbert envelope and normalized Discrete Fourier Transform DFT expose hidden structures.

The gravitational shadow is interpreted not as silence, but as a measurable energy dip—an imprint of absorption rather than absence. Euler's identity is employed to map signal phase and symmetry into polar and complex domains, providing an intuitive mathematical pathway toward the event horizon.

By applying foundational acoustic concepts such as resonance, interference, and entropy, the field surrounding the black hole is reinterpreted as a complex communication signal. This interdisciplinary framework unifies digital signal processing, electromagnetic theory, and acoustics into a novel methodology for astronomical analysis. Notably, when a full noise assessment is conducted, EHT images exhibit a significant enhancement in resolution and information transmission.

***Keywords*—** *black hole imaging, digital signal processing, Hilbert analytic envelope, frequency-domain analysis*

***Resumen*—** Cuando la luz se encuentra con el sonido, emerge una nueva dimensión de análisis. Este trabajo examina las observaciones de agujeros negros a través de la teoría de señales y la mecánica de ondas acústicas. Utilizando datos del Telescopio del Horizonte de Sucesos EHT, las imágenes de agujeros negros se tratan como señales digitales tridimensionales, donde la envolvente analítica de Hilbert y la Transformada Discreta de Fourier (DFT, sigla en inglés) normalizada revelan estructuras y simetrías ocultas.

La sombra gravitacional se interpreta no como silencio, sino como una caída medible de energía—una huella de absorción en lugar de una simple ausencia. La identidad de Euler se emplea para mapear la fase y la simetría de la señal en planos polares y complejos, ofreciendo un camino matemático intuitivo hacia el horizonte de eventos.

Al aplicar conceptos acústicos fundamentales como la resonancia, la interferencia y la entropía, el campo que rodea al agujero negro se convierte en una señal comunicativa. Este enfoque interdisciplinario unifica el procesamiento digital de señales, la teoría electromagnética y la acústica en una metodología innovadora para el análisis astronómico. Cabe destacar que, al realizar una evaluación completa del ruido, se logra una mejora significativa en la resolución y transmisión de información de las imágenes publicadas por el EHT.

***Palabras clave*—** imágenes de agujeros negros, procesamiento digital de señales, envolvente de Hilbert, análisis acústico, análisis en frecuencia

I. Introduction

Information transfer is a universal principle bridging quantum mechanics and classical communication, where all signals carry energy, meaning, and noise encapsulated in discrete packages such as numbers, letters, bits or waveforms.

Sonic language emerges when wave patterns become mutually intelligible between two or more individuals, enabling them to convey meaning. Written language, in turn, is a system of abstract symbols that represent the sound of the waveform; in this sense, a text functions like a musical score.

For example, vowels represent the shape the mouth must take to produce a given tone, while consonants define the articulation and structural rhythm of pronunciation. Although the combination of these symbols is remarkably expressive, different languages that share the same basic alphabet often act as acoustic privacy filters, where unfamiliar waveforms or combinations may be heard but not understood or readable.

Architectural acoustics addresses how signals travel from emitter to receiver, aiming to reduce distortion and preserve intelligibility particularly in the articulation of consonants, which are most susceptible to masking. In this analogy, amplitude corresponds to font size or pixel intensity, noise to typographic clutter or distortion, and reflections to the overlapping of tints and shadows that blur the visual message.

Epistemology refers to the study of knowledge itself: how we know what we know, what counts as valid information, and what frameworks we use to extract meaning from observation, therefore visual images from black holes can be studied like waves composed of discrete points or pixels.

In this study, images from EHT and PRIMO will serve as reference benchmarks to test the hypothesis that, by approaching the problem as an acoustic engineering task with the application of digital signal processing, it is possible to improve information transfer from black holes observations.

ISSN:1390-9266 e-ISSN:1390-9134 LAJC 2025
DOI: https://doi.org/10.33333/lajc.vol12n2.04

II. DIGITAL DOMAIN WAVES

In sound engineering, natural signals such as speech or the sound produced by a musical instrument are identified as unique, non-repeatable events that exist only once in life. Information transfer between source and receiver occurs within fractional time intervals, relative to a synchronization function. If a message is not understood, the receiver may request repetition from the emitter.

In other cases, such as in noisy classrooms or Moiré-style animations, the brain demonstrates the ability to reconstruct incomplete signals. This occurs because familiar waveforms are stored within a perceptual database, allowing the cognitive system to interpolate missing information and preserve semantic meaning.

Digital audio, image and video work with this cognitive behavior, where a continuous data frame of discrete voltage values creates the illusion of sound or motion perception, known as sampling frequency or frames per second fs.

To encode an analog waveform with minimal information loss, the Nyquist–Shannon sampling theorem must be satisfied, the sampling frequency fs must be at least twice the highest frequency component present in the signal to ensure accurate reconstruction [1]. In architectural practice, this concept finds a parallel: defining a distance or magnitude requires at least two reference points, from L_0 to L_x. Once these boundaries are established, the midpoint can be calculated as the arithmetic mean.

To increase resolution, the interval between limits can be subdivided by increasing the fs, however, this is constrained by both the capabilities of the measurement tools and the limits of human perception. For instance, a one-meter length can be divided into 1.000 millimeters, approaching the practical threshold of visual or mechanical resolution, for greater precision, microscopy techniques become necessary.

Moreover, the meter itself is an abstract standard of length defined independently of individual perception. This is precisely why standardization is essential in commercial transactions, where relying solely on human perception could lead to misinterpretation or dispute.

A. Bit Depth

In binary encoding, the number of bits determines the possible amplitude levels that a digital signal can adopt (1). This relationship follows natural binary reproduction growth.

$$N_n = 2^{bits}, \tag{1}$$

For an 8-bit signal, this results in 256 levels ranging from N_0 to N_{n-1} , and a 32-bit audio signal has over 4 billion possible discrete states, providing extremely fine resolution as represented in Fig. 1.

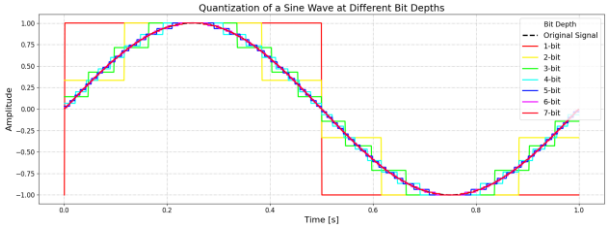

Fig. 1. Bit depth influence in waveform amplitud representation

In Python, tools from matplotlib library such as histogram, contour maps, 3D surface plots and colormaps are useful to analyze the distribution of amplitude across the pixel intensities in each image channel.

Fig. 2 presents the channel analysis for the M87 EHT image. On screen pixel intensity often results in perceptual masking of lower levels. To enhance the visual interpretation of channel information, an HSV colormap has been applied on the 3D surface plot.

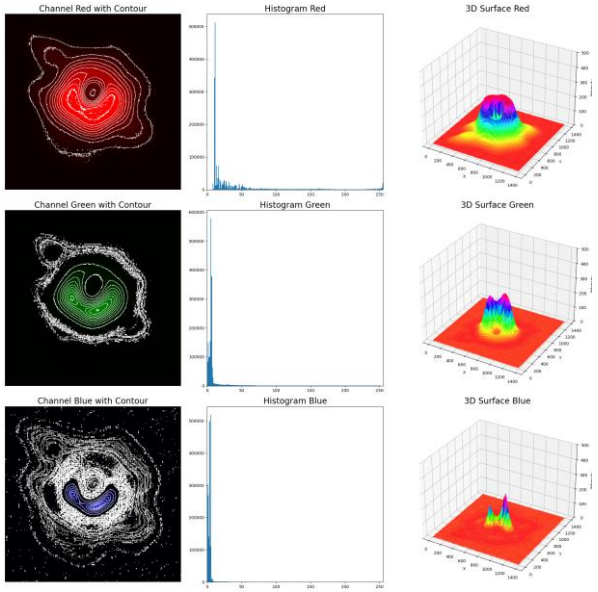

Fig. 2. Amplitude distribution in M87 EHT in RGB channels M87 EHT.

By applying a simple level adjustment in Photoshop to the M87 images presented in the work of Lia Medeiros et al. which used the PRIMO algorithm on the original 2019 EHT data [2], sharp transitions in brightness become immediately visible in Fig. 3. These features are not apparent in the original images due to perceptual masking, much like how background noise blurs speech intelligibility in architectural spaces.

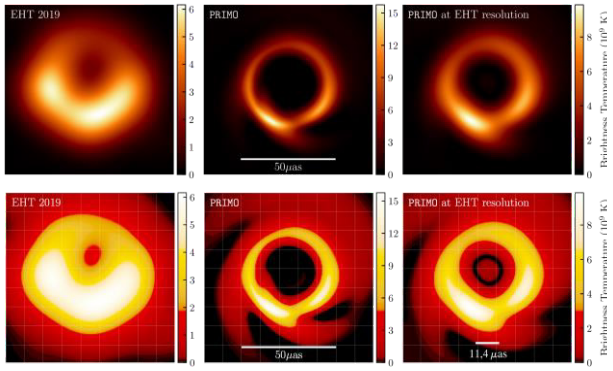

Fig. 3. Level adjustment in Photoshop applied to M87 black hole images from Lia Medeiros *et al* 2023 *ApJL* **947** L7.

In image analysis, the histogram allows study the distribution of pixel intensity values across discrete levels. Applying the Discrete Fourier Transform (DFT) to the histogram allows the pixel intensity distribution to be treated as a finite signal, enabling the analysis of tonal structure in terms of frequency components [3].

ISSN:1390-9266 e-ISSN:1390-9134 LAJC 2025
DOI: https://doi.org/10.33333/lajc.vol12n2.04

The histogram DFT is defined as (2):

$$X[k] = \sum_{n=0}^{N_n-1} x[n] \cdot e^{-\frac{j2\pi nk}{N_n}} \quad k = 0,1,2,\dots N_n - 1, \quad (2)$$

Where x[n] is the histogram value at intensity level n, N_n is the number of bins, k is the frequency index, and X[k] are the DFT coefficients representing the frequency content of the histogram.

Fig. 4 shows a comparison between different black holes available images including M87 and Sagittarius A*. A consistent spectral pattern can be observed: the red channel exhibits a higher concentration of high-frequency components, while the green and blue channels are dominated by lower-frequency content, that tends to resemble a modal shape present in room acoustics response.

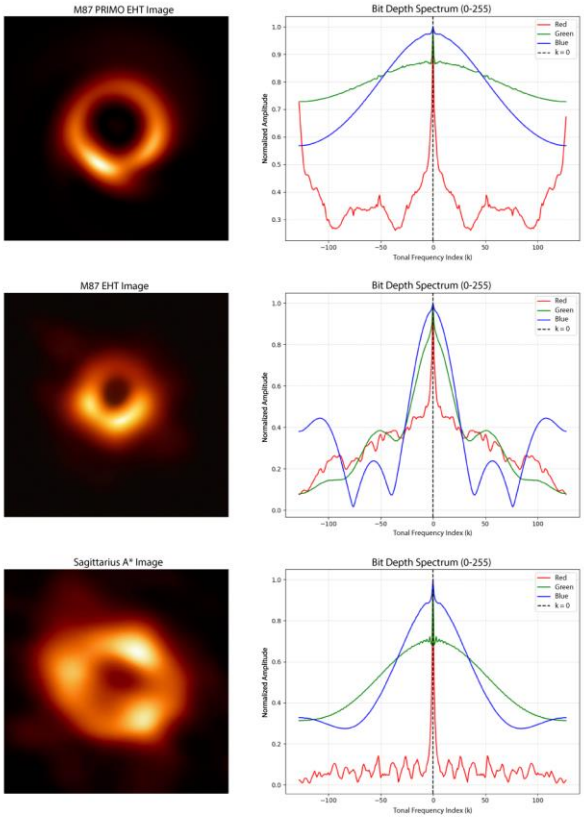

Fig. 4. Histogram DFT comparision of black holes images.

B. *Entropy*

To relate how bit depth links amplitude to discrete values through quantization, it is worth taking a quick detour into quantum mechanics. In his foundational paper [4], Max Planck introduced a statistical interpretation of entropy in systems of electromagnetic resonators, he stated that "Entropy implies disorder, and this disorder, according to the theory of electromagnetic radiation, arises in monochromatic oscillations of a resonator".

In an RGB image, each channel can be thought of as an independent monochromatic resonator as considered before.

Planck mentions that entropy S of such a system is related to the Boltzmann constant k_b and the number of microstates N_n (3):

$$S = k_b \cdot \log(N_n) \quad (3)$$

Harry Nyquist, on the other hand [5], considered that the maximum speed W of transmission is related to the number of current values m, where in a circuit a line speed (4) is:

$$W = K \cdot \log(m) \quad (4)$$

Where K is a constant and m represents the number of characters, in this case the number of available levels, the higher the number of signal elements, the higher the amount of intelligence. Nyquist explains that if n is the number of signal elements per character, the total number of characters that can be constructed is m^n, given binary code has two characters 2^n levels can be generated, reinforcing the connection between entropy, information capacity, and bit depth.

Claude Shannon, in his foundational work A Mathematical Theory of Communication , formalized this link by defining entropy H as a measure of uncertainty in the information source. The Shannon entropy (5) is given by:

$$H = -K \sum_i p_i \log_2(p_i) \quad (5)$$

Where p_i is the probability of observing state i, and K is a constant depending on the system that may be taken as the Boltzmann constant, as Planck suggested. The probability pi is a function of the available states (6):

$$p_i = \frac{1}{N_n} \quad (6)$$

In Fig. 5, using the entropy filter from scikit-image, with a 5-pixel moving window is used to extract hidden informational patterns, then a denoised gaussian filter was applied to achieve a more stable image from grayscale data.

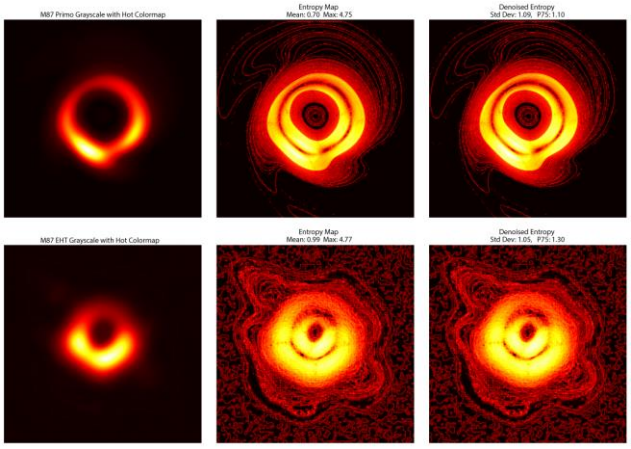

Fig. 5. Shannon`s entropy analysis of M87 PRIMO and EHT.

Fig. 6 shows entropy profiles for each monochromatic channel considered independently as well as for DFT. In the green and blue channels, informational content that was previously hidden in the lower tonal levels of these systems is now perceptual. In contrast, the red channel exhibits a DFT response that strongly resembles a sinc function, a behavior well-known in the electroacoustic of multiple speaker arrays.

ISSN:1390-9266 e-ISSN:1390-9134 LAJC 2025
DOI: https://doi.org/10.33333/lajc.vol12n2.04

This pattern implies the presence of coherent constructive interference and well-defined transitions between ordered and disordered zones within the red entropy field.

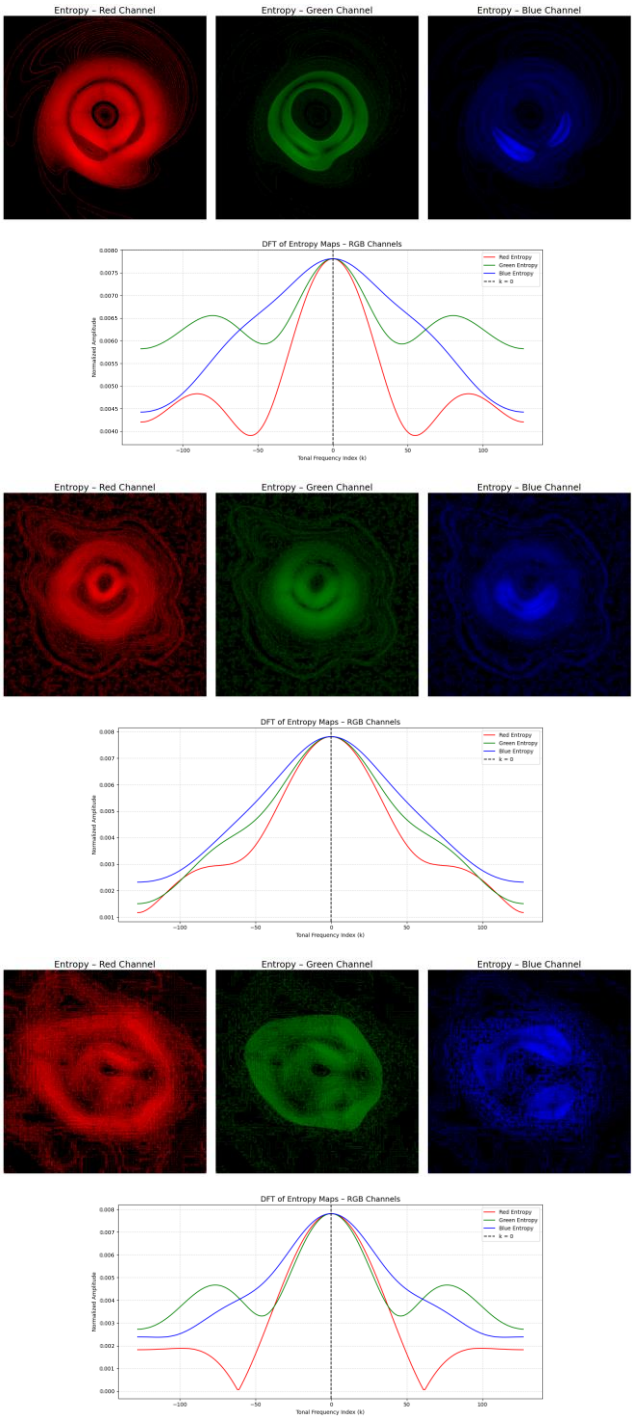

Fig. 6. Entropy comparison between M87 EHT, M87 PRIMO and Sag A* and DFT histogram analysis

If each state is equally probable in a uniform quantization system (7), and the number of possible states at level 2^n:

$$H_n = -K \sum_{i=1}^{2^n} \frac{1}{2^n} \log_2 \left(\frac{1}{2^n}\right) = -K \log_2(2^n) = Kn \qquad (7)$$

Increasing bit depth increases quantization states, raising entropy and information resolution. However, this depends on the sample rate, while post-production quantization or posterizing is possible, lost information can't be restored unless artificial data is added adding uncertainty.

Interestingly, this growth in informational potential can be likened to Hooke's law (8), where the restoring force in a spring is proportional to its displacement:

$$F = -K \cdot \Delta x \qquad (8)$$

In this analogy, K represents the stiffness of the system or its informational elasticity, and Δx corresponds to the amplitude of motion, which can relate to Nyquist speed information or intelligence transmission.

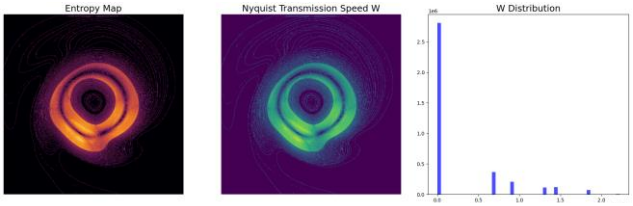

Fig. 7. Nyquist transmission speed distribution

John William Strutt also known as Lord Rayleigh, in The Theory of Sound [6] explains that stiffness constants K governs the propagation speed of wavefront in stretched string and can be derived from Hooke`s Law, where K as in entropy depends on the material properties as the Young's modulus E and the cross-sectional area A.

In elastic theory, the tension T (9) stored in a string of natural length L when stretched to a length L′ is given by:

$$T = E \cdot A \cdot \frac{L` - L}{L} \qquad (9)$$

The wavefront speed c (10) is related to the tension and the linear mass density μ, or as in special relativity theory to the energy e and the mass of the particle m:

$$c = \sqrt{\frac{T}{\mu}} = \sqrt{\frac{e}{m}} \qquad (10)$$

As in quantum mechanics, standing waves in strings respond to discrete modes. Their natural frequencies (11) are harmonically related and constrained by the length of Lx, where the fundamental mode corresponds to a wavelength that is twice the length λ = 2Lx:

$$f_n = \frac{nc}{2Lx} = \frac{nc}{\lambda_n} = nf \qquad (11)$$

The greater the stretch of a string, the greater the tension, the greater wavefront speed c, where higher elastic energy storage state leads to higher frequency oscillations. This behavior mirrors Planck's quantum energy relationship (11):

$$E = hf = \frac{nhc}{2Lx} = \frac{nhc}{\lambda_n} \qquad (11)$$

Where h is the Planck`s constant, that is the linear expression of the reduce Planck's constat $h = 2\pi\hbar$, that represent the angular momentum of the electron in Bohr radius of the hydrogen atom where $\hbar = 1{,}05\ x\ 10^{-34}$ (kg·m²·s⁻¹).

The rest of the energy is stored as passive energy in a system due to its configuration. For example, tension in a stretched string allows the system to oscillate, where the potential energy is at equilibrium (12), in relativistic terms:

$$E_0 = mc^2 \tag{12}$$

In a stretched string or elastic system, the static displacement x_0 (13) due to pre-tension increase speed:

$$E_{rest} = \frac{1}{2} K {x_0}^2 \tag{13}$$

Dynamic energy is the energy fluctuating around the equilibrium due to a disturbance (14), where the acoustic pressure emitted by a string instrument if proportional to the initial input force or the amplitude Δx of motion, which relates to mass times acceleration, as in Newton's second law:

$$E_{dyn} = \frac{1}{2} K \Delta x^2 \tag{14}$$

Without a triggering force, the system remains at rest, but already energized, like a compressed spring or a charged field, the higher the tension the lower the amplitude of motion available thus less string is available to oscillate (15):

$$E_{total} = E_{rest} + E_{dyn} \tag{15}$$

This principle has analogies in electronic and acoustic systems, for instance, a camera shutter requires a baseline voltage to operate or rest energy, generating a background noise floor, especially evident at high ISO settings.

Fig. 8 completes the entropy analysis, where the histograms are flattened and smoothed using a Gaussian filter. The first and second derivatives are then calculated using NumPy.Gradient. The relative mass is defined as the normalized pixel intensity x_i relative to the entropy scale 8-bit scale where $m = x_i/8$.

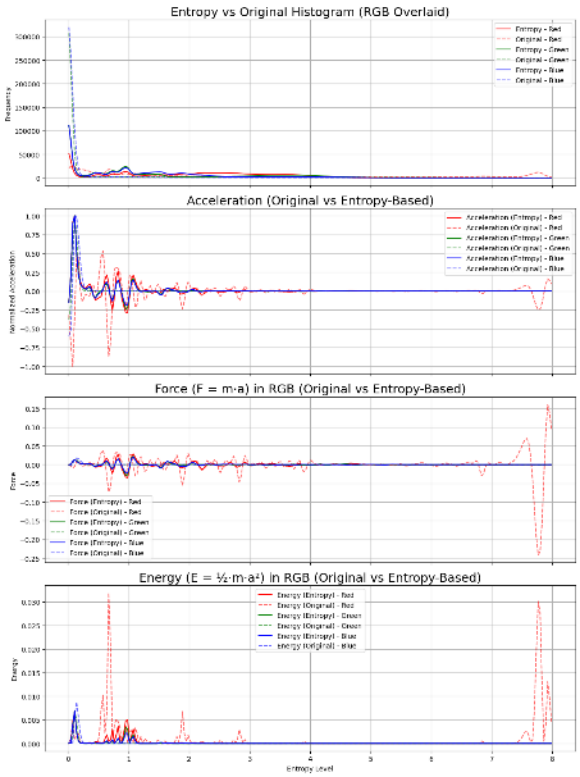

Fig. 8. Comparison between entropy-based and original histograms of the M87 PRIMO image

C. *Histogram equalization*

In digital image processing, histogram equalization is a contrast enhancement technique that redistributes pixel intensities to span the full dynamic range. This prevents the clustering of values within a narrow band, as seen in earlier unprocessed images.

This implementation, shown in Fig. 9, applies OpenCV's cv2.equalizeHist function, followed by a Gaussian blur to reduce noise and improve local uniformity. The resulting intensity distribution is visualized both as a 2D heatmap and as a 3D surface using Axes 3D

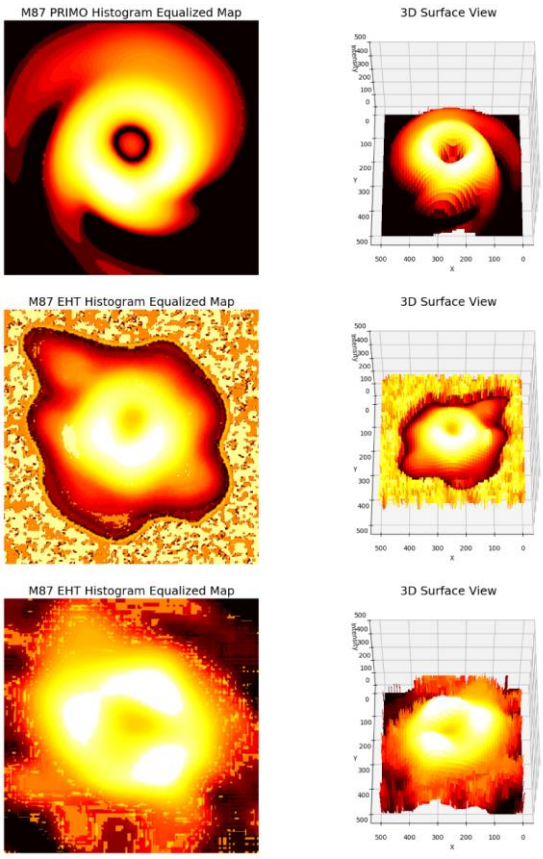

Fig. 9. Visualization of histogram equalization and 3D Surface

For a more detailed 3D representation, in Fig. 10 Plotly was used to generate interactive surfaces with real-time control over lighting, angle, and zoom. This not only enhances visual analysis but also enables the export of the surface as a 3D printable heightmap, bridging digital signal processing and physical modeling.

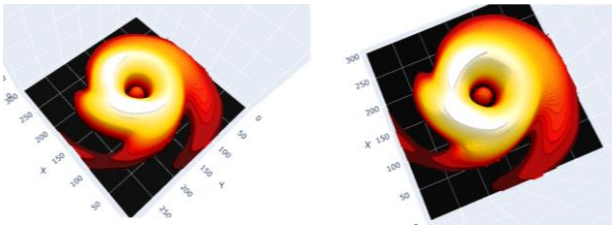

Fig. 10. M87 PRIMO Plotly 3D histogram equalization

From this analysis PRIMO-enhanced image reveals a lower rest energy, evidenced by its reduced background entropy and more efficient use of dynamic range.

ISSN:1390-9266 e-ISSN:1390-9134 LAJC 2025
DOI: https://doi.org/10.33333/lajc.vol12n2.04

D. Bit planes

Bit plane decomposition is a technique used in digital image processing to analyze the contribution of each individual bit in the binary representation of pixel intensity values [7]. In an 8-bit RGB image, each channel contains 8 binary layers ranging from the most significant bit MSB or bit 7 to the least significant bit LSB or bit 0.

Applying this analysis to M87 PRIMO in Fig. 11, it reveals that in the green and blue channels, most of the structural information is concentrated at the LSB level.

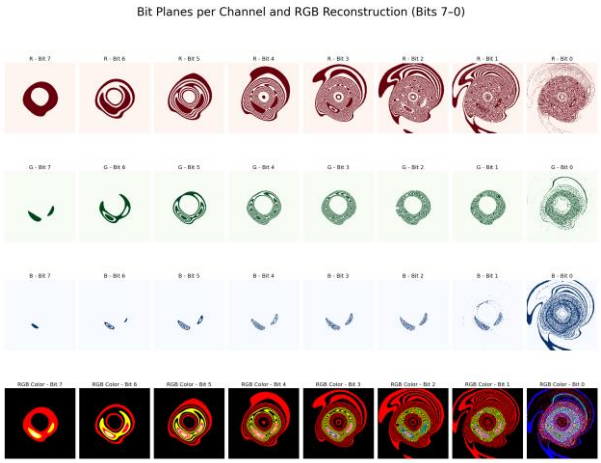

Fig. 11. Bit plane descomposition of M87 PRIMO

In bit 2 and bit 1, spherical or radial surfaces are notable in the area near the central body, this reveals that coherent information of low order is present in Fig. 12, while on M87 and Sag A* EHT background noise and distortion begin to be predominant in this area.

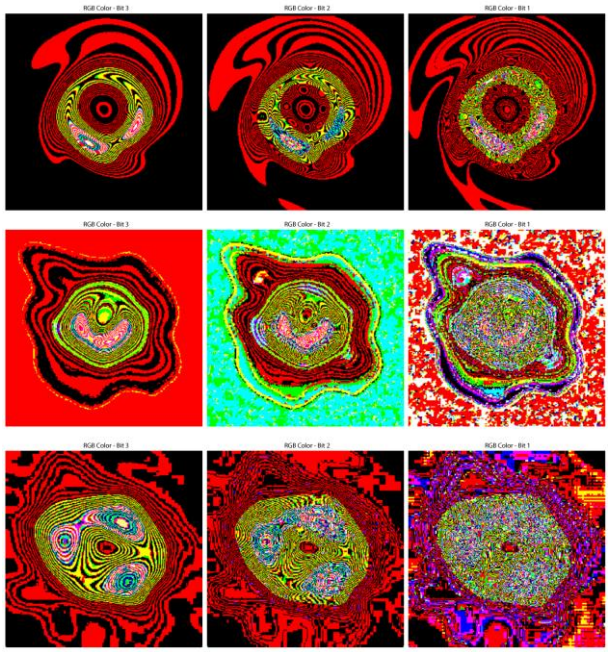

Fig. 12. Bit plane 3,2,1 closeup for M87 PRIMO, EHT and Sag A*.

In acoustics, sound diffusers are based on the quadratic residue series discovered by Carl Friederich Gauss, which were later explored by Manfred Schroeder in his book Number Theory in Science and Communication [8]. These sequencies have been used from signals analysis to acoustic design of concert halls.

Bit-plane's phase level is determined by the modulus of the prime number (16) of the MSB plane.

$$d_n = n^2 mod(p) \tag{16}$$

By analogy, this principle can be applied to bit planes in digital images or signals, such that the bit index n∈[0,7] acts as the spatial sample, a prime modulus p defines the residue cycle, the resulting d_n acts as a phase level assigned to each plane as in Fig. 13.

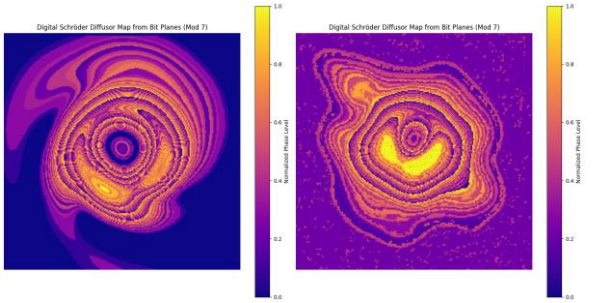

Fig. 13. QRD mod 7 of bit plane descomposition of M87 PRIMO and EHT

In binary encoding, the number of bits determines the possible frequencies or energy levels that can be represented inside the Nyquist theorem, where 1-bit or binary ground state can hold two digits like the number of electrons in Bohr radius. The Sommerfeld and Pauli exclusion model establish that an electron can occupy a specific energy level, determined by the possible combinations of the quantum numbers n, l, m, and the electron spin up and down.

The quadratic value then represents a sum of the odd numbers (17), that can start in 0 like in binary planes or in 1 like in quantum mechanics.

$$n^2 = \sum_{l=0}^{n-1}(2l+1) = \sum_{l=1}^{n-1}(2l-1) \tag{17}$$

This can be extended to Girolamo Cardano theorem for the cubic root or the basic of complex numbers, where nonlinear combinations of bit layers reconstruct coherent energy.

$$x = \sqrt[3]{\frac{q}{2} + \sqrt{\left(\frac{q}{2}\right)^2 + \left(\frac{p}{3}\right)^3}} + \sqrt[3]{\frac{q}{2} - \sqrt{\left(\frac{q}{2}\right)^2 + \left(\frac{p}{3}\right)^3}} \tag{18}$$

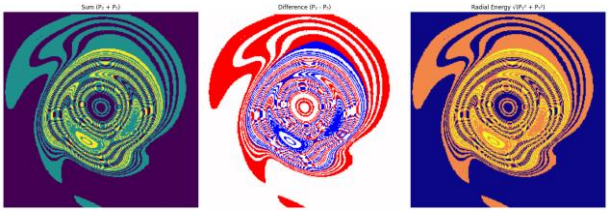

Fig. 14. DFT of centered frequency and pixel intensity values

ISSN:1390-9266 e-ISSN:1390-9134 LAJC 2025
DOI: https://doi.org/10.33333/lajc.vol12n2.04

III. INTERFERANCE PATTERNS

Digital images behave much like an audio signal, a composition of discrete values to storage a mix of oscillations, harmonics, and amplitude. The key distinction lies in the domain; these modulations are distributed across a two-dimensional spatial plane rather than time.

Considering the Nyquist-Shannon theorem, a pixel with intensity 1 can be represented at the other side of the central or neutral value 127 or fs/2. This means that when the image is inverted in phase, the new pixel values is 254 and vice versa.

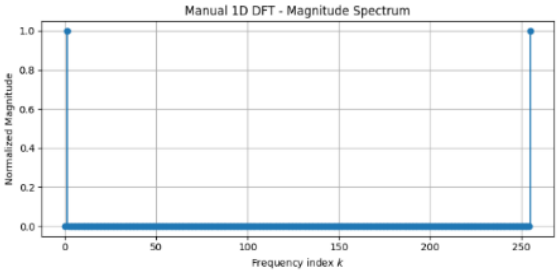

Fig. 15. DFT of centered frequency and pixel intensity values

This interpretation allows us to understand a digital image as a frozen waveform, where each pixel captures a discrete amplitude value. In the RGB color model, its inverse corresponds to the CYM (Cyan–Yellow–Magenta) color complement. Thus, both representations are mathematically linked, forming a dual system where color and anti-color are symmetrically encoded, or energy and dark energy.

By combining the original image with its inverted version, various interference patterns can be generated using simple mathematical operations—such as addition, subtraction, multiplication, division, mean, or root sum of squares. These operations simulate constructive or destructive interference, which can be used to enhance color contrast, suppress noise, or reveal latent geometric structures within the image.

Fig. 16 shows that for M87 PRIMO the sum of squares improves image quality notable; it tends to be the same representation of the bit plane 2 with the difference that the radial shapes are not present. This is a simpler process that can be performed in any digital image software but in python, mathematics between signals can represent physics equations.

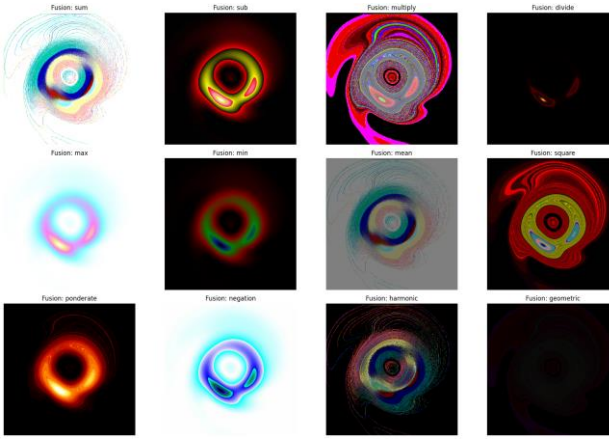

Fig. 16. Interference patterns for M87 PRIMO

This process behaves like a quick tool allowing comparative evaluations and signal chain optimizations, that can be conceptualized like auxiliary channels or parallel image processing, side-chain compression or frequency-space filtering.

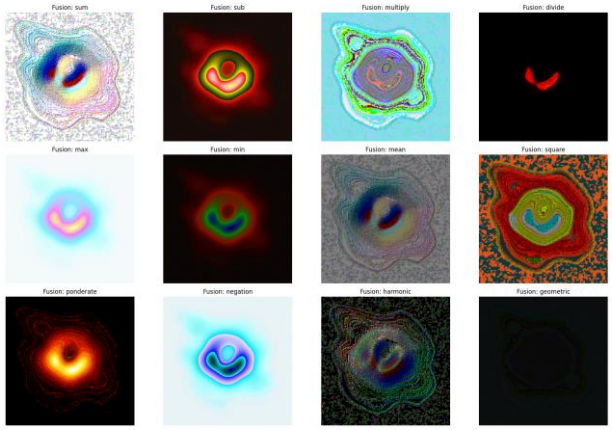

Fig. 17. Interference patterns for M87 EHT

Each image behaves like a reverberant space, analogous to an acoustic room, where every geometry responds uniquely. Therefore, image fusion becomes site-specific engineering, requiring tailored mathematical approaches for each context.

For example, Fig. 18 shows the mantissa fusion method for M87 EHT, this allows the increase of detail, where around the accretion disk radial bodies are present.

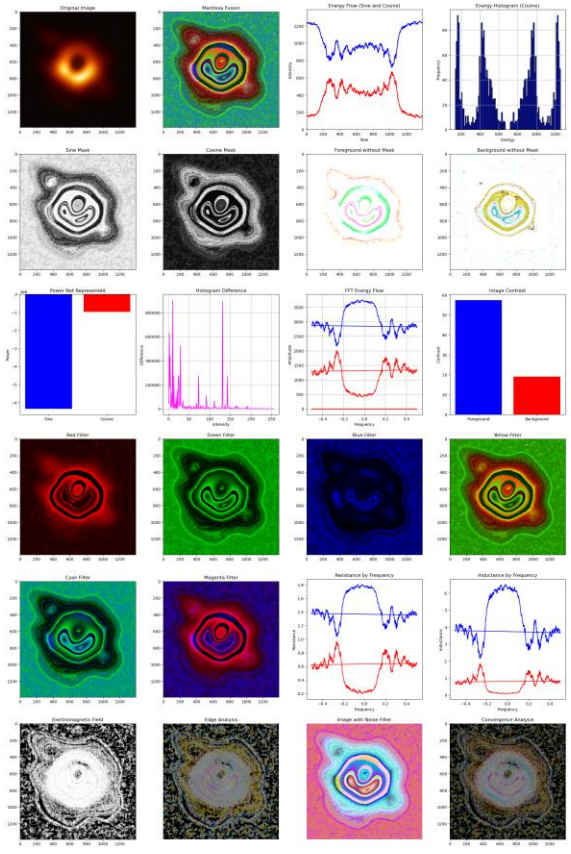

Fig. 18. Mantissa fusion for M87 PRIMO with color filters

ISSN:1390-9266 e-ISSN:1390-9134 LAJC 2025
DOI: https://doi.org/10.33333/lajc.vol12n2.04

IV. Complex Signal Analysis

Every signal carries more than just what is visible or audible, it encodes phase, rotation, frequency content, and damping. In the case of naturally damped waves, these properties define how energy propagates and fades. All systems inherently possess a natural reverberation time, dictated by their boundary conditions, constructive interference from wave superposition and energy dissipation.

Emerging from Cardano's solutions to cubic equations, later formalized by Gauss and explored by Euler, complex numbers have become indispensable in signal analysis, they allow to model phase, represent signal rotation in the complex plane, and analyze spectral components with far greater precision.

For any real-value wave, the Hilbert function form SciPy provides a powerful tool for constructing its complex analytic signal. This transformation enables the creation of a Hilbert analytic envelope (19), which reveals the instantaneous amplitude and phase of the original waveform.

$$s(t) = x(t) + j\hat{x}(t) \tag{19}$$

Fig. 19 shows the basic script to get the complex signal that can be decomposed on positive and negative phases, that can be useful to study interferometric asymmetries, signal polarity, and resonance structure, which are crucial for analyzing wave behavior, modulated textures, and perceptual balance in images and acoustic fields.

```python
import numpy as np
import matplotlib.pyplot as plt
from scipy.signal import hilbert
from PIL import Image

def hilbert_envelope(image):
    """
    Apply Hilbert Transform to get the analytic signal.
    This function computes the analytic signal (complex), then extra
    the envelope (magnitude) and instantaneous phase.
    """
    # Apply Hilbert Transform to get the analytic signal
    analytic_signal = hilbert(image)

    # Calculate the envelope (magnitude of the analytic signal)
    envelope = np.abs(analytic_signal)

    # Calculate the instantaneous phase (angle of the analytic signa
    instantaneous_phase = np.angle(analytic_signal)

    # Apply Hilbert Transform and get envelope and instantaneous pha
    envelope, instantaneous_phase = hilbert_envelope(image)

    # Create a mask for positive and negative phases
    positive_phase_mask = instantaneous_phase > 0
    negative_phase_mask = instantaneous_phase <= 0

    # Extract the positive and negative phase components
    positive_phase = np.zeros_like(image)
    negative_phase = np.zeros_like(image)

    # Fill the positive and negative phases based on the masks
    positive_phase[positive_phase_mask] = image[positive_phase_mask]
    negative_phase[negative_phase_mask] = image[negative_phase_mask]

    return positive_phase, negative_phase, instantaneous_phase
```

Fig. 19. DFT of centered frequency and pixel intensity values

Fig. 20 shows that black hole observations carry phase information, when processed through a Hilbert-based algorithm directional interference patterns emerge.

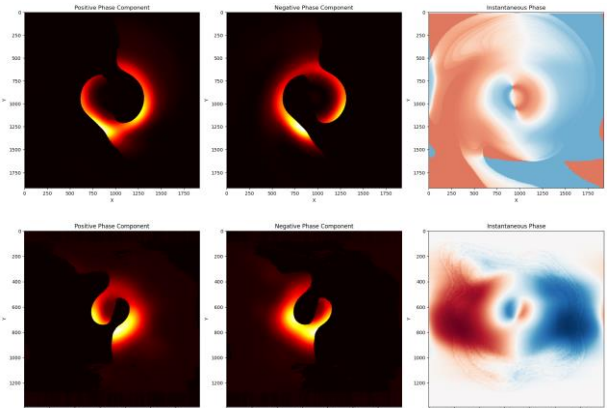

Fig. 20. Filtered phase decomposition with Hilbert-based environment

Applying a Gaussian high-pass filter before computing the Hilbert envelope to reduce bass helps enhance fine detail. This procedure, commonly used in audio processing, shows that each phase carries complete information. A standing wave pattern simulates resonance within a bounded system, like a membrane or room, as a synthetic interferogram, where positive and negative phases are spatially modulated to simulate real wave superposition. What is interesting about this procedure is that rarefaction and compression is visible on the accretion disk.

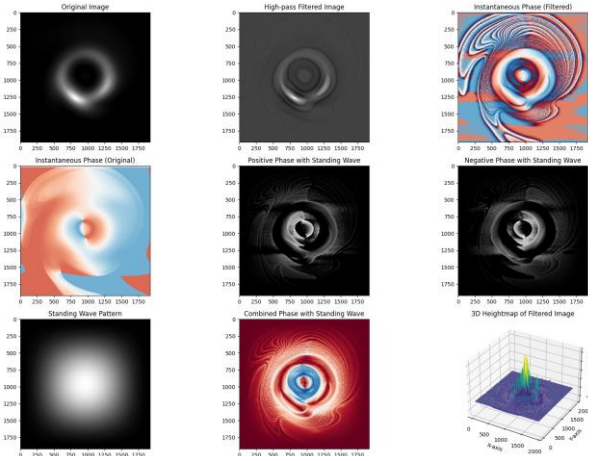

Fig. 21. Filtered phase with interferogram standing wave M87 PRIMO

Applying cosine and sine mask to the instantaneous phase a complex angular wave can be obtained; this shows that more information is present on the background noise.

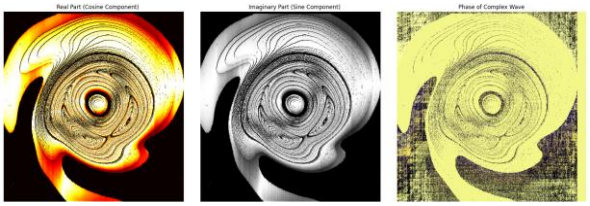

Fig. 22. DFT of centered frequency and pixel intensity values

ISSN:1390-9266 e-ISSN:1390-9134 LAJC 2025
DOI: https://doi.org/10.33333/lajc.vol12n2.04

Another type of analysis derived from Hilbert space representations includes the construction of vector fields using quiver plots, 3D point cloud visualizations for modeling, phase histograms, polar representations of the complex waveform, and even streamlines of the electric field. In this case, the electric field is estimated by applying a Sobel operator to the cosine component. For this approach, sine and cosine masks were first applied to the image, and then the Hilbert analytic envelope was computed separately.

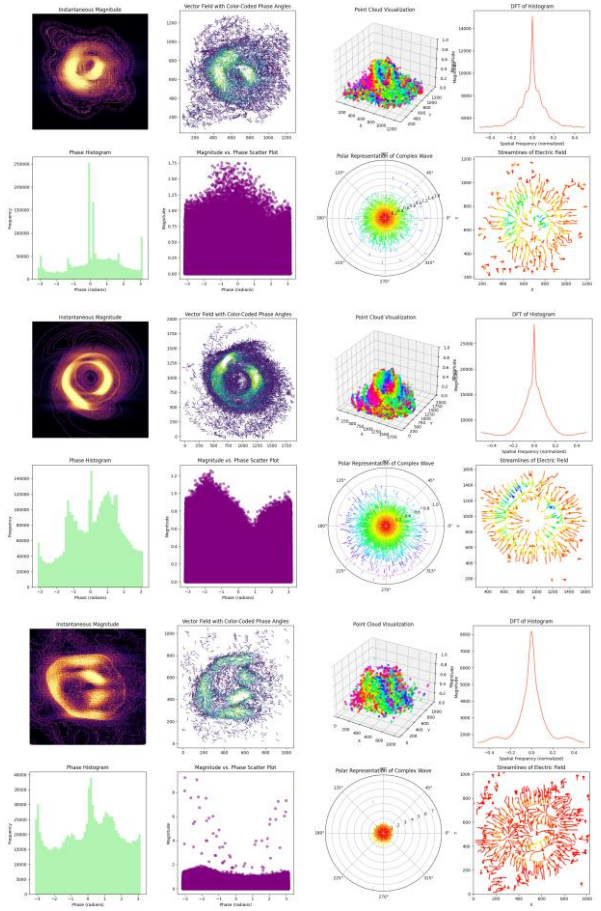

Fig. 23. Quiver, streamlines, and polar representation derived from analytic Hilbert envelope of sine and cosine mask of M87 EHT, PRIMO and Sagittarius A*

V. CONCLUSSIONS

By analyzing data from the EHT and PRIMO reconstructions, digital images were treated as multidimensional signals within a finite boundary space analogous to a reverberant room.

Although the event horizon is considered the theoretical boundary beyond which light cannot escape, and the accretion ring marks this luminous frontier, this study shows that valuable structural and energetic information can still be extracted both within and around that limit. Radial features previously obscured become perceptible, which may suggest the presence of multi-orbital structures or, alternatively, highlight artifacts introduced by the image reconstruction algorithms themselves. More profound research is needed to confirm the nature of these structures to get a valid scientific affirmation.

The PRIMO algorithm yields a more stable and coherent representation of the M87 black hole with a lower background level. However, to ensure greater data fidelity and structural insight, it is recommended that the Event Horizon Telescope Collaboration apply the same analytical approach to the Sagittarius A* dataset to compare results.

All the signal and image analysis presented in this work has been conducted using Python-based open-source tools and exclusively using publicly available images released by EHT Collaboration. Due to file compression, noise artifacts, and potential preprocessing steps applied during data publication, RAW datasets could bring more valid scientific conclusions.

ACKNOWLEDGMENT

The author wish to thank the comments and feedback from the anonymous reviewer for giving this paper a more coherent form.

This research received no external funding and is a small part of a broader research effort carried out over the past two years. All findings result from mathematical operations rooted in signal theory and acoustics, although artificial intelligence provided coding assistance, the true spark of understanding stems from human connection. A book, in this sense, is not just a container of information, it is a short circuit between minds, bridging time, space, and lived experience.

As Marshall Long points out in Architectural Acoustics, “Houtgast, Steeneken, and Plomp reasoned that stars are the spatial equivalent of an acoustical impulse source” idea that eventually led to the Speech Transmission Index STI, derived from the Modulation Transfer Function MTF. In that same spirit, this research proposes that when light meets sound, acoustic engineering can provide a robust framework for analyzing astrophysical phenomena.

REFERENCES

[1] C. E. Shannon, A Mathematical Theory of Communication, The Bell System Technical Journal, Vol. 27, pp. 379–423, 623–656, 1948.

[2] L. Medeiros, D. Psaltis, T. R. Lauer, and F. Özel, The Image of the M87 Black Hole Reconstructed with PRIMO, The Astrophysical Journal Letters, 947:L7 , 2023.

[3] J.W. Cooley, J. W. Tukey, An algorithm for the mathematic calculation of complex Fourier series, Mathematics of Computation, Vol. 19, pp. 297–301, 1965

[4] M. Planck, Über das Gesetz der Energieverteilung im Normalspectrum. Annalen der Physik, 4, pp. 553–563, 1901.

[5] H. Nyqusit, Certain Factors Affecting Telegraph Speed, The Bell System Technical Journal, vol. 3, no. 2, pp. 324-346, 1924

[6] J. W. Strutt, Lord Rayleigh, Theory of Sound, Volume 1, Macmillan and Co, London, pp. 127-128, 1877.

[7] J. W. Schwartz and R. C. Barker, Bit-Plane Encoding: A Technique for Source Encoding, in IEEE Transactions on Aerospace and Electronic Systems, vol. AES-2, no. 4, pp. 385-392, 1966

[8] M. Schoeder, Number Theory in Science and Communication, Fifth Edition, Springer-Verlag Berlin Heidelberg, pp. 219-226. 2009 ISBN: 978-3-540-85297-1

AUTHORS

Guillermo Bolaños Rodríguez

Guillermo Bolaños Rodríguez is an acoustic engineer and signal analyst specializing in the intersection of quantum physics, architectural acoustics, and digital signal processing. His work explores how concepts like resonance, energy dissipation, and modal behavior can be unified across physical and astrophysical systems. He develops computational models that treat digital images and acoustic spaces as energy landscapes, applying techniques such as Fourier analysis, Hilbert transforms, and phase-based visualization to uncover hidden structures in both architectural environments and astronomical observations. His experience includes the acoustic design of theaters and recording studios in several cities across Ecuador, where he integrates theoretical frameworks with real-world applications. Currently, he is seeking to develop an educational initiative to address the widespread lack of acoustic awareness in Ecuadorian society, aiming to bridge scientific knowledge with public understanding.

G. Bolaños Rodríguez, "When Light Meets Sound: Signal Analysis of Black Holes", Latin-American Journal of Computing (LAJC), vol. 12, no. 2, 2025.

ISSN:1390-9266 e-ISSN:1390-9134 LAJC 2025

Development of a desktop application prototype for blood banks

ARTICLE HISTORY
Received 1 May 2025
Accepted 10 June 2025
Published 7 July 2025

Lucrecia Llerena
Quevedo State University
Software Engineering Program
Quevedo, Ecuador
lllerena@uteq.edu.ec
ORCID: 0000-0002-4562-6723

Belinda Toaquiza
Quevedo State University
Software Engineering Program
Quevedo, Ecuador
btoaquizaz@uteq.edu.ec
ORCID: 0009-0001-1487-7757

Nancy Rodríguez
Quevedo State University
Software Engineering Program
Quevedo, Ecuador
nrodriguez@uteq.edu.ec
ORCID: 0000-0002-0861-4352

ISSN:1390-9266 e-ISSN:1390-9134 LAJC 2025

L. Llerena, B. Toaquiza, and N. Rodríguez, "Development of a desktop application prototype for blood banks", Latin-American Journal of Computing (LAJC), vol. 12, no. 2, 2025.

Desarrollo de un prototipo de aplicación de escritorio para bancos de sangre

Development of a desktop application prototype for blood banks

Lucrecia Llerena
Quevedo State University
Software Engineering Program
Quevedo, Ecuador
lllerena@uteq.edu.ec

Belinda Toaquiza
Quevedo State University
Software Engineering Program
Quevedo, Ecuador
btoaquizaz@uteq.edu.ec

Nancy Rodríguez
Quevedo State University
Software Engineering Program
Quevedo, Ecuador
nrodriguez@uteq.edu.ec

Resumen —En esta investigación, se desarrolló un prototipo de aplicación de escritorio orientado a optimizar la gestión de bancos de sangre, con énfasis en el control de inventarios y la programación de citas para donaciones. El objetivo del estudio fue desarrollar una solución informática accesible que automatice procesos administrativos y contribuya a una gestión más eficiente y segura de los recursos sanguíneos. La metodología empleada fue el marco ágil Scrum, con el desarrollo organizado en iteraciones quincenales. La herramienta utiliza SQL Server como sistema gestor de base de datos por su fiabilidad y seguridad. La validación se llevó a cabo en un entorno simulado representativo de un banco de sangre, utilizando escenarios diseñados para emular tareas reales en la gestión de donaciones. Además, se realizó una evaluación de usabilidad con usuarios reales mediante entrevistas estructuradas, quienes identificaron fortalezas y oportunidades de mejora en la interfaz. Los resultados evidenciaron una reducción significativa de errores en los registros, mayor eficiencia operativa y una mejora en la interacción con los donantes. La evaluación de usabilidad reveló necesidades de refinamiento en la experiencia visual, propuestas como la incorporación de tutoriales interactivos y mejoras en los formularios de entrada de datos. Se concluye que el prototipo cumple satisfactoriamente los objetivos planteados, representando una solución tecnológica eficaz para fortalecer la seguridad transfusional y apoyar la toma de decisiones clínicas en contextos de infraestructura limitada.

Palabras clave— *bancos de sangre, gestión de inventarios, donaciones voluntarias, aplicación de escritorio, seguridad transfusional, automatización*

Abstract —In this research, a prototype desktop application was developed to optimize the management of blood banks, with emphasis on inventory control and scheduling appointments for donations. The objective of the study was to develop an accessible software solution that automates administrative processes and contributes to a more efficient and secure management of blood resources. The methodology used was the agile Scrum framework, with the development organized in biweekly iterations. SQL Server was used as the database manager due to its robustness and security. Validation was carried out in a simulated environment representative of a blood bank, using scenarios designed to emulate real tasks in the management of donations. In addition, a usability evaluation was conducted with real users through structured interviews, who identified strengths and opportunities for improvement in the interface. The results showed a significant reduction in record-keeping errors, greater operational efficiency and improved interaction with donors. The usability evaluation revealed needs for refinements to the visual experience, proposals such as the incorporation of interactive tutorials and improvements to the data entry forms. It is concluded that the prototype satisfactorily fulfills the proposed objectives, representing an effective technological solution to strengthen transfusion safety and support clinical decision making in contexts of limited infrastructure.

Keywords— *blood banks, inventory management, voluntary donations, desktop application, transfusion safety, automation*

I. INTRODUCCIÓN

Los bancos de sangre desempeñan un papel crucial en la atención médica, especialmente en situaciones de emergencia, donde la disponibilidad inmediata de hemo componentes es vital. Estos componentes, también denominados derivados sanguíneos, incluyen glóbulos rojos, plaquetas y plasma, obtenidos mediante la separación de la sangre donada, y se utilizan en el tratamiento de diversas patologías [1]. No obstante, los bancos de sangre enfrentan importantes desafíos debido a la escasez de estos productos, una situación agravada por el incremento de enfermedades crónicas, accidentes y otras condiciones críticas que requieren transfusiones frecuentes [2]. La creciente demanda de servicios transfusionales evidencia la necesidad urgente de incrementar las donaciones [3], mediante campañas dirigidas en espacios públicos, instituciones educativas, empresas y redes de apoyo familiar. Estas estrategias no solo buscan aumentar las reservas sanguíneas, sino también mitigar el riesgo de infecciones asociadas a las transfusiones, subrayando la relevancia de fortalecer los protocolos de seguridad en los procesos de donación y transfusión.

Uno de los principales problemas que enfrentan los bancos de sangre es el déficit de donantes. La donación de sangre implica una pérdida considerable de hierro en cada extracción, lo que conlleva una posterior movilización de las reservas corporales, que suelen ser limitadas. La deficiencia de hierro es especialmente prevalente entre los donantes frecuentes, en particular en las mujeres, y no está necesariamente relacionada con la frecuencia de donación. Esta alta prevalencia resalta la necesidad de implementar métodos de detección más precisos, dado que la evaluación basada únicamente en los niveles de hemoglobina [4] puede resultar insuficiente para identificar casos de deficiencia de hierro sin anemia. Los criterios actuales de aceptación basados en la hemoglobina podrían afectar significativamente la elegibilidad de los donantes [4].

ISSN:1390-9266 e-ISSN:1390-9134 LAJC 2025
DOI: https://doi.org/10.33333/lajc.vol12n2.05

Por ejemplo, elevar en 0,5 g/dl el umbral mínimo para mujeres podría reducir en un 25 % la aceptación de donantes con deficiencia de hierro, pero también generaría un 16,6 % de descartes innecesarios. Un incremento de 1 g/dl disminuiría en un 58 % la inclusión de donantes con deficiencia, aunque conllevaría un aumento del 35,6 % en los descartes sin justificación clínica.

La gestión eficiente de los bancos de sangre requiere estrategias adaptativas que equilibren la disponibilidad de hemo componentes con la seguridad transfusional, minimizando el riesgo de infecciones y garantizando la salud del donante. Sistemas tecnológicos como Rakt Sewa [5] han logrado avances en la automatización de procesos, aunque enfrentan limitaciones relacionadas con su complejidad operativa, la necesidad de infraestructura tecnológica robusta y la ausencia de validaciones de usabilidad. Estas restricciones dificultan su implementación en bancos de sangre con recursos limitados o en contextos de menor escala. Aún persisten brechas en la literatura en cuanto al diseño y validación de soluciones informáticas accesibles, eficientes y adaptadas a entornos que demandan simplicidad operativa y bajo costo de implementación, lo cual representa una oportunidad para la innovación tecnológica en este campo.

A partir de esta problemática, el presente estudio tiene como objetivo desarrollar un prototipo de aplicación de escritorio que facilite la gestión de bancos de sangre, con énfasis en el control de inventarios y la programación de citas para donaciones. Además, se incorpora una evaluación estructurada de usabilidad con el fin de validar la eficacia de la interfaz y la experiencia del usuario. A diferencia de soluciones más complejas, este prototipo busca ofrecer una herramienta práctica, directa y accesible, que facilite las tareas esenciales del personal administrativo y contribuya a una gestión más ordenada y segura de los recursos sanguíneos. Además, este estudio identifica como problema de investigación la escasez de soluciones tecnológicas accesibles, validadas y adaptadas a contextos con baja alfabetización digital para la gestión de bancos de sangre. La principal contribución científica radica no solo en el desarrollo del prototipo funcional, sino también en la adaptación de la técnica Entrevista Estructurada como método de evaluación de usabilidad, lo cual representa un aporte original en contextos con limitaciones tecnológicas y educativas.

II. Revisión de Literatura

En esta sección, se presenta la revisión de literatura, sustentada mediante un Mapeo Sistemático de Literatura (SMS). Esta revisión permite identificar las principales soluciones tecnológicas implementadas en la gestión de bancos de sangre, así como los vacíos existentes en cuanto a herramientas accesibles, automatizadas y validadas desde la usabilidad. Los estudios seleccionados respaldan la necesidad del desarrollo propuesto y orientan los requisitos funcionales del prototipo.

De acuerdo con Erno Vanhala et al. [6], el SMS es un enfoque relativamente reciente que permite generar nuevo conocimiento a partir de estudios previos. Su utilidad radica en la capacidad para filtrar información existente y obtener perspectivas innovadoras sobre un campo de investigación, identificando líneas emergentes de estudio. En este caso, el presente SMS se orienta a dar respuesta a la siguiente pregunta de investigación: ¿Qué herramientas tecnológicas y enfoques se han demostrado eficaces para fomentar la participación de donantes en bancos de sangre? El procedimiento comenzó con la selección de términos clave y la elaboración de la cadena de búsqueda. La cadena de búsqueda utilizada fue la siguiente: ("blood bank management system" OR "donor management system" OR "blood donation software" OR "blood inventory management" OR "blood transfusion management" OR "blood safety software" OR "process improvement blood supply") AND ("technology" OR "software" OR "application" OR "desktop software")

Para identificar los estudios relevantes, se aplicaron criterios de inclusión y exclusión, los cuales se detallan en la Tabla I. Asimismo, la Tabla II presenta un resumen del número de investigaciones recuperadas en cada base de datos (BBDD) tras aplicar la cadena de búsqueda establecida.

TABLA I. Condiciones para la selección y descarte de estudios

Criterios de inclusión:
Se consideraron aquellos artículos publicados entre los años 2010 y 2024 que describen el desarrollo de sistemas vinculados a la gestión de bancos de sangre. Asimismo, se incluyeron aquellos que describan el empleo de metodologías o herramientas tecnológicas que contribuyan a mejorar la gestión y el proceso de donación.
Criterios de exclusión:
Quedaron excluidos los artículos que no abordan aspectos relacionados con sistemas aplicables a la gestión o a la donación en bancos de sangre. También se descartaron aquellos que no guardan vínculo directo con la temática de gestión en bancos de sangre.

TABLA II. Resultados obtenidos tras la búsqueda en cada base de datos

BBDD	Encontrados	Preseleccionados	Estudios Considerados
IEEE Xplore	20	10	4
SprigerLink	15	1	1
TOTAL	35	11	5

A continuación, se sintetizan los hallazgos clave que sustentan esta investigación:

El sistema Blood Bank Management System and Inventory Optimization, desarrollado por Khairnar P. [7], constituye una solución integral orientada a modernizar la gestión de bancos de sangre en la India, un país que enfrenta una escasez crítica en el suministro sanguíneo. La propuesta se basa en una base de datos estructurada y una interfaz intuitiva que optimiza la gestión de donantes y receptores, facilita el registro y actualización de datos, y emite notificaciones sobre oportunidades de donación y disponibilidad de hemo componentes. Aunque se menciona el uso de un Sistema de Gestión de Bases de Datos (DBMS), el estudio no especifica cuál fue empleado. Entre las funcionalidades destacadas, se incluyen la gestión de inventarios en tiempo real, el monitoreo de fechas de caducidad y alertas automáticas ante niveles bajos de stock. Los resultados evidencian mejoras en la eficiencia operativa, una reducción de errores en el manejo de datos y un incremento en la participación comunitaria en actividades de donación, favoreciendo un ecosistema sostenible y una atención médica más oportuna.

Por su parte, el estudio propuesto por Wijai B. y Phongchai J. [8] presenta una herramienta tecnológica para la gestión de inventarios de sangre entre bancos y hospitales en Tailandia.

ISSN:1390-9266 e-ISSN:1390-9134 LAJC 2025
DOI: https://doi.org/10.33333/lajc.vol12n2.05

Este sistema permite a las instituciones hospitalarias realizar solicitudes de sangre y actualizar sus existencias en tiempo real, lo que agiliza la verificación de disponibilidad y la aprobación de pedidos por parte del personal del banco de sangre. Utiliza MySQL para administrar la información relacionada con requisiciones y distribución. Los resultados muestran una reducción significativa en el tiempo de búsqueda, así como una mejora en la precisión del inventario y en la eficiencia de la toma de decisiones, lo que contribuye a un manejo más efectivo de la sangre y, en consecuencia, a la preservación de vidas.

El sistema Rakt Sewa, desarrollado por Yadav H. et al. [5], constituye una solución informática avanzada que optimiza la gestión de bancos de sangre en hospitales. Este software automatiza el seguimiento en tiempo real de la disponibilidad de sangre, con la capacidad de generar informes y alertas personalizables. Sustituye procesos manuales ineficientes, y permite al personal de salud identificar rápidamente los tipos y cantidades disponibles, monitorear su uso y recibir notificaciones ante niveles críticos de inventario. El sistema utiliza MongoDB, para almacenar y administrar información sobre donantes, solicitudes e inventarios, lo que asegura un acceso ágil y preciso a los datos. Su integración con los sistemas hospitalarios existentes mejora la toma de decisiones críticas y optimiza la gestión de recursos, y esto contribuye a una atención médica más eficiente.

Por otro lado, el trabajo de Diana et al. [9] propone una solución innovadora basada en una red blockchain privada de Ethereum para mejorar la trazabilidad y seguridad en las donaciones de sangre. El sistema busca establecer un entorno transparente, auditable y descentralizado para el seguimiento del origen de las unidades sanguíneas. Integra IPFS para superar limitaciones de almacenamiento, contratos inteligentes para automatizar procesos y mecanismos de análisis de seguridad para proteger los datos. Aunque la validación del sistema se realizó en el entorno de desarrollo Remix IDE y no se presentan resultados sobre aplicaciones móviles o web, se destaca su adaptabilidad a múltiples contextos industriales, lo cual evidencia su potencial de escalabilidad y aplicación práctica.

Mouncif C. et al. [10] subrayan que la gestión de bancos de sangre puede mejorarse significativamente mediante la aplicación de metodologías de optimización. Entre las estrategias más eficaces, se encuentran la programación de citas para donantes, que permite balancear la recolección de diferentes tipos de sangre, y el uso de modelos de simulación que reducen tiempos de espera. Estos enfoques han demostrado mejorar la eficiencia operativa, aumentar la satisfacción del donante y elevar la cantidad de unidades recolectadas. Además, los modelos de localización y asignación aplicados a bancos de sangre móviles resultan cruciales para ampliar la cobertura en situaciones de emergencia y zonas afectadas por desastres.

A través de la revisión sistemática de la literatura, se han identificado múltiples soluciones tecnológicas avanzadas que abordan dimensiones críticas de la gestión de bancos de sangre, tales como la optimización del inventario, la eficiencia operativa y la promoción de la donación. Sistemas como Rakt Sewa y el Blood Bank Management System and Inventory Optimization han demostrado impactos positivos tanto en la gestión del inventario como en la comunicación con donantes. A partir del análisis de los estudios revisados, se establecieron los requisitos funcionales esenciales para el desarrollo del prototipo propuesto, detallados en la siguiente sección.

III. Metodología de Desarrollo de Software

Para el desarrollo de esta aplicación software orientado a la gestión de bancos de sangre, se empleó la metodología ágil Scrum, destacada por su adaptabilidad frente a entornos de desarrollo cambiantes y exigentes. Esta metodología promueve un desarrollo iterativo e incremental, facilita la adaptación continua a los requisitos del usuario y asegura que se cumplan tanto los requerimientos funcionales como los no funcionales previamente definidos [11]. El proceso de trabajo bajo el enfoque Scrum se ilustra en la Figura 1.

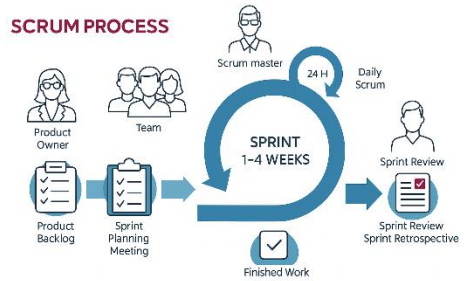

Fig. 1. Proceso Scrum.

Fuente: Adaptada de [12].

A. Definición de Requisitos

La definición de requisitos se fundamentó en una revisión sistemática de literatura, que permitió identificar las funcionalidades esenciales para optimizar la gestión de donaciones y control de inventarios en bancos de sangre.

a) Recolección de Requisitos: Los requisitos fueron clasificados en dos categorías: Funcionales y No Funcionales. Esta distinción asegura que el sistema propuesto responda de manera integral a las necesidades operativas, considerando tanto las funcionalidades del software como sus atributos de calidad.

b) Documentación de Requisitos: Las Tablas III y IV presentan los requisitos definidos para el sistema. La Tabla III detalla los requisitos funcionales, como el registro de donantes, la gestión de citas y la actualización de inventarios.

TABLA III. Requisitos Funcionales

Requisito	Descripción
Registro de Donantes	Permitir el ingreso de nuevos donantes con datos (nombre, tipo de sangre, contacto).
Actualización de Donantes	Facilitar la modificación de la información de los donantes existentes.
Formulario Pre-Donación	Habilitar un formulario que recopile información antes de cada donación.
Registro de Unidades de Sangre	Registrar unidades de sangre en el inventario, incluye tipo, fecha de donación y caducidad.
Actualización del Inventario	Actualizar el inventario tras nuevas donaciones o utilización en transfusiones.
Agendamiento de Citas	Permitir a los donantes programar citas de manera autónoma.
Confirmación de Citas (Administrador)	Posibilitar que el administrador revise y confirme las citas agendadas.
Notificaciones por Correo Electrónico	Integrar un sistema automatizado de envío de correos mediante Gmail.
Ingreso de Administradores	Permitir el acceso de usuarios con permisos especiales para la gestión completa del sistema.

ISSN:1390-9266 e-ISSN:1390-9134 LAJC 2025
DOI: https://doi.org/10.33333/lajc.vol12n2.05

La Tabla IV, por su parte, recoge los requisitos no funcionales, enfocados en la usabilidad, adaptabilidad del diseño a distintos dispositivos y tiempos de respuesta. Estos requisitos aseguran que el sistema cumpla con los objetivos establecidos de eficiencia, accesibilidad y calidad del servicio.

TABLA IV. REQUISITOS NO FUNCIONALES

Requisito	Descripción
Interfaz Intuitiva	Diseñar una interfaz clara, accesible y fácil de utilizar.
Diseño Responsivo	Garantizar que la aplicación se adapte correctamente a diferentes tamaños de pantalla.
Tiempo de Respuesta	Asegurar una interacción ágil y eficiente con el usuario.

B. Planificación del Proyecto

a) Elaboración del Product Backlog: Se definió un Product Backlog que incluye todas las funcionalidades y tareas identificadas para el desarrollo del sistema, priorizadas según su valor para los usuarios y las partes interesadas.

b) Planificación de Sprints: Se estableció sprints de dos semanas de duración. Al inicio de cada sprint se seleccionan, del Product Backlog, aquellas tareas que pueden ser completadas en ese período, y se definen objetivos claros y medibles para guiar el avance del desarrollo.

c) Desarrollo Iterativo: La Tabla V presenta la planificación de los sprints, y detalla las tareas, objetivos definidos y tiempos estimados. Este enfoque iterativo permite una implementación progresiva, con revisiones, retroalimentación y validaciones constantes.

TABLA V. PLANIFICACIÓN DE SPRINTS

Sprint	Fase	Tiempo (Semana)	Tareas	Objetivos
Inicio	Definición de arquitectura y tecnología base	0-1	Seleccionar arquitectura (MVC) y base de datos (SQL Server)	Establecer la estructura técnica para el desarrollo posterior
1	Diseño de la Interfaz de Usuario	1-2	Elaborar bocetos y maquetas de la interfaz.	Crear un diseño visual intuitivo y centrado en el usuario.
2	Gestión de Usuarios	3-4	Implementar autentificación y gestión de perfiles.	Establecer roles y accesos diferenciados para donantes y administradores.
3	Módulo de Gestión de Inventario	5-6	Desarrollar registro, seguimiento y actualización de inventario.	Permitir un control eficiente de unidades de sangre en tiempo real.
4	Citas y Notificaciones	7-8	Programación de citas y notificaciones automáticas por correo.	Optimizar donaciones y mantener comunicación activa.
5	Integración y Pruebas	9-10	Integrar módulos y ejecutar pruebas funcionales.	Verificar funcionamiento y usabilidad del sistema.
Fin.	Entrega del Prototipo	11-12	Presentar el prototipo funcional a los stakeholders.	Obtener retroalimentación final y validar cumplimiento de requisitos.

C. Mecanismos de automatización de procesos

El prototipo desarrollado automatiza tres procesos clave en la gestión de bancos de sangre: la administración de usuarios y donantes, el control de inventarios, y la programación de donaciones. Esta automatización se logra mediante funcionalidades específicas codificadas en el backend del sistema y conectadas a una base de datos relacional en SQL Server. En el proceso administrativo, el sistema permite registrar, editar y consultar información de los donantes a través de formularios validados automáticamente. Los datos ingresados son almacenados de forma estructurada, lo que facilita la generación de reportes operativos y la trazabilidad de la información.

Para el control de inventarios, se implementaron formularios que registran automáticamente las unidades de sangre donadas, con atributos como tipo sanguíneo, fecha de recolección y fecha de caducidad. El sistema actualiza el inventario en tiempo real y genera alertas visuales cuando las unidades se acercan a su fecha de vencimiento. Además, se incorporaron restricciones lógicas para evitar duplicidades y asegurar la consistencia de los datos. En cuanto a la programación de donaciones, la aplicación permite que los usuarios seleccionen fechas disponibles desde un calendario interactivo. El sistema realiza validaciones para evitar solapamientos de citas y envía confirmaciones automáticas por correo electrónico mediante la integración con la API de Gmail; de esta manera, mejora la asistencia a las citas programadas.

Estas funcionalidades contribuyen a reducir errores manuales, agilizar el flujo de trabajo y mejorar la experiencia tanto del personal administrativo como de los donantes. Además, la automatización propuesta es escalable y adaptable a bancos de sangre con limitados recursos tecnológicos.

D. Diseño de la Base de Datos

El sistema implementó una base de datos relacional en SQL Server compuesta por tablas vinculadas entre sí mediante claves foráneas (Ver fragmento en la Figura 2). Esta estructura permite gestionar de forma eficiente usuarios, donantes, roles, preguntas y respuestas. La base de datos completa se presenta en el siguiente enlace (https://goo.su/rUt2Qd).

Fig. 2. Fragmento de la base de datos relacional

IV. EVALUACIÓN DE USABILIDAD DEL PROTOTIPO SGBS (SISTEMA DE GESTIÓN PARA BANCOS DE SANGRE)

Esta sección detalla la evaluación de usabilidad aplicada al sistema de escritorio para la gestión de bancos de sangre, a través de entrevistas estructuradas.

ISSN:1390-9266 e-ISSN:1390-9134 LAJC 2025
DOI: https://doi.org/10.33333/lajc.vol12n2.05

A. Descripción de la técnica de usabilidad Entrevista Estructurada

La Entrevista Estructurada es una técnica utilizada para recopilar información detallada sobre la interacción de los usuarios con un sistema, a través de un conjunto de preguntas previamente definidas [13]. Esta técnica permite explorar las percepciones, necesidades y dificultades de los usuarios en relación con el uso del software. Una de sus principales ventajas es que permite al investigador mantener el control del flujo de la conversación y asegurar la recolección sistemática y consistente de datos, con base en un guion preestablecido. La naturaleza estructurada de esta técnica implica que las preguntas deben ser diseñadas anticipadamente, en función de los aspectos específicos que se desean evaluar [14].

La Tabla VI presenta los pasos y actividades que conforman la aplicación de esta técnica, y detalla su estructura metodológica para garantizar la validez de los resultados obtenidos.

B. Adaptaciones de la técnica de usabilidad Entrevista Estructurada

La aplicación de entrevistas estructuradas no representa una dificultad significativa en contextos de evaluación de usabilidad, ya que esta técnica se emplea con frecuencia en investigaciones orientadas al análisis de la experiencia del usuario [13]. No obstante, al igual que otras técnicas cualitativas, su correcta implementación requiere la participación de un evaluador con conocimientos especializados y habilidades interpersonales que le permitan conducir la entrevista de forma eficaz y objetiva [16].

La Tabla VII presenta un resumen de las principales condiciones adversas identificadas durante la aplicación de la técnica Entrevista Estructurada [15], así como las adaptaciones implementadas según [17] , para garantizar la calidad y confiabilidad de los datos recopilados.

La técnica Entrevista Estructurada [15] fue adaptada en función de las adversidades observadas durante el desarrollo de este estudio. Para enfrentar dichas limitaciones contextuales, se definieron seis pasos específicos que conforman una versión ajustada de la técnica, incorporando insumos y medidas concretas que facilitaron su correcta aplicación. A continuación, se describen los pasos establecidos para la adaptación de la Entrevista Estructurada.

a) Paso 1: Prueba piloto. Se llevó a cabo una prueba piloto con el objetivo de evaluar la funcionalidad general del proceso de Entrevista Estructurada y validar los insumos iniciales diseñados. Esta etapa permitió detectar ajustes necesarios antes de su aplicación en el estudio principal de usabilidad.

b) Paso 2: Selección de herramientas de comunicación y colaboración. Dada la naturaleza distribuida de los proyectos de software libre, que imposibilita la presencialidad, se optó por realizar las entrevistas en modalidad virtual. Para ello, se emplearon herramientas accesibles como Gmail, para el envío de documentación formal, y WhatsApp, como canal de comunicación directa y continua entre participantes, facilitadores y mentores.

c) Paso 3: Adaptación del formato de entrevista. Se diseñó una versión preliminar del cuestionario con base en los factores de usabilidad definidos para la evaluación del sistema. Esta versión fue discutida con el mentor del proyecto y validada antes de su aplicación definitiva.

d) Paso 4: Diseño de plantillas y documentos de apoyo. Las preguntas validadas fueron incorporadas en un formato estructurado utilizando Microsoft Word. Este documento fue enviado a los participantes para su llenado una vez completadas las tareas asignadas en la prueba de usabilidad.

e) Paso 5: Ejecución de la evaluación de usabilidad. Con los insumos preparados, se procedió a ejecutar la evaluación en la fecha establecida. Los participantes recibieron un correo formal con el enlace a la sesión virtual en Google Meet, el acceso al grupo de WhatsApp para soporte técnico y varios documentos adjuntos: consentimiento informado para la grabación, invitación oficial con detalles logísticos, guía de instalación actualizada, conjunto de tareas a realizar, plantilla de preguntas de evaluación y un video tutorial para apoyar el proceso de instalación. Esta estructura permitió una participación eficiente en un entorno completamente virtual.

f) Paso 6: Análisis de datos y sistematización de resultados. Finalizada la prueba, las respuestas fueron recopiladas, depuradas (eliminando duplicados) y analizadas. Los hallazgos más relevantes fueron sintetizados y organizados en un documento denominado Entrevista Estructurada, lo cual sirve como insumo para retroalimentar el diseño del sistema.

TABLA VI. PASOS Y TAREAS DE LA TÉCNICA ENTREVISTA ESTRUCTURADA SEGÚN HIX [15]

N°	Nombre del paso	Tareas
1	Definición de los objetivos	Se debe identificar el objetivo de aplicar la técnica para mejorar la usabilidad de un proyecto open-source.
2	Identificar el público objetivo	Se deben seleccionar a los participantes para aplicar la técnica.
3	Diseñar las preguntas	Las preguntas deben formularse de manera precisa, directa y alineada con los objetivos definidos para la entrevista.
4	Validar las preguntas	Solicita a otros usuarios que revisen las preguntas para asegurarse de que sean claras y comprensivas
5	Analizar los datos	Se deben aplicar métodos estadísticos adecuados para interpretar los datos recopilados y derivar conclusiones.

TABLA VII. CONDICIONES ADVERSAS Y ADAPTACIONES DE LA TÉCNICA ENTREVISTA ESTRUCTURADA SEGÚN HIX [15]

N°	Nombre del paso	Condiciones adversas	Adaptaciones Propuestas
1	Definición de los objetivos	La participación de un especialista en usabilidad resulta esencial para la correcta aplicación de la técnica.	La función del especialista en usabilidad fue desempeñada por estudiantes de la UTEQ, con acompañamiento de un tutor académico.
2	Identificar el público objetivo	Se precisa la colaboración de los usuarios para implementar la técnica.	Los usuarios participan remotamente a través de: foros o correos electrónicos.
3	Diseñar las preguntas	La participación de un especialista en usabilidad resulta esencial para la correcta aplicación de la técnica.	La función del especialista en usabilidad fue desempeñada por estudiantes de la UTEQ, con acompañamiento de un tutor académico.
4	Validar las preguntas		
5	Analizar los datos		

ISSN:1390-9266 e-ISSN:1390-9134 LAJC 2025
DOI: https://doi.org/10.33333/lajc.vol12n2.05

La Tabla VIII resume los pasos y tareas implementadas en la adaptación de la técnica Entrevista Estructurada, diseñada específicamente para la evaluación de usabilidad en este proyecto. Esta secuencia metodológica ha sido clave para recopilar evidencia útil sobre la experiencia de los usuarios durante la interacción con el sistema evaluado.

TABLA VIII. PASOS Y TAREAS DE LA TÉCNICA ENTREVISTA ESTRUCTURADA ADAPTADA

N	Nombre del paso	Tarea
1	Realizar una prueba piloto	• Ejecutar una prueba inicial para verificar los recursos que se emplearán durante la aplicación de la técnica.
2	Utilizar herramientas de comunicación y colaboración	• Definir el perfil de usuario que será requerido para la aplicación de la técnica. • Enviar una invitación por correo electrónico para incentivar la colaboración de los participantes. • Contactar a los usuarios por medio de redes sociales.
3	Adaptar el formato de las entrevistas	• Diseñar una serie de preguntas para aplicar la entrevista según los elementos que se desean evaluar.
4	Diseñar plantillas para aplicar las entrevistas	• Usar herramientas como Google forms para diseñar la lista de preguntas.
5	Realizar la evaluación de usabilidad	• Realizar la evaluación mediante una reunión remota, en donde se envían los insumos necesarios para los usuarios.
6	Realizar un análisis de los datos y agrupar los comunes	• Agrupar los resultados en el documento Entrevista Estructurada.

V. RESULTADOS

Esta sección presenta los resultados derivados de las distintas etapas de evaluación, que comprenden pruebas de usabilidad, entrevistas estructuradas, observaciones realizadas a los usuarios y el diseño final de las interfaces.

A. Resultados de las pruebas de usabilidad

Durante la fase de validación, se llevaron a cabo pruebas funcionales en un entorno simulado, a través de escenarios diseñados para representar tareas comunes en la gestión de bancos de sangre. Estas pruebas se realizaron en condiciones controladas, no en un entorno de producción, pero sí con usuarios reales que se asemejan al perfil objetivo del sistema. En total, participaron cuatro estudiantes de primer semestre de la carrera de Ingeniería en Software, quienes interactuaron con el prototipo del Sistema de Gestión para Bancos de Sangre (SGBS). Aunque los resultados no corresponden a un entorno operativo real, las observaciones registradas permiten identificar tendencias positivas, especialmente en la reducción de errores y la simplificación de tareas frente a procedimientos manuales simulados. No obstante, estos hallazgos deben considerarse preliminares e indicativos, y constituyen una base para futuras validaciones en contextos reales de uso.

A cada participante se le asignaron tareas específicas para evaluar distintos módulos del sistema. Las instrucciones fueron enviadas con antelación mediante correo electrónico, junto con los insumos necesarios para la prueba. La sesión de evaluación se llevó a cabo de manera remota, y durante la misma se observó la ejecución efectiva de las tareas por parte de los usuarios, seguida de la aplicación de la Entrevista Estructurada. La Figura 3 muestra una de las sesiones de prueba de usabilidad realizadas virtualmente, donde se evidencia la interacción del participante con el sistema y el proceso de evaluación conducido.

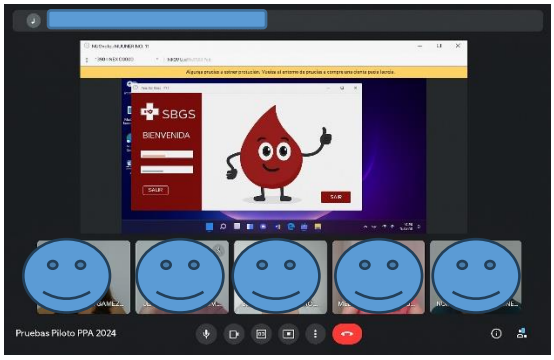

Fig. 3. Presenta la reunión remota a los usuarios para la posterior Entrevista Estructurada.

La Tabla IX presenta el conjunto de preguntas formuladas a los usuarios como parte del proceso de recolección de datos mediante la técnica Entrevista Estructurada.

TABLA IX. PREGUNTAS UTILIZADAS EN LA APLICACIÓN DE LA TÉCNICA ENTREVISTA ESTRUCTURADA ADAPTADA

N.	Pregunta
1	¿Cuáles son los principales problemas en las funcionalidades que encontraste?
2	¿Tienes alguna propuesta de mejora para la interacción con la herramienta?
3	¿Tienes alguna crítica en torno a la interfaz de usuario?
4	¿Cómo piensas que la interfaz de usuario (o una parte de ella) podría ser rediseñada?
5	¿Hubo alguna característica o proceso difícil de usar o de entender de la herramienta?

B. Análisis de respuestas de la Entrevista Estructurada

Para llevar a cabo este análisis, se examinaron cuidadosamente las respuestas proporcionadas por los cuatro entrevistados con el fin de identificar patrones comunes y puntos de interés particulares. Las observaciones y sugerencias se categorizaron en cuatro áreas principales: Problemas/Errores, Mejoras de Interfaz, Nuevas Funcionalidades y Usabilidad.

1. ¿Cuáles son los principales problemas en las funcionalidades? Las respuestas de los usuarios fueron las siguientes: Dos usuarios indicaron problemas con la creación de contraseñas, y mencionaron limitaciones en los caracteres permitidos. Un usuario señaló falta de claridad en la creación del nombre de usuario. Otro usuario mencionó problemas con la selección de la fecha de nacimiento. Adicionalmente, un participante indicó limitaciones en la selección de lugares de origen.

2. ¿Tienes algunas propuestas de mejora para la interacción con la herramienta? Para mejorar la interacción con la herramienta, los usuarios indicaron lo siguiente: Un usuario sugirió implementar un tutorial interactivo para nuevos usuarios. Otro usuario propuso mejorar el diseño de la interfaz haciéndolo más interesante. Dos usuarios coincidieron en la necesidad de mejorar la interacción con la selección de fechas, y sugirieron permitir la entrada mediante teclado.

ISSN:1390-9266 e-ISSN:1390-9134 LAJC 2025
DOI: https://doi.org/10.33333/lajc.vol12n2.05

3. ¿Tienes alguna crítica de la interfaz de usuario? Los usuarios reportaron las siguientes críticas con respecto a la interfaz: Dos usuarios mencionaron que la interfaz es demasiado simple o "retro". Un usuario señaló problemas con el contraste de colores, especialmente en los botones. Otro usuario indicó que las letras son demasiado pequeñas.

4. ¿Cómo piensas que la interfaz de usuario podría ser rediseñada? Para mejorar el diseño de la interfaz, los usuarios indicaron lo siguiente: Tres usuarios coincidieron en la necesidad de mejorar el diseño visual, y sugirieron el uso de más colores. Un usuario propuso rediseñar la sección de tablas de bases de datos. Otro usuario sugirió aumentar el tamaño de las letras.

5. ¿Hubo alguna característica o proceso difícil de usar dentro de la herramienta? Tres usuarios hicieron referencia a que el proceso de selección de la fecha de nacimiento fue complicado o confuso. Dos usuarios mencionaron dificultades con la creación de contraseñas debido a las restricciones de caracteres. Un usuario indicó problemas para seleccionar su lugar de origen debido a limitaciones en las opciones disponibles.

C. Análisis de observaciones dadas por el usuario

Este análisis refleja las principales observaciones y sugerencias de los usuarios entrevistados, proporcionando una visión general de las áreas que requieren atención y mejora en el Sistema de Gestión de Bancos de Sangre. En la tabla X, se resume los hallazgos más relevantes, junto con la frecuencia con la que cada aspecto fue mencionado por los participantes. Esta información resultará fundamental para orientar las próximas iteraciones y optimizaciones del sistema, y permitirá establecer prioridades en los ajustes según las expectativas y experiencias reportadas por los usuarios.

TABLA X. INFORMACIÓN RECOPILADA MEDIANTE LA ENTREVISTA A USUARIOS, CLASIFICADA POR CATEGORÍAS, HALLAZGOS Y FRECUENCIA

Categoría	Hallazgo	Frecuencia
Problemas	Limitaciones en la creación de contraseñas (no permite ciertos caracteres)	2
	Dificultad para seleccionar la fecha de nacimiento	3
	Falta de opción para crear nombre de usuario	1
Mejoras de Interfaz	Mejorar el diseño visual (más colores, menos aspecto "retro")	3
	Aumentar el tamaño de las letras	1
	Mejorar el contraste de colores (especialmente en botones)	2
	Rediseñar la sección de tablas de bases de datos	1
Nuevas Funcionalidades	Agregar opción para verificar/mostrar contraseña	1
	Implementar un tutorial interactivo para nuevos usuarios	1
	Permitir entrada de fecha mediante teclado	2
Usabilidad	Uniformar el diseño de los botones	1
	Ampliar el número de caracteres permitidos en la contraseña	1
	Permitir el uso de la letra "ñ"	1

D. Diseño de Interfaces resultantes

La Figura 4 muestra la interfaz principal del prototipo del Sistema de Gestión para Bancos de Sangre (SGBS). Esta pantalla corresponde al módulo de autenticación, en el cual se solicita al usuario el ingreso de sus credenciales (nombre de usuario y contraseña) para acceder de forma segura al sistema.

Fig. 4. Interfaz principal del prototipo SGBS

La Figura 5 presenta la interfaz correspondiente al módulo de agendamiento de citas, diseñada para que los donantes puedan seleccionar de manera intuitiva una fecha y hora preferencial para programar su donación.

Fig. 5. Interfaz de agendar cita

La Figura 6 ilustra la interfaz correspondiente al perfil de administrador, en la cual se visualizan los distintos módulos funcionales que integran el prototipo del Sistema de Gestión para Bancos de Sangre (SGBS).

Fig. 6. Interfaz de administrador y los módulos del prototipo SGBS

VI. DISCUSIÓN DE RESULTADOS

La evaluación del prototipo de gestión de bancos de sangre (SGBS) demostró que la solución desarrollada logró alcanzar los objetivos establecidos, especialmente en la automatización

ISSN:1390-9266 e-ISSN:1390-9134 LAJC 2025
DOI: https://doi.org/10.33333/lajc.vol12n2.05

de tareas esenciales como el ingreso de donantes, la gestión de citas y el manejo de inventario. Los resultados obtenidos mediante la técnica Entrevista Estructurada evidenciaron una percepción favorable por parte de los usuarios respecto a la facilidad de uso, aunque también revelaron áreas de mejora relacionadas con la experiencia visual y la interacción.

Respecto a la usabilidad, los usuarios destacaron la facilidad de navegación y la comprensión general del sistema, lo que evidencia la efectividad del enfoque de diseño intuitivo adoptado. No obstante, se registraron observaciones importantes que deben considerarse en futuras iteraciones del prototipo. Entre ellas se incluyen: la necesidad de mejorar el diseño visual para hacerlo más atractivo, optimizar el selector de fechas, aumentar el tamaño de las fuentes para favorecer la accesibilidad, y ampliar las opciones de configuración al momento de crear nombres de usuario y contraseñas.

Comparado con soluciones más robustas como Blood Bank Management System and Inventory Optimization de Khairnar P. [7] y Rakt Sewa de Yadav H. et al. [5], el prototipo desarrollado presenta ventajas relativas a su simplicidad de uso y menor curva de aprendizaje, aspectos cruciales para entornos donde se requiere una rápida implementación sin necesidad de capacitación especializada. A diferencia de los sistemas mencionados, que incorporan funcionalidades avanzadas, pero exigen mayores recursos técnicos y administrativos, el presente prototipo se orienta a solucionar de forma directa los procesos fundamentales en bancos de sangre de pequeña y mediana escala.

Por otro lado, se identificó que el módulo de agendamiento de citas fue uno de los más apreciados por los usuarios, al permitir organizar las donaciones de manera eficiente. No obstante, la apariencia general de la aplicación fue considerada simple, lo que indica que la incorporación de buenas prácticas en el diseño de interfaces gráficas podría mejorar significativamente la interacción con el sistema y transmitir una imagen más moderna y profesional.

Como resultado final, las observaciones recogidas a través de la Entrevista Estructurada proporcionan una base sólida para establecer mejoras específicas que fortalecerán la usabilidad del sistema. La aplicación de técnicas de evaluación como la Entrevista Estructurada permitió identificar puntos críticos que podrían ser abordados en futuras iteraciones del prototipo, y consolidar así su viabilidad como solución accesible y efectiva para bancos de sangre de pequeña y mediana escala.

VII. Conclusiones

El desarrollo de la solución informática orientada a la administración de bancos de sangre demostró ser una herramienta eficaz para optimizar procesos clave, lo que facilita la gestión de donaciones y mejora el control del inventario de hemo componentes. El Sistema de Gestión para Bancos de Sangre (SGBS) logró simplificar tareas esenciales, como el registro de donantes y la programación de citas, lo cual proporciona una base funcional alineada con los objetivos propuestos.

Asimismo, la automatización de procesos críticos contribuyó a reducir errores operativos y a fortalecer la seguridad transfusional mediante una trazabilidad más confiable de las unidades sanguíneas. Las herramientas tecnológicas más efectivas identificadas incluyen sistemas automatizados para la gestión de inventarios, agendamiento de citas y envío de notificaciones personalizadas, como recordatorios por correo electrónico.

Estas soluciones no solo mejoran la eficiencia operativa, sino que también elevan la experiencia del donante, al ofrecer procedimientos más ágiles, accesibles y confiables. Dichos factores pueden influir significativamente en la disposición de los usuarios para participar de manera activa en campañas de donación, lo que contribuye a consolidar un ecosistema más sostenible y seguro en torno a la gestión de bancos de sangre.

La adaptación de la técnica Entrevista Estructurada para entornos con baja alfabetización digital representa un aporte metodológico original, ya que facilita evaluaciones de usabilidad en contextos vulnerables, y amplia el alcance y aplicabilidad de esta técnica en estudios de interacción persona-computadora.

A futuro, se plantea el rediseño de la interfaz con el fin de mejorar la experiencia del usuario mediante la incorporación de un enfoque visual más moderno, intuitivo y accesible. Asimismo, se considera la integración de nuevas funcionalidades, como tutoriales interactivos y herramientas predictivas, que podrían ampliar notablemente el impacto del sistema en la gestión eficiente de bancos de sangre, lo cual fortalece tanto la toma de decisiones como la participación activa de los donantes.

Referencias

[1] Denise. Harmening, *Modern blood banking & transfusion practices*, vol. 6. F.A. Davis, 2012.

[2] J. & C. A. J. A. Flórez-Duque, *Marcadores de infecciones transmisibles vía transfusional: el caso del banco de sangre de la Escuela de Microbiología de la Universidad de Antioquia, 2015-2016*, vol. 0. Colombia: 2015-2016, 2019.

[3] L. Fiorentini *et al.*, "Consideraciones para el uso del equivalente de hemoglobina reticulocitaria en la práctica diaria," *Revista Hematología, ISSN 0329-0379, ISSN-e 2250-8309, Vol. 24, Nº. 1 (Enero-Abril 2020), 2020, págs. 40-48*, vol. 24, no. 1, 2020.

[4] Y. López Vallejo, P. A. Acevedo Toro, J. Q. Franco Aguirre, and K. S. Restrepo Velásquez, "Hemoglobina reticulocitaria en donantes de sangre repetitivos," *CES Medicina*, vol. 37, no. 2, 2023, doi: 10.21615/cesmedicina.7266.

[5] H. Yadav, H. Pandey, G. Tandon, A. Rangare, and A. Tiwari, "Blood Bank Inventory Control," vol. 12, 2024, doi: 10.22214/ijraset.2024.61694.

[6] E. Vanhala, J. Kasurinen, A. Knutas, and A. Herala, "The Application Domains of Systematic Mapping Studies: A Mapping Study of the First Decade of Practice With the Method," *IEEE Access*, vol. 10, pp. 37924–37937, 2022, doi: 10.1109/ACCESS.2022.3165079.

[7] Prof. D. Khairnar, "Blood Bank Management System and Inventory Optimization," *International Scientific Journal of Engineering and Management*, vol. 03, no. 03, pp. 1–22, Mar. 2024, doi: 10.55041/ISJEM01349.

[8] W. Boonyanusith and P. Jittamai, "The development of web-based system for blood requisition within blood supply chain," *ITNG2010 - 7th International Conference on Information Technology: New Generations*, pp. 48–52, 2010, doi: 10.1109/ITNG.2010.156.

[9] D. Hawashin *et al.*, "Blockchain-based management of blood donation," *IEEE Access*, vol. 9, pp. 163016–163032, 2021, doi: 10.1109/ACCESS.2021.3133953.

[10] C. Mouncif and A. Bellabdaoui, "Blood collection supply chain management: A critical review and future perspective," *6th International Conference on Optimization and Applications, ICOA 2020 - Proceedings*, Apr. 2020, doi: 10.1109/ICOA49421.2020.9094514.

[11] J. Victor. Sutherland, "Scrum : the art of doing twice the work in half the time," p. 248, 2019.

[12] Ausum Cloud, "Scrum: qué es y por qué se ha convertido en una de las metodologías ágiles más populares," Ausum Cloud. Accessed: Jun. 06, 2025. [Online]. Available: https://ausum.cloud/scrum-metodologia-agil-mas-popular-en-empresas

[13] C. Lopezosa, "Entrevistas semiestructuradas con NVivo: pasos para un análisis cualitativo eficaz," *Methodos Anu. Métodos Investig. en Comun. Soc.*, vol. 1, pp. 88–97, 2020, doi: 10.35009/methodos.2020.i01.08.

[14] M. A. Mijancos, "Evaluación de la Usabilidad de una Aplicación para Alfabetización Digital," Universidad Politécnica de Madrid Escuela Técnica Superior de Ingenieros Informáticos, 2025. Accessed: Dec. 10, 2024. [Online]. Available: http://repositorio.unsa.edu.pe/handle/UNSA/3864

[15] D. Hix and H. R. Hartson, *Developing User Interfaces: Ensuring Usability Through Product & Process*. Ney York: John Wiley & Sons, Inc., 1993.

[16] D. De, I. De, L. A. Usabilidad, E. N. El, and P. De Desarrollo, "Incorporación de la usabilidad en el proceso de desarrollo Open Source Software," 2014, Accessed: Dec. 21, 2024. [Online]. Available: https://repositorio.uam.es/handle/10486/663405

[17] J. W. Castro, "Incorporación de la usabilidad en el proceso de desarrollo open source software," Tesis doctoral, Universidad Autónoma de Madrid, Madrid, España, 2014.

AUTHORS

Lucrecia Llerena

Lucrecia Llerena finalizó su Doctorado en Informática y Telecomunicaciones con mención CUM LAUDE, y obtuvo también el Máster Universitario en Investigación e Innovación en Tecnologías de la Información y las Comunicaciones (I2TIC), ambos en la Escuela Politécnica Superior de la Universidad Autónoma de Madrid (UAM). Además, cursó una Maestría en Educación a Distancia y Abierta, así como su título de Ingeniera en Sistemas, en la Universidad Autónoma de Los Andes (Ecuador). Actualmente se desempeña como profesora titular en la Facultad de Ciencias de la Computación y Diseños Digitales de la Universidad Técnica Estatal de Quevedo (UTEQ), donde labora desde el año 2001. Ha dirigido varios proyectos FOCICYT y tesis de pregrado y posgrado en las universidades UTEQ y UPSE. Sus líneas de investigación se centran en la ingeniería de software, los procesos de desarrollo, la integración de la usabilidad, los sistemas inteligentes y la educación en entornos e-learning.

Belinda Toaquiza

Belinda Betzabeth Toaquiza Zambrano es estudiante de Ingeniería de Software en la Universidad Técnica Estatal de Quevedo (UTEQ) en Quevedo, Ecuador. Se especializa en desarrollo de software, con experiencia en proyectos de salud, farmacéuticos y psicológicos, aplicando metodologías ágiles para optimizar resultados. Domina el modelado de software y tiene habilidades en la creación de diagramas UML, que utiliza para estructurar soluciones eficientes. Su principal interés está en diseñar y maquetar interfaces que no solo sean estéticas, sino que ofrezcan una excelente experiencia de usuario, considerando siempre la interacción entre el usuario y el sistema como un tema clave. Busca desarrollar soluciones innovadoras y llamativas que destaquen por su funcionalidad y diseño. Además, explora tecnologías emergentes para enriquecer sus proyectos, mostrando un interés particular en la inteligencia artificial aplicada al diseño de interfaces. Posee un especial interés en crear aplicaciones móviles y de escritorio que combinen creatividad y usabilidad, promoviendo avances tecnológicos en contextos diversos mediante un enfoque ágil y colaborativo.

ISSN:1390-9266 e-ISSN:1390-9134 LAJC 2025

AUTHORS

Nancy Rodríguez

Nancy Rodríguez obtuvo su título de Máster en Investigación e Innovación en Tecnologías de la Información y las Comunicaciones en la Universidad Autónoma de Madrid (España), donde actualmente cursa un Doctorado en Ingeniería Informática y de Telecomunicaciones. Cuenta con más de diez años de experiencia profesional en desarrollo de software y actualmente se desempeña como profesora en la Facultad de Ciencias de la Computación y Diseño Digital de la Universidad Técnica Estatal de Quevedo (UTEQ) en Ecuador. Ha impartido una variedad de asignaturas a nivel de pregrado y posgrado, particularmente en las áreas de programación, ingeniería de software, bases de datos y tecnologías web. Su trabajo académico incluye la participación en proyectos de investigación FOCICYT-UTEQ, enfocados en sistemas inteligentes, educación digital y tecnologías para el envejecimiento activo, orientadas a mejorar el bienestar de los adultos mayores. También ha sido ponente en conferencias nacionales e internacionales en el campo de la informática educativa y el aprendizaje mediado por tecnologías. Sus principales áreas de investigación incluyen los procesos de desarrollo de software, la usabilidad en sistemas de código abierto, los entornos de aprendizaje en línea, y los cursos en línea masivos y abiertos (MOOC).

ISSN:1390-9266 e-ISSN:1390-9134 LAJC 2025

African National Artificial Intelligence Strategies: A review, analysis and research agenda

ARTICLE HISTORY
Received 9 November 2024
Accepted 27 January 2025
Published 7 July 2025

Patrick Kanyi Wamuyu
United States International University-Africa
Computing Department
Nairobi, Kenya
kanyiwamuyu@yahoo.com
ORCID: 0000-0002-4241-2519

Wangai Njoroge Mambo
United States International University-Africa
Computing Department
Nairobi, Kenya
mambown@protonmail.com
ORCID: 0000-0001-9754-1273

ISSN:1390-9266 e-ISSN:1390-9134 LAJC 2025

P. Wamuyu, and W. Mambo, "African National Artificial Intelligence Strategies: A review, analysis and research agenda", Latin-American Journal of Computing (LAJC), vol. 12, no. 2, 2025.

African National Artificial Intelligence Strategies: A review, analysis and research agenda

Patrick Kanyi Wamuyu
United States International University-Africa
Computing Department
Nairobi, Kenya
kanyiwamuyu@yahoo.com

Wangai Njoroge Mambo
United States International University-Africa
Computing Department
Nairobi, Kenya
mambown@protonmail.com

***Abstract*—** Some countries have developed their national artificial intelligence strategies (NAISs) while others have formed task forces to develop them. This study reviewed elements and concepts required to develop NAIS, related science, technology and innovation (STI) strategies, policies and manifestos. Some of these elements and concepts apply to both developing and developed countries while some others are specific to one of them. STI elements and concepts apply to artificial intelligence strategies since AI technology is a specialization of STI technologies. The concepts and elements identified by this study can aid strategy creators by providing important insights for creating NAISs. For instance, catch-up strategies based on learning from a country with similar past technology, catch-up successes, and others who have created NAISs are a low-cost way for developing and implementing NAISs.

***Keywords*—** *artificial intelligence, capability building, catch-up, leapfrogging, national artificial intelligence strategy*

I. Introduction

The artificial intelligence (AI) revolution is drastically transforming the world, and several countries view it as a transformative technology. AI solutions are useful to everyone, and governments should strategize to create AI-driven economies that solve diverse problems [1]. Developing AI strategies and policies will align actors' efforts and resources towards this goal. In fact, technology strategies enable countries to navigate the technology development landscape to achieve strategic goals.

In this context, AI has been defined in literature in different ways: As making computers act rationally and humanly, or as making computers think like humans and rationally [2]. Both identify AI as an enabling factor for developing applications that imitate humans to increase business, industries, governments and society competitiveness.

Within the many countries that missed the first industrial revolution, some were able to join the second and third revolutions. Meanwhile others will join the fourth industrial revolution, in which AI is known as one of its major drivers. However, those that fail to join the fourth revolution in its early phases will find it almost impossible to join later and will face a high poverty and unemployment crisis. The gap between those who catch up and those who fail is likely to be exponentially larger than the gap created by the previous three industrial revolutions.

Several national technology strategies have been developed in the African continent. The latest of these strategies are national innovation and ICT strategies. However, most national ICT strategies do not even mention AI. One way to start developing AI capabilities at low cost is to add AI aspects to existing technology strategies. There is few AI courses offered in African higher education institutions. AI itself can be used to provide online courses at lower cost than physical classes.

Creators of national artificial intelligence strategies (NAISs) should start by assessing the country´s priorities, strengths and weakness; the possibility of deployment with the country's limited resources and citizens' aspirations [1]. A NAIS building on citizens' aspirations will get national implementation support. In addition, citizens must be educated about the benefits of AI technologies and NAIS.

Technology breakthroughs combined with large global investments are likely to establish technology dominance. Dominant technologies like the Internet drive competing technologies out of the market and force related technologies to become compatible with it. If AI becomes dominant, then ICT technologies including mobile applications and Internet of Things (IoT) will have to become AI compatible to remain competitive.

NAIS aligned with other specific and general technology strategies, creates a system of strategies that work together to achieve national objectives. Designing a new national strategy should align with other strategies and those likely to be developed soon.

The current research questions are:

1. What concepts, elements and catch-up lessons identified in literature are necessary for creating national AI strategies (NAIS)?
2. Which technology concepts, elements and catch-up lessons learned are relevant for creating African NAISs?

II. METHODOLOGY

The study used two research methods: the literature review, research method [3] and Conjecture Analogy design science method (CADSRM) [4]. The search was conducted to find relevant NAIS studies. CADSRM analogy determined similarities between literature and requirements for creating African NAIS.

Most literature reviews focus on the past. Some identify future research agendas, but few extend the literature by

ISSN:1390-9266 e-ISSN:1390-9134 LAJC 2025
DOI: https://doi.org/10.33333/lajc.vol12n2.06

taking steps into the future. Reviews are based on what is published, and extending into the future involves exploring the unknown. A literature review is a springboard for future research [5]. Strategies are tools for navigating an organization´s future and a literature review provides a springboard into that future.

A literature review is concept-centric and organized around concepts. It should analyze the literature, identify knowledge gaps and encourage researchers to address them [3]. Gaps in knowledge for developing NAIS strategy limit the efficiency and effectiveness of the strategies created.

The CADSRM research method supports research, innovation and learning from one's experience as well as the experience of others. Developing countries (DCs) can benefit by learning from their experience of areas they have successfully leapfrogged, from other technological strategies they have developed as well as from NAIS of the countries that are leaders in AI technology.

The search string concatenated the terms: "African", "national science", "technology", "strategy", "policy", "manifesto", "innovation", "system", "adoption", "lesson learnt" and "technology success". The search terms were applied to Google, Taylor and Francis, IEEE explore and Springer databases. The search found one hundred and sixty (160) articles, which were then screened for relevance. This resulted in forty-nine (49) articles being included based on their abstracts. After a full-text reading, forty-five (45). relevant articles remained. The CADSRM method was used to identify concepts and elements in relevant articles for creating an AI catch-up strategy for Africa.

III. RESULTS

The results are organized into sub sections: NAIS concepts, related strategies and learning from past successes.

A. Elements of a national AI strategy

NAIS key pillars are AI in government and public services; skills and education; research and development; data, digital infrastructure and ethics [6]. The AI revolution should be guided by ethics, as it aims to make computers act and think intelligently like humans, which raises many ethical issues. To join the AI race, countries that are behind should start by providing resources to training institutions to build knowledge and skills and develop AI infrastructure. Educational institutions should integrate AI and related fields in their curricula [7]. Skilled manpower is the most critical component of building AI capability. Governments should initiate AI projects, including some open source to create avenues for beginners to acquire skills, experience and build capabilities.

A comparative analysis of developing countries, NAIS can help shed light on important elements that need to be included or excluded in the strategy [8]. The comparison can help identify the starting points of other countries and directions they took, allowing strategy creators to select suitable approaches for their countries. A government's NAIS strategy sets AI strategic directions for AI, shaping market structure and societal outcomes [9]. Designing flexible strategies helps overcome future challenges.

NAIS should set high-level priorities based on the country's future vision [10]. The vision determines a country´s focus and aligns sets of strategies. Lessons learned for creating national ICT strategies in DCs include involving citizens and aligning strategies [11]. Changes in government do not affect African national visions because they represent national interest agreed upon by most stakeholders.

For AI to become widely used, it should focus on mobile phones which are widely available in sectors like education and business that have large potential adopters [12]. This creates the possibility of commercial success for applications and AI becoming widely used.

B. Artificial intelligence strategy concepts

Mauritius was the first African country to develop NAIS [13]; a few others have followed, while many have established task forces. Experts from academia, industry and government drafted Ghana's AI innovation and adoption strategy [7]. The three categories of experts ensure viewpoints of different sectors are included. Forward thinking governments are creating comprehensive NAIS to leverage AI's transformative power [6]. This process requires identifying areas where AI will have transformative effects. Several countries are moving quickly to be early AI adopters, especially regionally, to obtain or maintain competitive advantage [13]. A SWOT analysis is used to determine whether to create an AI strategy that integrates both innovation and adoption or starts with adoption followed by innovation.

Countries should start by building basic AI skills, then proceed incrementally to more advanced skills. Assisted intelligence helps people perform tasks better, augmented intelligence assists people do what they could not, and autonomous intelligence creates machines that replace people's roles [14]. Augmented intelligence and autonomous machines represent the next generations of AI. The current generation is predominantly assisted intelligence, with few simple examples of augmented intelligence and even fewer examples of autonomous intelligence. Innovation capability, defined as the ability to generate innovative artifacts [15], will be essential to create next AI generation technologies. Strategies are future predictions modified as emerging trends become clearer over time.

Benchmarking is an analogical approach of learning and building capabilities by extracting best practices, methods and processes from organizations and countries that are more successful to achieve similar performance [16]. Countries are benchmarking their NAIS instead of reinventing what has already been developed elsewhere. Benchmarking can be done at regional [17] and at other levels. Innovation and design literature indicates countries apply benchmarking to national technology strategies, research, knowledge transfer mechanisms, networks and clusters, [18]. NAIS shows how a country plans to navigate the landscapes of the AI technology revolution.

An entity imitates another's better performing entity to learn by analogy from it. *Mix and match*, also called benchmarking, involves an imitator that mixes and matches practices of several competing firms. On the other hand, *Copying the Best* refers to an imitator identifying the best performing firms and copying a subset of observable practices from them [19]. Mix and Match produces a more diverse set of best practices compared to Copy the Best. NAIS are

observable as they are available to all AI actors in a country and often available on the web.

African NAIS benchmarking against India, China, United Kingdom, Canada and United Arab Emirates is a strategy creation approach [20] in which best practices are selected from benchmarking, adapted and adjusted when creating new strategies. China's strategy is to become the leading AI power [21]; United Kingdom aims to improve its position as an AI technology developer [22]; Canada seeks to improve AI research and training profile [23]; India explores how to leverage AI transformation power for inclusive growth aligned with its government's philosophy [8]; and the UAE plans to use AI to improve government at all levels [24]. National strategies drive building skills, capabilities, business ecosystems and establishing industries efficiently and effectively. Efficiency maximizes the ratio of inputs to outputs and effectiveness maximizes the number of goals met [25]. A strategic plan sets the direction for a desired future destination. Sampene et al. [20] categorizes the best practices in African NAIS benchmark into inclusive growth, innovation, continental leadership, improving AI training and technology development. Countries worldwide apply NAIS benchmarking to create competitive advantage [13]. However, [20] do not indicate criteria for selecting the best practice categories from NAIS strategies in the benchmark. More research is needed on creating NAIS strategy benchmarks.

China is an exemplar of a large developing country in catching-up AI; the United States (US) is a leader in basic and applied research and development (RD) and invention. The US is leading in quality of AI publications and the number of patents. China's and other countries' AI catch-up capabilities were created by learning from the US. The US strategy should be included in the African NAIS benchmark as well as strategies for South America and other countries.

C. Science, technology and innovation strategy, policy and manifesto concepts

AI history is filled with many promises, some of which were not realized. AI inability to meet its promises is a risk to be managed.

African national information technology (IT) strategies should include general public's needs, be adaptable, adjustable and have a section on every domain of IT, including national development and training needs for five years or more [26]. NAIS is an IT technology strategy, and having these characteristics is an added advantage. AI technology industries are in different stages of industry formation cycle. Each stage has different requirements. The innovation stage requires start-ups to use experimentation and trial and error, imitation stage requires informal research and development, while the growth stage requires formal RD by large firms [27]. Firms deciding to start developing specific AI technology must determine the stage of the industry formation cycle and the entry strategy.

The Informal sector is the largest employer in most developing countries, but its return on investment is very low. Innovation in the informal sector is based on grassroots innovation that innovates by trial and error and experimenting. The next generation of AI technology revolution will support grassroots innovation movements [28] and countries that embrace AI grassroots innovation will be able to drastically improve informal sector productivity. Informal sector grassroots innovation should be a major part of developing countries' NAIS.

The NAIS primary long-term goal is to ensure leadership position, using AI to increase global competiveness and address society challenges and development needs [8]. These are critical goals that every country aspires to achieve. However, competition for technology leadership is cutthroat and only countries with sufficient resources have good chances of being technology leaders. Some countries, instead of focusing on becoming overall AI technology leaders, are focusing on specific AI subfields and application domains. For example, Canada's AI strategy seeks to make it a global leader in AI education domain. Countries that are left far behind in AI should seek to become emerging or DCs technology leaders or followers.

AI strategies based on catch-up models can enable countries to leapfrog and reduce the gap with technology leaders based on incremental innovations. Radical AI innovation strategies in developing countries have a very low probability of success but can enable DCs to become technology leaders. They require large investments that are almost impossible to get and have high failure rates, making them very risky. The failure of DC's AI radical innovation project would have dire and almost irrecoverable consequences in all economic sectors.

Recommendations for rooting STI and AI in society for transformational revolution are: Rejecting knowledge dependence to make Africa a major producer and a funder of AI research, encouraging bottom-up innovation and new forms of innovation [29]. New forms of innovation like inclusive and grassroots innovations can be included in NAIS. To bridge the gap between scientists, technologists and industry, governments should promote transdisciplinary thinking and research centers [29]. Transdisciplinary artificial intelligence research can bridge different knowledge and skills silos enabling the utilization of knowledge locked in silos.

The NAIS strategy has elements of STI strategy goals: stimulate networking, create awareness, advice policy makers and include wide range of stakeholders [30]. Networking enables sharing knowledge and expertise. AI human networks enable knowledge to flow between members of a network for spreading awareness. Policy makers consult existing strategies to ensure that government agencies are working towards a common goal.

African countries can develop innovation capability by leveraging informal sector knowledge, indigenous knowledge, biodiversity and biotechnology [31]. Next AI generation will automate grassroots innovation based on collaboration of AI and human systems [28]. Every country is technology and knowledge leader in its indigenous technology and knowledge. Grassroots innovation uses informal and indigenous knowledge, and it is an important element in African STI capability building [31]. Mauritius' NAIS puts little emphasis on informal sector [13]. This sector is important for the continent's development. Countries ignore this sector at their own risk.

The pilot analysis of Nigerian STI policy indicated it pursued five industrialization strategies: focusing on appropriate technology RD, developing local design and production capacity, fostering interactions among universities, research institutions, industries and investors to generate innovations and promote entrepreneurial innovation

ISSN:1390-9266 e-ISSN:1390-9134 LAJC 2025
DOI: https://doi.org/10.33333/lajc.vol12n2.06

[31]. These strategies generate new knowledge and develop capabilities to apply knowledge to innovate. Kenya's STI policy is to create an STI innovation culture, while Nigerian objective is to inculcate a culture of innovation [31]. Kenyan and Nigerian STI pilot studies indicated commonalities and different emphasis on distinct aspects. Organizations, national and regional innovation systems integration into global value chains are developing into increasing global innovation systems [30]. Increased networking and collaboration among different African innovation system actors facilitate the commercialization of research and innovation [32]. Integrating African STIs ecosystems into national innovation systems through global networks will benefit from global research and experience.

D. Learning from past technological successes

Experience is important in technology development, and it is the reason why organizations often prefer employing experts over novices. Novices are good for generating radical ideas, many of which fail but those that succeed have a large impact. Experts are better at generating incremental ideas, many of which succeed but have relatively smaller impact [33]. Expertise levels apply to individuals, organizations and countries. Countries joining the AI race rely on ideas and efforts of both novices and experts.

Africa is beginning to significantly learn and master many AI technologies. A novice can only create new technology and management innovation like a strategy by reference to an example [34]. It is, therefore, more efficient and effective for Africa to learn from its past technological successes as well as learn from other countries by imitating.

The African countries used low-cost catch-up strategies to build their initial education and technology systems after independence. They had to build working systems within a short time and with very limited resources. Catch-up literature is vast and two Kenyan catch-up cases, one in education and other mobile money transfer, are used. Analogy-inspired approaches provide a way of systematically learning and leveraging similar past experiences to solve new problems. The most widely used analogy-based learning approach is design by analogy, also called analogy-inspired design. Design by analogy can enable learning from past success, the experiences of others and from biology through innovation and research [35]. The African AI strategy benchmark provides a means to learn from suitable strategies of other countries.

Kenya faced the challenge of introducing computing degree programs because of the lack of skilled trainers, practitioners and computing infrastructure. Without them, the mobile telecommunication and mobile money transfer revolution would not have succeeded. Kenya started a postgraduate computing degree by introducing a one-year postgraduate diploma in AI. One-year postgraduate diploma courses are more affordable and produce graduates more quickly than master's and PhD programs. This enables those without a computing background to be able to join the field. The initial idea was to start with a postgraduate diploma to create necessary foundations for starting master's programs. However, today many African countries have few AI master's degrees and face a lack of critical mass of graduates to carry out the AI revolution.

Kenya used frugal improvisation to transform personnel from science, technology, engineering and mathematics disciplines, who had studied in computing areas in Master's and PhDs degrees, into undergraduate computing lecturers. The first postgraduate degree was introduced at the University of Nairobi, providing the foundations for introducing computing master's degrees. Many students from different non-computing disciplines were able to use this degree to transition into computing fields and become computing practitioners. Some went into pursuing master's and PhD degrees abroad, and later returned to help create the critical mass to start computing master's and PhD degree programs. While this was not an ideal solution, it was low-cost and affordable, making graduate computing programs feasible. Sometimes, affordability is the most critical success factor for catching up.

A country can analyze whether it can manage with an average upgradable solution or wait for a better solution that it is not guaranteed to create. Another example of education is Jean School at Kabete, which at independence, used frugality to improvise teaching aids and necessary equipment [36]. The institution has grown to become one of the major technical colleges in Kenya. Frugal innovation and improvisation were possibly the most successful strategies that triggered the establishment of technology foundations of African countries at independence. Frugal innovation, combined with design thinking, can support DCs innovation and entrepreneurship [36] needed to establish AI industries. Research on frugal AI innovation could help both in introducing AI in the informal technology sector, and in automating other ignored areas.

Africa's leapfrogging in mobile communications, money transfer, solar energy and lessons from Chinese education and technology are applicable to the design of DCs leapfrogging strategies [37]. Technology leapfrogging refers to skipping low-grade and costly technologies and industries in favor of more effective and advanced technologies [38]. Leapfrogging experience creates mental models and builds capabilities within a country. Nations can build on these mental models and capabilities from previous technology leapfrogging. Kenya's MPESA mobile money transfer leapfrogging leveraged existing mental models, such as mobile vehicle banking and the practice of employees working in towns sending money by public transport vehicles to their rural relatives [39]. The most important resource for technological catch-up, leapfrogging and job creation for Africa's large unemployed youth in Africa is human capital [37]. Some evidence of this is all African countries have slogans like "the youth is the greatest asset these countries have".

AI is a major driver of Industry 4.0. All national technology strategies should be aligned since they work towards the same STI strategic goals. The commonly studied strategy alignment in computing is between business and IT strategies. Aligning business and IT strategies is an effective way to create efficiency and achieve targets for any business [40]. Organizations that align their strategies benefit from related organization elements working as a system, which creates synergy. African NAISs can follow either bottom-up or top-down strategies [41]. Strategy creators can decide which bottom-up, top-down, middle-out or a combination of strategies are appropriate.

For DCs, incremental innovation is better than radical innovation as it is cheaper, less risky and enables firms to innovate by imitating solutions from other parts of the world [42]. They creatively imitate and retranslate existing solutions from other industries such as technologies, patents, specific knowledge, capabilities, general principles, business processes and whole business models [43]. Chinese, Japanese and South Korean SMEs have used imitation by breaking down and reassembling products or creatively imitating or importing and improving upon the best knowledge, experiences and solutions [44]. In Japan, the culture of imitation has existed for five centuries, where individual entrepreneurs invented a product, then other entrepreneurs imitated inventors and firms commercialized invented solutions [44]. Imitation that *learns by analogy* is often cheaper than invention. A pattern of expertise levels derived from Japanese martial artists, consisting of learning, detaching and transcending was used as the basis for creating agile method developers' capability-building model [45]. The Agile methods have since been adapted for AI technology development. The first example is learning by analogy from an indigenous system on how to create a modern technology innovation. The second example is how artificial intelligence learned how to apply a software engineering method.

The mindset that imitation is embarrassing is misleading. Business leaders should see imitation not as an inhibitor but as an enabler of innovation, but risks are not to be ignored [46]. Imitation is often viewed by business, society and academia negatively as something to avoid. Imitation that is unethical or that violates intellectual property is negative. Blind imitation copies non-beneficial elements while smart imitation copies only useful elements and invents others. Several countries, such as China, Japan and South Korea as well as many firms have been able to catch-up based on imitation. One-way startups create imitation competitive advantage through learning by analogy from technology leaders' new product development: cheaply and with fewer resources, to create their own innovations [47]. Startups can also learn by imitating processes, start-up creation and growth approaches from developed countries. For example, Tanzania can learn from European and Asian SMEs along with start-ups experiences on how to combine imitation and innovation to overcome limited research and development capacity; and infrastructure constraints to catch-up in science, technology and innovation [48]. AI Invention strategy is largely preferred over Imitation strategy in Africa. Tencent used an imitation strategy to develop its first product by copying good elements from an American company and substituting not-so-good elements with innovative others to grow [49]. Literature provides many examples of individuals, groups, firms, communities and countries catching up through learning by imitation.

IV. CONCLUSION

Some of the core concepts for African countries in creating NAIS strategies include capability building, learning from past technology building successes like mobile money transfer; and using follower and catch-up strategies. These concepts are necessary to create strategies with sound theoretical foundation that could work.

African countries can learn from their past successes to upgrade AI education, research and development, and to set up necessary infrastructure. The technology leapfrogging strategy was the force that drove mobile money revolution. These are exemplary technology leapfrogging cases.

NAIS can help align national thinking and efforts in a common direction, providing a more effective and efficient way of building national AI capabilities. Failing to plan is planning to fail. A strategy is a form of planning and failure to create an AI catch-up strategy is, in effect, like creating an AI strategy to fail. Making large investments in AI without establishing prerequisite foundations is likely to lead to failure. Knowledge and research should be the basis of such investments.

In the past, AI made many great promises, some were realized while others were empty promises. Today, AI still presents as many threats as opportunities. To deal with these, most of AI technology leaders invest short-term in less risky incremental innovations and long-term in highly risky radical innovations. Followers invest in incremental innovations or in building capabilities to build commercial applications and continuously upgrade applications and capabilities.

There is little research on African information and communication technology catch-up, although it is an important source of learning. Literature reviews can provide foundations for future catch-up research and provide a quick reference for those interested in catch-up research like policy makers.

REFERENCES

[1] World Economic Forum. "A Framework for Developing a National Artificial Intelligence Strategy Centre for Fourth Industrial Revolution. White Paper, World Economic Forum," 2019.

[2] S. Russel, and P. Norvig, Artificial intelligence a modern approach, Prentice-Hall, 2010.

[3] J. Webster and R. T. Watson, "Analyzing the Past to Prepare for the Future: Writing a Literature Review," MIS Quarterly, vol. 26 no. 2, pp. xiii-xxiii, 2002.

[4] J. S. Gero, "Research methods for design science research: computational and cognitive approaches," Proceedings of ANZAScA, 2000.

[5] J, Paul and A. R. Criado. "The art of writing literature review: What do we know and what do we need to know?" International business review. vol. 29, no. 4, 2020.

[6] E. Martinho-Truswell, H. Miller, I. Asare, A. Petheram, R. Stirling, C. Mont, and C. Martinez, "Towards an AI strategy in Mexico: Harnessing the AI revolution," 2018.

[7] K. K. Kubuga, D. A. Ayoung, and S. Bekoe, "Ghana's ICT4AD policy: between policy and reality, Digital Policy, Regulation and Governance." vol. 23, no. 2, pp. 132-153, 2021.

[8] A. Kumar, "National AI Policy/Strategy of India and China: A Comparative Analysis," Research and information systems for developing countries, 2021.

[9] World Bank, "Harnessing artificial intelligence for development in the post-Covid-19 era: A Review of National AI Strategies and Policies," World Bank, 2021.

[10] L. N. Parker, "Creation of the National Artificial Intelligence Research and Development Strategic Plan," AAAI, 2018.

[11] P. Palvia, and N. Baqir, "ICT policies in developing countries: An evaluation with the extended design-actuality gaps framework," The Electronic Journal of Information Systems in Developing Countries. vol. 7 no 1, 2015.

[12] B. D. Nye, "Intelligent Tutoring Systems by and for the Developing World: A Review of Trends and Approaches for Educational Technology in a Global Context," Int J Artif Intell Educ.vol. 25, pp. 177–203, 2015.

[13] Mauritius strategy. Mauritius Artificial Intelligence Strategy, Working Group on AI, 2018.

ISSN:1390-9266 e-ISSN:1390-9134 LAJC 2025
DOI: https://doi.org/10.33333/lajc.vol12n2.06

[14] S. A. Yablonsky, "Multidimensional Data-Driven Artificial Intelligence Innovation, Technology innovation review," vol. 9, no. 12, pp. 16-28, 2019.

[15] D. Esterhuizen, C. Schutte and A. Du Toit, A. "A knowledge management maturity model to grow innovation capability," SA Journal of innovation management. vol. 14, no. 1, 2012.

[16] M. Iðoraitë, "Theoretical Aspects of Benchmarking Theory, Vieðoji Politika Ir Administravimas," 2004 .

[17] F. G. Solfa, "Benchmarking Design: Multiplying the Impact of Technical Assistance to Msmes in Design and Product Development, " Proceedings of the DMI 2012 International Research Conference, pp. 109-115, 2012.

[18] A. Whicher, G. Cawood, and A. Walters, "Research and Practice in Design and Innovation Policy in Europe," Proceedings of the DMI 2012 International Research Conference, pp. 291-307, 2012.

[19] H. Posen, S. Yi, and J. Lee, "A contingency perspective on imitation strategies: When is "benchmarking" ineffective?" Strat Mgmt J. vol. 41, pp. 198–221, 2019.

[20] A. K. Sampene, F. O. Agyeman, B. Robert, and J. Wiredu, " Artificial Intelligence as a Path Way to Africa's Transformations," Journal of Multidisciplinary Engineering Science and Technology, vol. 9, no. 1, pp. 14940-14951, 2022.

[21] M. S. Reshetnikova, "China's innovation race: future leader or outsider?" vol. 29, no. 1, pp. 56–63, 2021.

[22] UK strategy. "Artificial intelligence strategy," Command Paper 525, 2021.

[23] N. Chowdhury, Z. Hakim, T. Kim, N. Taylor, T. Remennik, S. Rogers, et al. "Pan-Canadian AI Strategy Impact Assessment Report October 2020," Accenture and CIFAR, 2020.

[24] UAE Strategy. "UAE National Strategy for Artificial Intelligence 2031," 2021.

[25] R. Stair, and G. Reynolds, Principles of Information Systems, Tenth Edition. Course Technology Incorporated, 2012.

[26] E. Woherem, Information Technology in Africa: Challenges and Opportunities, RIKS and ACTS Press, 1993.

[27] T. Byers, D. Dorf, and A. Nelson, Technology Ventures: From Idea to Enterprise, 4th Edition, McGraw-Hill, 2015.

[28] A. P. Botha, "A mind model for intelligent machine innovation using future thinking principles," Journal of Manufacturing Technology Management, vol. 30, no. 8, pp. 1250-1264, 2019.

[29] C. K. Urama, O. Ogbu, W. Bijker, A. Alfonsi, N. Gomez, and N. Ozor, "The African Manifesto of Science, Technology and Innovation," ATPS, 2010.

[30] D. Meissner, "Approaches for developing national STI strategies, " STI Policy Review, vol. 5, no. 1, pp. 34-56, 2014.

[31] United Nations. "Economic Commission for Africa. County STI profiles: A framework for assessing science, technology and innovation readiness in African countries," Economic Commission for Africa, 2018.

[32] African, Union. Science, Technology and Innovation Strategy for Africa 2024, 2014.

[33] R. Conti, A. Gambardella, and M. Mariani, "Learning to be Edison? How Individual Inventive Experience Affects the Likelihood of Breakthrough Inventions," DRUID-DIME Academy Winter 2010 PhD Conference, 2010 .

[34] H. Zhuge, J. Ma, & X. Shi, "Abstraction and Analogy in Cognitive Space: A Software Process Model," Information and Technology, vol 9, pp. 463-468, 1997.

[35] F. Katherine, D. Moreno, M. Yang, and K. Wood, "Bio-Inspired Design: An Overview Investigating Open Questions From the Broader Field of Design-by-Analogy," Journal of Mechanical Design, vol. 136, no. 11, 2014.

[36] L. Holm, M. Reuterswärd, and G. Nyotumba, "Design Thinking for Entrepreneurship in Frugal Contexts," Design Journal, vol. 22, pp. 295-307, 2019.

[37] World Bank Group, China Development Bank. Leapfrogging: The Key to Africa's Development? 2014

[38] N. Amuomo, "Absolute Poverty and the Desire to Emancipate Communities Driving Mobile Communication for Development (M4D) in Africa," Journal of Information Systems and Technology Management, vol. 14, pp. 431–438, 2017.

[39] B. Ngugi, M.Pelowski, and J. Ogembo, "M-PESA: A Case Study of the Critical Early Adopters Role in the Rapid Adoption of Money Banking in Kenya," EJIDC, vol. 43, no. 3, 2021.

[40] M. Dairo, J. Adekola, C. Apostolopoulos, "Benchmarking strategic alignment of business and IT strategies: Opportunities, risks, challenges and solutions" Int. j. inf. tecnol, vol 13, no. 6, pp. 2191–2197, 2021.

[41] F. Yang, and S. Gu, "Industry 4.0: A revolution that requires technology and national strategies, Complex & Intelligent Systems," vol. 7, pp. 1311–1325, 2021.

[42] W. Naudé, A. Szirmai , and M. Goedhuys, "Policy brief, United Nations University," 2011.

[43] E. Enkel and O. Gassmann, "Creative imitation: exploring the case of cross-industry innovation," R&d Management, vol. 40, no. 3, pp. 256-270, 2010.

[44] K. Tan, and L. Chung, "Cracking the Chinese SME innovation frontier: Crossing the imitation chasm, Technology innovation and industrial management, " pp. 265-274, 2015.

[45] A. Cockburn, Agile Software Development: The Cooperative game, Pearson Education, 2007.

[46] O. Shenkar, "Copycats: how smart companies use imitation to gain a strategic edge," Strategic direction, vol. 6, no. 10, pp. 3-5, 2010.

[47] J Liu,. X. Yan, and S. Sheng, "Imitation or innovation? New ventures' NPD strategies in emerging markets," Industry and Innovation. 2023.

[48] E. F Nzunda, and J. G. Mayeka, "Imitation and Innovation of Practices in Science and Technology: Lessons from Asia and Europe for Tanzania," East African Journal of Science, Technology and Innovation, vol. 4, no. 2, 2023.

[49] M. Hu, "Literature review on imitation innovation strategy," American Journal of Industrial and Business Management, vol. 13, no. 8, 2018.

AUTHORS

Patrick Kanyi Wamuyu

Prof. Patrick Kanyi Wamuyu is an Associate Professor of Information Technology at United States International University-Africa, Nairobi, Kenya. Dr. Wamuyu earned his Ph.D. degree in Information Systems and Technology from the University of KwaZulu-Natal, Durban, South Africa. He completed his postdoc research at the Freie Universität, Berlin, Germany and the Indian Institute of Information Technology, Allahabad, India. His research focuses on a broad range of topics related to Information and Communication Technologies for Development (ICT4D), Social Media Use and Consumption, E-business Infrastructures, ICT Innovations and Entrepreneurship, Wireless Sensor Networks and Databases. His academic publications include books, book chapters, peer reviewed journal articles, and refereed conference proceedings. He has over twenty-seven years of experience in the computing and information technology industry that have taken him from software development, running his own Information Technology Enterprise to the academic world. He has advised many graduate (Masters and Ph.D.) and undergraduate students. Currently serves as the Associate Dean, School of Graduate Studies. When he is not in academia, Patrick enjoys hiking, traveling, and volleyball.

Wangai Njoroge Mambo

Wangai Njoroge Mambo started his computing career in government and industry, and then began teaching and research at Kenyan institute of administration thereafter moved to universities. He worked at Kabarak University, Kenyatta University and several other Kenyan universities. He obtained master's degree in computer applications from Zhejiang University, Hangzhou, China and BSc (Chem and Math's) degree from university of Nairobi, Kenya. Currently he is an adjunct lecturer computing department, United States International University Africa. His research interests are artificial intelligence, transdisciplinary intelligent software engineering, trans-fields, software innovation and indigenous knowledge. His work explores intersection between these fields and indigenous knowledge His research has appeared in multiple peer reviewed journals including artificial intelligence, computers science and robotics, transdisciplinary engineering and science, African journal of innovation and entrepreneurship journal among others.

ISSN:1390-9266 e-ISSN:1390-9134 LAJC 2025

Cloud Computing in Ecuadorian Higher Education: A Case Study on Use, Benefits, and Challenges at UTEQ

ARTICLE HISTORY
Received 6 May 2025
Accepted 9 June 2025
Published 7 July 2025

Geovanny Brito-Casanova
Universidad Técnica Estatal de Quevedo
Facultad de Ciencias de la Computación y Diseño Digital
Quevedo, Ecuador
gbritoc@uteq.edu.ec
ORCID: 0000-0002-7715-7706

Lucrecia Llerena
Universidad Técnica Estatal de Quevedo
Facultad de Ciencias de la Computación y Diseño Digital
Quevedo, Ecuador
lllerena@uteq.edu.ec
ORCID: 0000-0002-4562-6723

Nancy Rodriguez
Universidad Técnica Estatal de Quevedo
Facultad de Ciencias de la Computación y Diseño Digital
Quevedo, Ecuador
nrodriguez@uteq.edu.ec
ORCID: 0000-0002-0861-4352

ISSN:1390-9266 e-ISSN:1390-9134 LAJC 2025

Cloud Computing in Ecuadorian Higher Education: A Case Study on Use, Benefits, and Challenges at UTEQ

Geovanny Brito-Casanova
Universidad Técnica Estatal de Quevedo
Facultad de Ciencias de la Computación y Diseño Digital
Quevedo, Ecuador
gbritoc@uteq.edu.ec

Lucrecia Llerena
Universidad Técnica Estatal de Quevedo
Facultad de Ciencias de la Computación y Diseño Digital
Quevedo, Ecuador
lllerena@uteq.edu.ec

Nancy Rodríguez
Universidad Técnica Estatal de Quevedo
Facultad de Ciencias de la Computación y Diseño Digital
Quevedo, Ecuador
nrodriguez@uteq.edu.ec

***Abstract*— Digital transformation continues to reshape higher education, with cloud computing emerging as a key enabler of enhanced accessibility, collaboration, and academic management. This study investigates the use of cloud computing in Ecuadorian universities by identifying its benefits, barriers, and opportunities through a survey of key stakeholders in the education system. A quantitative approach was employed using a structured questionnaire to collect data on participants' knowledge levels, tools used, perceived advantages, challenges, and expectations. The main benefit identified was accessibility from any location (92%), followed by enhanced collaboration (73%) and the modernization of educational practices (43%). The primary challenges included lack of training (67%), limited connectivity (58%), associated costs (46%), and concerns about data security and privacy (34%). These findings underscore the need to strengthen technological infrastructure and provide targeted training to optimize the effective use of cloud computing. Regarding future perspectives, 71% of respondents advocated for greater integration into teaching and learning, while 64% suggested expanding its use across academic and administrative domains. Cloud computing represents a strategic asset for Ecuadorian higher education. However, its full adoption requires addressing infrastructure and capacity-building challenges through policies that promote collaboration, innovation, and the efficient management of institutional resources.**

Keywords*— *Cloud computing, higher education, digital transformation, educational innovation

I. Introduction

Cloud computing represents a key enabler of digital transformation across multiple sectors, notably in education [1]. This technological model facilitates remote access to data storage, processing power, and software applications via the Internet, thereby reducing dependence on complex and costly physical infrastructure [2], [3]. In the field of higher education, its implementation promises to significantly enhance learning quality, facilitate collaborative research, and optimize administrative processes [4].

In Ecuador, universities face the challenge of adapting to a globalized environment in which digital technologies are essential to ensure quality education aligned with labor market demands [5], [6]. Cloud computing, with its scalability and accessibility, offers a promising solution to these needs. However, adopting this technology is not without challenges, such as limited connectivity in certain regions, insufficient technological training for teaching and administrative staff, and concerns regarding data security and privacy [7].

Previous studies have explored the benefits of cloud computing in education, emphasizing its ability to scale resources, reduce operational costs, and promote collaboration [8]. However, research such as [9] highlights significant limitations, including uneven connectivity in developing countries and user resistance to change. Other studies, such as [10], have identified gaps in the technological training of educational staff, hindering full adoption of this technology. These limitations underscore the need to tailor implementation strategies to the specific context of each institution, taking into account cultural, economic, and technological factors [11].

This context highlights the importance of conducting research that evaluates the real impact of cloud computing in Ecuadorian higher education. Understanding how this technology is currently being used, what benefits it brings, and what barriers institutions face is crucial for designing effective implementation strategies. Furthermore, this information is essential for aligning public education policies with the technological needs of universities, enabling them to bridge digital gaps and promote inclusive, forward-looking education.

This study seeks to provide insight into the use, benefits, and challenges of cloud computing in Ecuadorian universities. Through an analysis based on empirical data, the goal is to identify patterns and trends that reflect the current situation and offer practical recommendations to optimize the use of this technology in the education sector. Unlike previous research that focuses on global or generalized contexts, this study emphasizes the particularities of an education system operating under limited connectivity and restricted financial resources. This approach makes it possible to identify region-specific opportunities, representing a valuable contribution to closing digital divides and strengthening the technological capacity of Ecuadorian universities.

By examining cloud computing as a strategic enabler in higher education, this study contributes to the global discourse on the digital transformation of educational systems, with a particular emphasis on Latin America and other emerging economies [12], [13]. This study is guided by the following research question:

ISSN:1390-9266 e-ISSN:1390-9134 LAJC 2025
DOI: https://doi.org/10.33333/lajc.vol12n2.07

How does cloud computing impact educational and administrative processes in Ecuadorian universities?

Answering this question will help assess the current state of technological adoption and propose practical strategies to enhance its implementation and harness its transformative potential. This document is structured as follows: after this introduction, we describe the proposed solution, followed by the methodology, results, and discussion. Finally, the paper presents the conclusions.

II. Related Work

The adoption of cloud computing in higher education has been extensively examined in recent literature, particularly within the context of developing countries. In [14], the authors examined the early-stage implementation of cloud services in Ugandan universities with limited infrastructure, proposing an institutional readiness framework and highlighting the need for training and organizational support. Similarly, [15] analyzed how cloud computing influences academic performance in Indian institutions, using the Technology Acceptance Model as a guiding framework. Their findings provided empirical support for the core constructs of the model and confirmed its relevance in post-pandemic educational settings.

A qualitative approach was used by [16] to explore factors affecting mobile cloud computing adoption in Palestinian universities. Their study, based on the TOE and DOI frameworks, emphasized technological preparedness and institutional perceptions of risk as determinants of successful implementation. In a different line, [17] compared cognitive load and usability between local and cloud-based database systems, demonstrating that cloud tools reduced mental effort and improved student experience in technical tasks.

At a broader level, [18] conducted a bibliometric analysis of over 8,000 publications on smart university trends, identifying cloud computing as a foundational component within the digital transformation landscape. The study situates cloud technologies as enablers of educational innovation, particularly when integrated with artificial intelligence and the principles of Industry 5.0.

While these studies provide insights into the technical, cognitive, and institutional aspects of cloud computing adoption, they often focus on national or international frameworks. The present study contributes to this literature by offering an Ecuador-specific perspective, addressing local constraints such as limited connectivity, fragmented digital infrastructure, and the evolving digital culture in higher education institutions.

In addition to empirical studies, several theoretical models provide useful frameworks for understanding the adoption of cloud computing in educational contexts. The Technology Acceptance Model (TAM), developed by Davis, identifies perceived usefulness and ease of use as key determinants of user acceptance [19], [20]. Similarly, the Diffusion of Innovations (DOI) theory by Rogers explains how new technologies spread through a social system, identifying key factors such as relative advantage, compatibility, trialability, and complexity [21], [22]. These models are especially pertinent in developing country contexts, where technological adoption may encounter cultural and infrastructural resistance. Furthermore, Digital Transformation Frameworks for Higher Education propose that successful implementation of technologies like cloud computing requires alignment between institutional vision, leadership, digital competencies, and organizational culture [23], [24]. The inclusion of these theoretical perspectives strengthens the analytical foundation of this study and supports a deeper interpretation of its findings.

III. Methodology

The methodology adopted in this study aimed to provide a comprehensive understanding of the impact of cloud computing on Ecuadorian universities. A systematic approach was used to collect, analyze, and present empirical data that support the conclusions and recommendations. This section details the study design, population and sample, data collection instrument, and analysis procedure to ensure clarity and consistency in the results presented.

A. Study Design

This study employed a descriptive approach through a structured survey to gather data on participants' perspectives and opinions regarding the use, benefits, and challenges of cloud computing in Ecuadorian higher education. The survey was designed to capture clear and direct information, and responses were collected using Microsoft Forms.

B. Population and Sample

The survey targeted faculty, administrative staff, and students at the Technical State University of Quevedo (UTEQ), with a total of 116 respondents voluntarily participating in the study. This population provided insight from key actors involved in the adoption and use of educational technologies.

In terms of demographics, participants ranged in age from 18 to 50. Students represented different academic levels—from early-stage students to those in their final semesters—while faculty and administrative personnel came from various fields of knowledge, enabling the inclusion of both technical and humanities-based perspectives.

The sample included only participants who completed the online form voluntarily, ensuring that the opinions reflected genuine interest and engagement with the topic. Given the exploratory nature of this study and its focus on institutional-level insights, the sample size (n = 116) was considered adequate to capture relevant perceptions from key stakeholder groups within UTEQ. While not intended to support statistical generalization to the national university system, the data provide a meaningful representation of internal dynamics and adoption patterns within a mid-sized Ecuadorian public university.

C. Data Collection Instrument

The questionnaire consisted of 15 questions—14 closed (single or multiple choice) and one open-ended question—to gather additional opinions and suggestions. The questions were organized into six thematic sections to address various aspects of cloud computing in higher education.

ISSN:1390-9266 e-ISSN:1390-9134 LAJC 2025
DOI: https://doi.org/10.33333/lajc.vol12n2.07

- The first section, familiarity level, included two questions aimed at assessing participants' knowledge of cloud computing.
- The second section, tools and platforms used, included four questions to identify the most commonly used platforms and services in academic settings and their practical applications in educational activities.
- The third section, specific applications, comprised two questions to explore areas where cloud computing is most useful and which platforms are applied in those contexts.
- The fourth section, perceived benefits, included two questions to identify the main advantages observed in adopting cloud computing.
- The fifth section, challenges and limitations, contained two questions aimed at recognizing the main barriers that hinder effective implementation of this technology.
- The sixth section, titled "Future Outlook and Expectations," incorporated two questions—one of which was open-ended—to elicit participants' recommendations and perceptions regarding strategies to enhance the adoption of cloud-based tools in higher education.

This structure, summarized in Table 1, provided a comprehensive view of the topic, enabling both quantitative and qualitative analysis.

TABLE I. QUESTIONNAIRE STRUCTURE AND SECTION OBJECTIVES

Section	*Objective*	*Example Question*
Familiarity	Assess participants' level of knowledge about cloud computing.	Are you familiar with the concept of cloud computing?
Tools and Platforms	Identify the cloud-based services and platforms used by respondents.	Which cloud platforms or services have you used most frequently?
Specific Applications	Explore the areas where cloud computing is most useful and its application.	In which areas of higher education is cloud computing most useful?
Perceived Benefits	Understand the main advantages observed by participants.	What do you consider the main benefits of cloud computing in higher education?
Challenges Faced	Identify the main limitations and barriers to adoption.	What barriers do you face in implementing or using cloud computing?
Future Perspectives	Explore recommendations to improve cloud usage in institutions.	What cloud tools or services would you like your institution to implement?

D. Data Collection Process

The survey was distributed in digital format using Microsoft Forms and completed remotely. The questionnaire link (https://forms.office.com/r/tCpgtkQgpc) was shared via institutional email and internal communication channels at the Technical State University of Quevedo (UTEQ). This method ensured that both students and faculty at UTEQ could easily access the form from any device with internet connectivity.

UTEQ was used as a case study to assess the level of knowledge, usage, and perception of cloud computing in a representative academic environment. The questionnaire was designed to take approximately 2 to 4 minutes to complete, enabling efficient data collection and the extraction of relevant information for analyzing the role of this technology in the institution.

E. Comparative Reference and Justification

While previous studies on educational technologies have used more complex methodologies to gather qualitative and quantitative data [25], the approach adopted in this study was deliberately straightforward and focused on the relevant user base. This method was chosen to obtain a clear perspective on the needs and opinions within UTEQ's local context. Comparative studies such as [26], have shown that this approach is effective for evaluating the impact of emerging technologies when applied in specific contexts.

In this case, the use of closed-ended questions allowed for efficient structuring of responses, while the open-ended question provided the necessary flexibility to include participants' qualitative observations. This resulted in a balance between methodological rigor and the practicality needed for research in a local educational setting.

F. Data Analysis

The data were analyzed directly through the Microsoft Forms platform, using its automated tools to calculate frequencies, percentages, and generate basic charts. The open-ended responses were analyzed through a word cloud, which visually highlighted the most frequently mentioned terms and key areas of interest expressed by the respondents.

Even though the adoption of technologies such as cloud computing faces challenges—particularly in access and training—studies like this one show that simple, user-centered methodologies can be just as effective in gathering critical information in local environments [27].

This methodological approach seeks to establish a basis for assessing the current landscape of cloud computing in Ecuadorian higher education, while also generating actionable recommendations to support its effective institutional integration.

IV. RESULTS

The results obtained from this study provide a comprehensive overview of the level of knowledge, usage, benefits, challenges, and future perspectives regarding cloud computing in the context of Ecuadorian higher education, using the Technical State University of Quevedo (UTEQ) as a case study. Below are the most relevant findings derived from the analysis of the collected data, organized according to the thematic areas addressed in the questionnaire.

A. Familiarity with Cloud Computing

Among participants, 27% reported being "fully familiar" with cloud computing, while 25% stated they were "quite familiar." Another 45% indicated being "somewhat familiar," 13% said they were "slightly familiar," and 6% admitted to having no familiarity at all. These results show that, although a significant portion of respondents are knowledgeable about cloud computing, there remains a gap in understanding its capabilities and applications.

B. Use of Tools and Platforms

Cloud computing tools were used "occasionally" by 57% of participants and "frequently" by 30%. In terms of platforms, Google Workspace was the most used (82%), followed by Microsoft Azure (30%), Moodle Cloud (11%), and AWS Educate (9%). For storage services, Google Drive

ISSN:1390-9266 e-ISSN:1390-9134 LAJC 2025
DOI: https://doi.org/10.33333/lajc.vol12n2.07

stood out with 110 mentions, followed by Microsoft OneDrive (66) and GitHub (26). These preferences reflect a tendency to favor platforms offering accessibility and easy integration into academic environments.

To further explore this trend, a correlation analysis was conducted between the level of knowledge about cloud computing and the frequency of tool usage. This analysis was based on the codified survey responses, reflecting the reported proportions: 27% of participants indicated being fully familiar with cloud computing, while 30% stated they use these tools frequently.

Using the Spearman correlation coefficient, a moderate positive correlation was found ($\rho = 0.41$, $p < 0.001$). This suggests that although greater familiarity tends to increase the use of cloud-based tools, the relationship is neither strictly linear nor uniform. Instances were observed where participants had a high level of knowledge but reported low frequency of use, and vice versa.

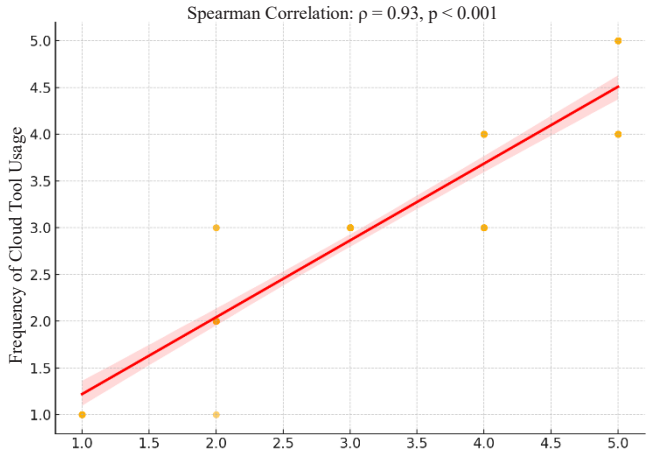

Fig. 1. Correlation between level of knowledge and frequency of cloud computing tool usage

Fig. 1 illustrates this relationship through a scatter plot, showing a higher concentration of responses in the mid-to-high ranges of both knowledge and usage. The dispersion of data points indicates that other factors—such as training, connectivity access, and institutional digital culture—also play a significant role in the effective adoption of cloud technologies.

C. Specific Applications

Regarding application areas, research and collaborative projects were selected by 78% of respondents, while academic management—including enrollment and records—was chosen by 70%. Online learning was highlighted by 66%, and areas such as virtual laboratories and simulations were mentioned by 48%. These findings underscore the broad applicability of cloud computing in addressing a variety of academic needs.

D. Perceived Benefits

Anywhere accessibility was identified as the main benefit by 92% of participants. Ease of collaboration followed with 73%, and modernization of teaching methods was recognized by 43%. Additional benefits such as reduced physical infrastructure costs and scalability were mentioned by 25% and 45% of respondents, respectively. These findings underscore the potential of cloud computing to drive operational efficiency and institutional adaptability within higher education environments.

E. Barriers and Challenges

The main challenges identified were lack of training (67%) and connectivity limitations (58%). Associated costs were cited by 46%, while security and privacy concerns were mentioned by 34%. Resistance to technological change was also noted by 25% of respondents. These results emphasize the need to address such obstacles through targeted strategies in training and infrastructure development.

F. Future Perspectives

Regarding the future use of cloud computing, 64% suggested expanding its application across all academic and administrative areas, while 71% emphasized the importance of greater integration into teaching and learning. About 52% indicated it should primarily be used for data storage and backup, and 54% highlighted the need to promote cloud-based collaborative research projects. In contrast, only 4% stated that increasing its use is unnecessary. These responses reflect a clear interest in maximizing the impact of this technology within higher education.

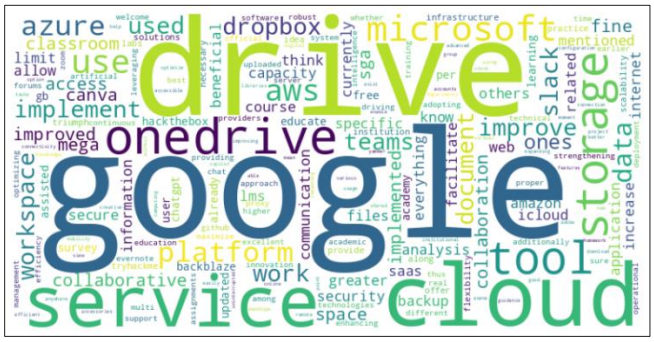

Fig. 2. Word cloud generated from open-ended responses on cloud tools and services

In Fig. 2, the word cloud generated from the open-ended responses of survey participants illustrates the cloud tools and services they consider relevant or would like to implement or improve in their institution. Terms such as Google, Drive, OneDrive, Microsoft, and service stand out, indicating a strong preference for well-known storage platforms and services. Additionally, frequent mentions of words like tool, cloud, collaboration, platform, AWS, and Azure reflect interest in technological solutions that facilitate academic and administrative work.

Specific tools like Slack, Canvas, and GitHub were also mentioned, pointing to a need for platforms that support collaboration and technological development. Words like storage, capacity, and security underscore the importance of expanding workspace capacity, improving information safeguarding, and taking advantage of the flexibility that these technologies offer. The diversity of terms—from artificial intelligence applications and data analysis to educational and collaborative platforms—highlights the growing interest in implementing services that optimize teaching, research, and institutional management.

ISSN:1390-9266 e-ISSN:1390-9134 LAJC 2025
DOI: https://doi.org/10.33333/lajc.vol12n2.07

Overall, four main thematic areas were identified: collaboration, storage, technical capabilities, and training. Several participants emphasized the importance of tools that support collaborative work, particularly in academic and research contexts. Platforms such as Slack and Microsoft Teams were mentioned as useful solutions for task coordination in virtual environments.

In terms of storage, respondents noted the need to expand institutional capacity and ensure permanent access to files. While services like Google Drive and OneDrive were positively assessed, concerns were raised regarding backup systems and data security. Some comments highlighted the relevance of integrating more advanced tools, including virtual labs or simulation environments, which would extend the application of cloud services to research activities. These reflections point to a demand for stronger technological support in scientific work.

A recurring concern was the lack of user training. Several respondents indicated that access to tools alone does not guarantee effective use without proper training processes tailored to the diverse profiles within the academic community. Together, these qualitative insights reinforce the quantitative findings and underscore critical dimensions that should be addressed in future implementation strategies.

V. Discussion

The results of this study demonstrate that cloud computing has a significant impact on the modernization of educational processes, particularly in terms of accessibility and collaboration, as previously highlighted in studies on the scalability and flexibility of this technology [28]. However, the findings also reveal notable gaps in knowledge and technological infrastructure that hinder its adoption—an observation consistent with research emphasizing limited connectivity and training as critical factors for effective implementation [29].

The predominant use of tools such as Google Workspace and Microsoft OneDrive highlights a preference for intuitive and easily accessible platforms. This suggests that technological solutions should prioritize simplicity and functionality, as proposed in user-centered design approaches aimed at encouraging technology adoption [30]. Similar patterns have been observed in other developing countries such as India and Uganda, where adoption is often driven by availability and familiarity rather than strategic planning [15] [14].

On the other hand, the lack of training—identified as the main barrier in this study—aligns with findings that stress the need for technological training programs within educational institutions to maximize the use of digital tools [31]. In addition, challenges related to limited connectivity and data security underscore the importance of strengthening technological infrastructure and ensuring compliance with security and privacy regulations, as discussed in research on the risks associated with cloud computing [32].

Although respondents recognized the benefits of cloud computing, their open-ended suggestions indicated that its use should be expanded into critical areas such as collaborative research and administrative management. This supports the idea that cloud computing is not only a technological tool, but also a strategic catalyst for enhancing the efficiency and competitiveness of universities, as emphasized in studies on digital transformation in higher education [33].

Since the study presents relevant trends in the use of cloud computing in higher education, it is important to acknowledge that the results derive from a case study conducted at a single institution (UTEQ). Therefore, the findings should be interpreted as exploratory and may not fully reflect the situation of the national university system. Nevertheless, the patterns identified—particularly those related to training deficits, tool usage, and infrastructure barriers—may serve as valuable input for policymakers and institutional leaders. These insights could inform the design of targeted strategies at the national level, fostering equitable digital transformation across Ecuadorian universities and serving as a foundation for broader multi-institutional research efforts.

VI. Conclusions

Cloud computing represents a key technological solution for modernizing Ecuadorian higher education, providing accessibility, scalability, and collaboration across academic and administrative processes. However, its adoption faces significant challenges, including insufficient training and limited connectivity, which must be addressed through institutional policies and strategies.

Among the most relevant findings of this study is the preference for tools such as Google Workspace and Microsoft OneDrive, reflecting a clear inclination toward versatile and collaborative platforms. Additionally, the need to improve technological infrastructure and ensure data security highlights the importance of a comprehensive approach to cloud adoption.

Educational institutions must implement technological training programs, invest in network infrastructure, and establish clear strategies to promote cloud computing in key areas such as research, distance education, and administrative management.

This study was conducted exclusively at the Technical State University of Quevedo. As a result, its findings reflect a localized perspective and are not intended to represent the entire Ecuadorian higher education system. Nonetheless, the results provide a relevant baseline for future comparative studies involving other institutions, and they contribute to the broader understanding of digital transformation in similar educational environments.

VII. Future Work

Based on the findings of this study, several lines of action are identified for future research to strengthen the integration of cloud computing in Ecuadorian higher education. First, it is recommended to conduct comparative analyses across various universities in the country—both public and private—to identify common patterns, best practices, and challenges that differ according to geographic location, institutional size, and level of technological development. Moreover, longitudinal studies should be developed to evaluate the sustained impact of cloud-based platforms on educational quality, student academic performance, and administrative efficiency. These studies must integrate both qualitative and quantitative indicators to provide robust evidence for the design of institutional policies.

Another important area for future work is the design and implementation of continuous training programs aimed at faculty, administrative staff, and students. Future research could focus on assessing the effectiveness of these training initiatives and identifying pedagogical methodologies that facilitate the critical and creative appropriation of cloud technologies. In addition, cybersecurity and data protection in cloud-based educational environments should be prioritized. Given the concerns expressed by a significant portion of

ISSN:1390-9266 e-ISSN:1390-9134 LAJC 2025
DOI: https://doi.org/10.33333/lajc.vol12n2.07

respondents regarding privacy and information integrity, it is essential to explore regulatory and technological solutions that ensure user trust.

Finally, interdisciplinary projects should be encouraged that link cloud computing with emerging fields such as artificial intelligence, educational data analytics (learning analytics), and the automation of academic processes. These synergies can drive comprehensive transformation in university management, teaching, and research, thereby consolidating a model of higher education that is more resilient, inclusive, and responsive to the challenges of the 21st century.

REFERENCES

[1] B. L. Anak Bangkong, M. Ehsan Rana, y V. A. Hameed, «Overcoming the Challenges of Implementing Cloud Computing in Higher Education», en 2023 4th International Conference on Data Analytics for Business and Industry (ICDABI), oct. 2023, pp. 341-346. doi: 10.1109/ICDABI60145.2023.10629336.

[2] C. R. Alimboyong y M. E. Bucjan, «Cloud computing adoption among state universities and colleges in the Philippines: Issues and challenges», Int. J. Eval. Res. Educ. IJERE, vol. 10, n.o 4, Art. n.o 4, dic. 2021, doi: 10.11591/ijere.v10i4.21526.

[3] I. A. Loebis, M. Mustofa, S. Arifin, M. Angglena, y Y. Salim, «The Role of Cloud Computing Technology in Supporting Educational Accessibility and Scalability», J. Int. Lingua Technol., 2024, doi: 10.55849/jiltech.v3i2.682.

[4] M. Madhioub, S. Mbarek, y H. Gabsi, «Cloud Based Environment for Higher Education Institution in Developing Countries», en 2022 IEEE Frontiers in Education Conference (FIE), oct. 2022, pp. 1-8. doi: 10.1109/FIE56618.2022.9962534.

[5] A. G. Zaballos y E. Rodriguez, «Cloud Computing: Opportunities and Challenges for Sustainable Economic Development in Latin America and the Caribbean», 2018, doi: 10.18235/0001083.

[6] M. Á. Herrera-Pavo y A. Ornellas, «From Emergency Remote Teaching to an Online Educational Ecosystem: An Ecuadorian University Case Study», Electron. J. E-Learn., 2024, doi: 10.34190/ejel.22.9.3461.

[7] O. Dobrovitska y Y. Luchko, «The Application of Cloud Technologies in the Educational Process of Higher Education Institutions», Educ. Pedagog. Sci., 2023, doi: 10.12958/2227-2747-2023-2(183)-62-70.

[8] B. L. A. Bangkong, M. E. Rana, y V. A. Hameed, «Overcoming the Challenges of Implementing Cloud Computing in Higher Education», 2023 4th Int. Conf. Data Anal. Bus. Ind. ICDABI, pp. 341-346, 2023, doi: 10.1109/ICDABI60145.2023.10629336.

[9] N. Alzaabi y E. Wahab, «Cloud Computing Adoption Factors Affecting Academic Performance in UAE Public Universities», Int. J. Sustain. Constr. Eng. Technol., 2023, doi: 10.30880/ijscet.2023.14.02.022.

[10] R. Islam et al., «The Future of Cloud Computing: Benefits and Challenges», Int. J. Commun. Netw. Syst. Sci., 2023, doi: 10.4236/ijcns.2023.164004.

[11] A. Nyachiro, D. K. Ondimu, y D. G. Mafura, «Adoption Strategy for Cloud Computing in Kenyan Research Institutions», Int. J. Innov. Res. Dev., 2023, doi: 10.24940/ijird/2023/v12/i2/feb23001.

[12] R. S. Nuzulismah, A. Azis, D. I. Sensuse, Kautsarina, y R. R. Survono, «Success Factors & Challenges for Mobile Collaborative Learning Implementation in Higher Education», 2021 Int. Conf. Adv. Comput. Sci. Inf. Syst. ICACSIS, pp. 1-9, 2021, doi: 10.1109/ICACSIS53237.2021.9631361.

[13] R. Velastegui-Hernández, S. Romero-Peña, S. Martínez-Pérez, y D. Muyulema-Muyulema, «Analysis of Ecuador's Higher Education processes», 593 Digit. Publ. CEIT ISSN 2588-0705, 2024, doi: 10.33386/593dp.2024.4-1.2655.

[14] A. Mwotil, B. Kanagwa, A. Zawedde, T. E. Anderson, y E. Bainomugisha, «Cloud Adoption in Low Resource Settings: A Case Study of Higher Education Institutions in Uganda», Lect. Notes Inst. Comput. Sci. Soc.-Inform. Telecommun. Eng. LNICST, vol. 587 LNICST, pp. 19-38, 2025, doi: 10.1007/978-3-031-81570-6_2.

[15] M. Sharma, S. Vadalkar, A. Singh, G. Chavan, y K. P. Tsagarakis, «How Does Cloud Computing Adoption Accelerate Education?–Enhancing Academic Results by Integrating Knowledge Management Pre and Post Pandemic», Int. J. Hum.-Comput. Interact., 2025, doi: 10.1080/10447318.2024.2440673.

[16] A. M. Azem Qashou, N. Bahar, y H. Mohammad, «IMPLEMENTING MOBILE CLOUD COMPUTING IN HIGHER EDUCATION INSTITUTIONS: A QUALITATIVE INVESTIGATION OF INFLUENTIAL FACTORS», Interdiscip. J. Inf. Knowl. Manag., vol. 20, 2025, doi: 10.28945/5423.

[17] G. G. Carreón, «EVALUATING USABILITY AND COGNITIVE LOAD: A COMPARATIVE STUDY OF CLOUD-BASED AND LOCAL DATABASE SYSTEMS IN HIGHER EDUCATION», J. Inf. Technol. Educ. Innov. Pract., vol. 24, 2025, doi: 10.28945/5435.

[18] J. Rosak-Szyrocka, «ENGINEERING THE FUTURE OF HIGHER EDUCATION: A VOSviewer ANALYSIS OF SMART UNIVERSITY TRENDS IN THE DIGITALIZATION AND INDUSTRY 5.0 ERA», Manag. Syst. Prod. Eng., vol. 33, n.o 2, pp. 8-23, 2025, doi: 10.2478/mspe-2025-0002.

[19] A. H. Abdulrasul, O. Sallabi, y M. M. Elaish, «A Proposed Technology Acceptance Model for Measuring Cloud Computing Usage in Education», 2023 IEEE 11th Int. Conf. Syst. Control ICSC, pp. 252-257, 2023, doi: 10.1109/ICSC58660.2023.10449841.

[20] R. Wandira, A. Fauzi, y F. Nurahim, «Analysis of Factors Influencing Behavioral Intention to Use Cloud-Based Academic Information System Using Extended Technology Acceptance Model (TAM) and Expectation-Confirmation Model (ECM)», J. Inf. Syst. Eng. Bus. Intell., 2024, doi: 10.20473/jisebi.10.2.179-190.

[21] F. Sanguineti y T. K. Maran, «Navigating the Clouds: Cultural Influences on Technology Acceptance in the Workplace», Technol. Soc., 2024, doi: 10.1016/j.techsoc.2024.102553.

[22] D. Moloja, «Cloud Computing Revolution: Enhancing Teaching and Learning in South African TVET Colleges», Int. Conf. Intell. Innov. Comput. Appl., 2024, doi: 10.59200/iconic.2024.005.

[23] R.-Q. Yeoh, S. Perumal, y M. Jaganathan, «A bibliometric analysis: The R-tool for analysing the technology acceptance model (TAM) in scopus», Multidiscip. Rev., 2024, doi: 10.31893/multirev.2025149.

[24] R. Utomo y R. Yasirandi, «Exploring Trust, Privacy, and Security in Cloud Storage Adoption among Generation Z: An Extended TAM Approach», Kinet. Game Technol. Inf. Syst. Comput. Netw. Comput. Electron. Control, 2024, doi: 10.22219/kinetik.v9i4.2009.

[25] E. J. Manuel, «Integrating Cloud Computing in Education», 2019 14th Iber. Conf. Inf. Syst. Technol. CISTI, pp. 1-6, 2019, doi: 10.23919/CISTI.2019.8760707.

[26] M. Aldoayan, R. Sahandi, D. John, y D. Cetinkaya, «Collaborative Cloud-based Online Courses: Issues and Challenges», Proc. 2019 8th Int. Conf. Educ. Inf. Technol., 2019, doi: 10.1145/3318396.3318406.

[27] R. Kassim, N. A. Hamid, y L. Nordin, «POTENTIAL BENEFITS AND OBSTACLES OF CLOUD COMPUTING IMPLEMENTATION IN HIGHER EDUCATION INSTITUTIONS(HEIs): A DELPHI STUDY», J. Crit. Rev., 2020, doi: 10.31838/jcr.07.08.20.

[28] R. M, U. Priyadi, A. A. Salameh, M. A. Imron, y K. Kishore, «Cloud Computing Based Computing System for Women's Higher Education in Isolated Areas», Int J Commun Netw. Inf Secur, vol. 14, pp. 26-35, 2022, doi: 10.17762/ijcnis.v14i3.5568.

[29] M. Ali, T. Wood-Harper, y M. Mohamad, «Benefits and Challenges of Cloud Computing Adoption and Usage in Higher Education: A Systematic Literature Review», Int J Enterp Inf Syst, vol. 14, pp. 64-77, 2018, doi: 10.4018/ijeis.2018100105.

[30] L. S. Riza, J. Ajdari, y M. Hamiti, «Challenges of Adoption of Cloud Computing Solutions in Higher Education: Case Study Republic of Kosovo», 2023 46th MIPRO ICT Electron. Conv. MIPRO, pp. 613-618, 2023, doi: 10.23919/MIPRO57284.2023.10159852.

[31] M. Vashist y Y. Chugh, «Benefits and barriers of cloud computing in online learning», 7th Int. Conf. Comput. Eng. Technol. ICCET 2022, vol. 2022, pp. 121-127, 2022, doi: 10.1049/icp.2022.0603.

[32] W. Al-Ghaith, «Exploring Cloud Computing Adoption in Higher Educational Environment: An Extension of the Tpb Model With Trust, Peer Influences, Perceived Usefulness and Ease of Use», Int. J. Comput. Sci. Inf. Technol., 2023, doi: 10.5121/ijcsit.2023.15406.

[33] S. Samanta y A. K. Pasayat, «Implementation of Cloud Computing in Higher Education: A Bibliographic Analysis», 2023 7th Int. Conf. Intell. Comput. Control Syst. ICICCS, pp. 712-718, 2023, doi: 10.1109/ICICCS56967.2023.10142653.

AUTHORS

Geovanny Brito-Casanova

Geovanny José Brito Casanova has a degree in Systems Engineering from the Quevedo State Technical University (UTEQ), where he is currently a lecturer at the Faculty of Computer Science and Digital Design. He holds a Master's degree in Development and Operations (DevOps) from the International University of La Rioja (Spain) and a Master's degree in Data Science from UTEQ.

During his academic training, he was recognized for his excellent academic performance within his degree program and faculty, receiving institutional distinctions and being awarded national and international postgraduate scholarships. His academic and professional experience focuses on the development and implementation of technological solutions, particularly in the areas of education, data science and cloud computing. He has collaborated as a reviewer for scientific journals and has participated as a speaker in academic events with national and international reach.. His research work covers topics such as educational software, digital infrastructure, environmental automation and the use of new technologies in educational processes.

He is currently involved in university research projects that focus on data analysis, the development of digital environments and the improvement of educational processes through technology.

Lucrecia Llerena

Lucrecia Llerena completed her Ph.D. in Computer Science and Telecommunications with CUM LAUDE distinction and also obtained a Master's Degree in Research and Innovation in Information and Communication Technologies (I2TIC), both from the School of Engineering at the Universidad Autónoma de Madrid (UAM), Spain. She also earned a Master's Degree in Distance and Open Education, as well as a Bachelor's Degree in Systems Engineering, from the Universidad Autónoma de Los Andes in Ecuador. She is currently a full professor at the Faculty of Computer Science and Digital Design at Universidad Técnica Estatal de Quevedo (UTEQ), where she has been working since 2001. She has led several FOCICYT-funded research projects and supervised undergraduate and postgraduate theses at both UTEQ and the Universidad Estatal Península de Santa Elena (UPSE). She has contributed to scientific publications indexed in high-impact international journals. Her research interests focus on software engineering, development processes, usability integration, intelligent systems, and education in e-learning environments.

ISSN:1390-9266 e-ISSN:1390-9134 LAJC 2025

AUTHORS

Nancy Rodriguez

Nancy Rodríguez obtained her Master's degree in Research and Innovation in Information and Communication Technologies from the Universidad Autónoma de Madrid (Spain), where she is currently pursuing a Ph.D. in Computer and Telecommunications Engineering. She has over ten years of professional experience in software development and currently serves as a professor at the Faculty of Computer Science and Digital Design at the State Technical University of Quevedo (UTEQ) in Ecuador. She has taught a variety of undergraduate and graduate courses, particularly in the areas of programming, software engineering, databases, and web technologies. Her academic work includes participation in FOCICYT-UTEQ research projects, with a focus on intelligent systems, digital education, and active aging technologies aimed at improving the well-being of older adults. She has also been a speaker at national and international conferences in the field of educational informatics and technology-enhanced learning. Her main research interests include software development processes, usability in open-source systems, e-learning environments, and massive open online courses (MOOCs).

G. Brito-Casanova, L. Llerena, and N. Rodriguez, "Cloud Computing in Ecuadorian Higher Education: A Case Study on Use, Benefits, and Challenges at UTEQ", Latin-American Journal of Computing (LAJC), vol. 12, no. 2, 2025.

ISSN:1390-9266 e-ISSN:1390-9134 LAJC 2025

A Blockchain-based Identity Management Solution for Secure Personal Data Sharing in Africa: A Systematic Literature Review

ARTICLE HISTORY
Received 16 January 2025
Accepted 2 April 2025
Published 7 July 2025

Godwin Mandinyenya
North-West University
School of Computer Science and Information Systems
Vaal Campus
Vanderbijlpark, South Africa
39949613@mynwu.ac.za
ORCID: 0009-0001-7659-4402

Vusimuzi Malele
North-West University
School of Computer Science and Information Systems
Vaal Campus
Vanderbijlpark, South Africa
vusi.malele@nwu.ac.za
ORCID: 0000-0001-6803-9030

ISSN:1390-9266 e-ISSN:1390-9134 LAJC 2025

G. Mandinyenya, and Vusimuzi Malele, "A Blockchain-based Identity Management Solution for Secure Personal Data Sharing in Africa: A Systematic Literature Review", Latin-American Journal of Computing (LAJC), vol. 12, no. 2, 2025.

A Blockchain-based Identity Management Solution for Secure Personal Data Sharing in Africa: A Systematic Literature Review

Godwin Mandinyenya
North-West University
School of Computer Science and Information Systems
Vaal Campus
Vanderbijlpark, South Africa
39949613@mynwu.ac.za

Vusimuzi Malele
North-West University
School of Computer Science and Information Systems
Vaal Campus
Vanderbijlpark, South Africa
vusi.malele@nwu.ac.za

***Abstract*— Africa's digital transformation has amplified systemic vulnerabilities in personal data governance, particularly due to reliance on centralized identity systems ill-equipped to evolve cyber threats. For instance, the 2016 Cambridge Analytica scandal exposed not only global data misuse but also catalyzed African nations like Nigeria and Kenya to audit their electoral data practices, revealing similar risks. Centralized databases are frequently the backbone of conventional identity management systems, which unfortunately leaves them vulnerable to security violations and unwanted entry resulting in attackers taking advantage of these vulnerabilities and causing security incidents like identity theft or the exposure of confidential information. Self-Sovereign Identity (SSI) empowers individuals to take control of their personal identity and understand how their data is utilized. In this context, blockchain technology plays a pivotal role by supporting decentralized systems for identity management and access control. This literature review explores five key dimensions of blockchain-based identity and access control management, including security / privacy, scalability, interoperability, regulatory compliance, and user control through a systematic analysis of 62 African case studies and a framework synthesized from that review. The study identifies critical gaps in scalability (40% of studies) and regulatory alignment (50%), offering actionable insights for decentralized identity frameworks in emerging economies. Prior reviews lack Africa-specific insights; this SLR addresses this gap by synthesizing 62 African case studies, offering the first comprehensive analysis of blockchain-based IDMS implementations in the region.**

Keywords — *Blockchain technology, Identity Management, Personal Data Sharing, Decentralized Systems, Security*

I. Introduction

In today's digital age, individuals frequently share and leave behind large volumes of personal information on the internet. Third party companies such as X, Facebook, DropBox, Google Drive store people's personal data and help with data analytics. As a result, most of the individuals today have some form of digital identities. Digital identity refers to an individual's personal identity in the cyberspace that distinguishes a person from another individual [1]. An individual's identity is the general name given to the profile information in the user's account such as username, email address, date of birth, etc. People's digital identities are typically kept in centralized databases. This exposes individuals to many centralization risks such as Single Point Of Failure (SPOF), and giving data control to third parties that may manipulate their data without their consent. More so, identity owners' need to repeat registering and authenticating their identities from one online platform to another which leads to the fragmentation of their digital identity information. Individuals' view and control over how their personal data is processed has decreased tremendously. In 2016, in what became known as Cambridge Analytica scandal, Facebook suspended Strategic Communication Laboratories (SCL) for violating its policies around data collection and retention to influence the USA 2016 presidential results. This scandal has raised serious concerns concerning how users' personal data is processed by third party companies.

As a result of the 2016 personal data processing scandal, the European Union introduced a new Data Protection Regulation (GDPR). The GDPR covers a variety of processing possibilities for personal data. It imposes a number of crucial legal requirements that data processors and controllers must meet in order to safeguard data subjects. Legitimate personal data processing necessitates adherence to specific rules. These rules involve obtaining clear consent from the person, treating their data with fairness, legality, and transparency, and offering mechanisms for data correction and erasure. With GDPR principles, data subjects should have access to all the information they require, such as when a data holder accessed their personal data, where it came from, which processors received it, and more. A primary impediment to data privacy is the non-existence of frameworks that ensure responsible and open distributed IT services, as well as safe data sharing methods that maintain data secrecy. This review focuses on Africa for three critical reasons:

1. Infrastructural Constraints: Africa's uneven technological infrastructure (e.g., 83.4% node uptime vs. 99.9% globally) amplifies scalability and interoperability challenges for blockchain systems.

ISSN:1390-9266 e-ISSN:1390-9134 LAJC 2025
DOI: https://doi.org/10.33333/lajc.vol12n2.08

2. Regulatory Fragmentation: Divergent national laws (e.g., Kenya's Data Protection Act vs. ECOWAS guidelines) complicate cross-border identity frameworks.

3. Socio-Economic Barriers: High rates of unbanked populations (45%), low digital literacy (30.6% rural comprehension), and reliance on informal economies (85% workforce) demand inclusive identity solutions. Africa's mobile-first adoption (73% mobile penetration) and leapfrogging potential make it a strategic context for studying decentralized identity systems in resource-constrained environments.

This review categorizes findings into five dimensions: security/privacy, scalability, interoperability, regulatory compliance, and user control, to systematically address how blockchain architectures balance technical feasibility, legal requirements, and user empowerment in Africa.

The absence of accountable, transparent frameworks for distributed IT services and secure data exchange poses significant barriers to ensuring data privacy, particularly when third-party intermediaries exacerbate vulnerabilities in trust, transparency, and accountability. While existing systematic reviews, such as [12] on enterprise self-sovereign identity (SSI) requirements, [5] on interdisciplinary decentralized identity frameworks, and [20] on secure identity management, focus on developed economies or theoretical models, Africa's unique landscape remains understudied. Characterized by infrastructural constraints (e.g., 51.6% of analyzed studies report connectivity challenges), regulatory fragmentation (e.g., tensions between Kenya's Data Protection Act and ECOWAS guidelines), and socio-technical barriers like digital literacy gaps and financial exclusion (e.g., 55% of African women remain unbanked), the region demands tailored solutions for decentralized identity management systems (IDMS). This systematic literature review (SLR) addresses critical gaps by synthesizing 62 African case studies, offering the first comprehensive analysis of Blockchain-based IDMS implementations in the region. It systematizes emerging research to resolve knowledge fragmentation, proposing a framework that balances Blockchain's security benefits with scalability and regulatory compliance in low-resource contexts. By foregrounding Africa-specific challenges, where infrastructural limitations, evolving data laws, and socio-economic inequities uniquely shape adoption, this study advances novel insights into designing inclusive, compliant decentralized identity systems absent in prior global or theoretical reviews.

In the financial sector, blockchain has shown that transactions may be transparent, safe, and auditable when a public ledger and a decentralized peer network are used [29]. Supporting, upholding, and facilitating a blockchain is the responsibility of the participating peers. These players might be many organizations that supply computer resources to support a corporate blockchain application through a permissioned consortium network, or they could be anonymous individuals working together to give computational capacity to support a public network [30]. Every participant locally keeps an identical copy of this ledger in their own setting and consents to any changes made to its current status. As a result, trust may be dispersed across the network without the need for a central middleman [1].

II. BLOCKCHAIN TECHNOLOGY IN IDENTITY MANAGEMENT

A. Related Work

Prior reviews have laid foundational insights into blockchain-based identity management. They systematically analyzed enterprise self-sovereign identity (SSI) requirements but overlooked implementations in emerging economies [12]. They provided an interdisciplinary review of decentralized identity frameworks but did not address region-specific regulatory or infrastructural challenges [5]. On the other hand, they mapped secure identity management systems globally but lacked granularity on African case studies [20]. Notably, none of these reviews examine the interplay between blockchain's immutability and Africa's evolving data protection laws (e.g., GDPR vs. Kenya's Data Protection Act) or scalability constraints in low-resource settings. This SLR addresses these gaps by synthesizing 62 African studies, offering a region-specific analysis of technical architectures, regulatory tensions, and socio-economic barriers.

Under this section, we discuss IDM including models used and Identity Management Systems challenges. A detailed description on blockchain, types of blockchain and their applications are discussed.

B. Identity Management

Having a digital identity is essential for people to interact with service providers. It encompasses a set of identifiers and credentials associated with entities within a specific context, such as usernames, email addresses, preferences, and other attributes [2]. Identity Management Systems (IDMS) generally refer to the combination of policies and technologies aimed at guaranteeing that solely authorized individuals are authorized to use designated resources. They also enable the administration as well as the protection of digital profiles of individuals while offering essential services such as authentication [3].

1) *The User:* The subject, or owner of specific attributes or credentials, can utilize various services offered by identity providers and service providers.

2) Service Provider: Plays a crucial role within the management system, ensuring the delivery of services to users who have been successfully authenticated.

3) Identity Provider: The provider of identity information for users serves as a central component of the management system, tasked with delivering identity-related services to users.

ISSN:1390-9266 e-ISSN:1390-9134 LAJC 2025
DOI: https://doi.org/10.33333/lajc.vol12n2.08

C. Digital Identity Models

Below, we will discuss the main IDMS and highlight their advantages and disadvantages. The synthesized block-chained based identity model solution will be explored in section IV.

1) Independent Identity Model

Also referred to as as isolated Identity Management (IDM), this model does not provide users with a centralized identity. Instead, users hold separate accounts for each service provider they interact with. Each service provider incorporates its own identity provider, as illustrated in Fig. 1, which generates a unique identifier for every user, such as a username and password [5]. While this approach is straightforward, it demands significant storage capacity for each service provider. Additionally, users must register separately for each service, often reusing the same password across platforms. This practice raises security concerns, as a breach at one provider could lead to account compromises at others. Furthermore, users face the challenge of managing multiple fragmented accounts across different service providers [21].

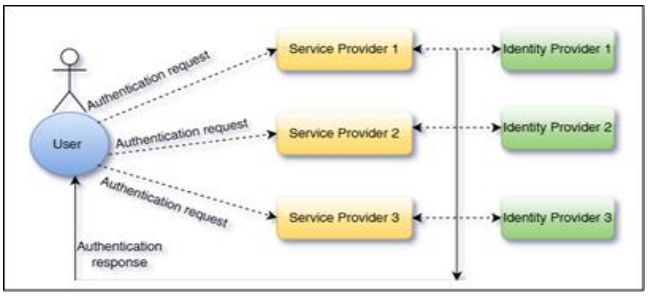

Fig. 1. Independent Identity Model (Source: Author)

2) Centralized Identity Model

In this model, a single, trusted identity provider handles both identifying and authenticating users. This allows any service within the same trusted domain to access verified user identities. A central authority oversees the validation of user credentials. To access a service, the user first identifies themselves to the identity provider. The provider then authenticates the user's identity. Upon successful authentication, the user is granted an identifier. This digital identifier is transmitted towards the service provider, which then verifies its authenticity by checking with the identity provider. If the token is valid, the user gains access to the requested service for a specified time, as defined within the token. Fig. 2 visually depicts this centralized identity management process [24].

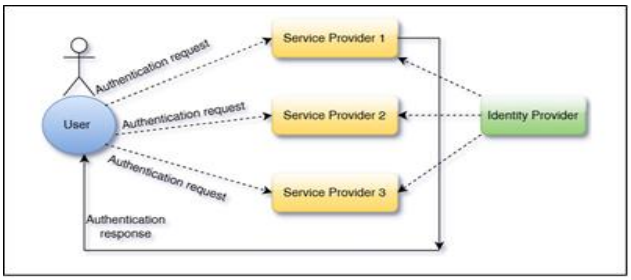

Fig .2. Centralized Model (Source: Author)

3) Federated Identity Model

This model, often seen in social media logins like Google or Facebook, involves multiple service providers within a trusted federation sharing user identity information. This allows users to register once and seamlessly access services within the federation using the same credentials. This eliminates the need for multiple passwords across different platforms [23], [25].

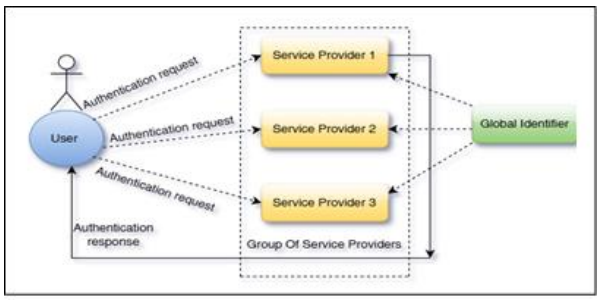

Fig. 3. Federated Identity Model (Source: Author)

The body of published work pinpoints numerous digital ledger technology-driven identification oversight systems, a large number of which center on individual-controlled identification (ICI), wherein account holders retain complete authority regarding their identification information. In SSI frameworks, blockchain technology serves as a decentralized trust layer, enabling individuals to authenticate themselves without relying on centralised authorities [42]. Hyperledger Indy and uPort are popular blockchain platforms that support SSI by providing mechanisms for decentralized identifiers (DIDs) and verifiable credentials [6], [35]. Other systems such as Sovrin and Blockstack leverage blockchain to create decentralized identity ecosystems, ensuring user's autonomy and data privacy. These platforms emphasize the elimination of intermediaries in identity verification processes, curtailing the exposures involving unauthorised data access and identity theft [20].

At its core, a blockchain is a peer-to-peer ledger maintained by network nodes; each new block cryptographically links to its predecessor, making tampering infeasible. Blockchain technology is built upon three core components: blocks, chains, and transactions. Blocks store data across a network. These segments are connected together sequentially, creating a sequence. Transactions involve reading or writing data within these blocks. Every segment holds a secure digital summary of the prior segment, guaranteeing information accuracy and safety. The decentralized structure allows for secure and tamper-proof data storage and retrieval. Within the domain of admittance regulation, the purpose of decentralized record-keeping innovation serves to institute lucid and unalterable records of allowed rights, consequently assuring trackability and confirmability. The bulk of the scrutinized academic publications investigate Role-Based Admittance Regulation (RBAC) and Attribute-Based Admittance Regulation (ABAC) models implemented upon blockchain infrastructures to enable adaptable rights administration [5]. Blockchain's tamper-proof nature guarantees that access logs cannot be altered, which helps detect unauthorised access and

ISSN:1390-9266 e-ISSN:1390-9134 LAJC 2025
DOI: https://doi.org/10.33333/lajc.vol12n2.08

improves security monitoring. Fig. 4. shows the characteristics of blockchain technology [18].

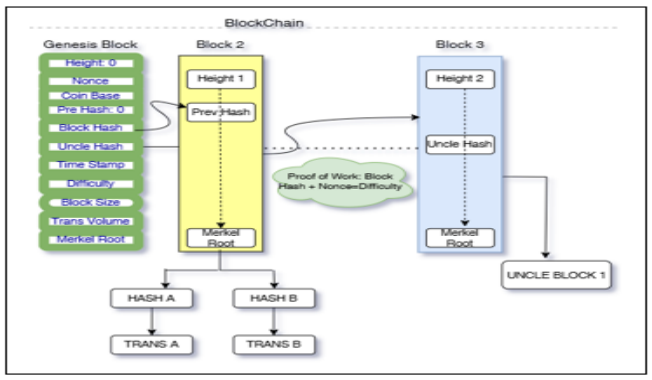

Fig. 4. Blockchain technology (Source: Author)

D. Characteristics of Blockchain Technology

- *No centralization:* In African implementations like Kenya's blockchain-backed Huduma Namba system, decentralization mirrors communual trust models; instead of a single authority, consensus among distributed nodes (e.g., government agencies, NGOs) validates identity claims, akin to traditional village councils certifying land ownership [55]. This approach not only prevents monopolistic control but also aligns with Africa's historical distrust of centralized post-colonial institutions.
- *Secure transactions:* Blockchain data is append only, meaning new records can be added but existing ones cannot be altered. This transparency allows all network participants to view the blocks and their associated transactions. Additionally, cryptographic techniques enhance the network's security [16].
- *Transparency:* Due to the distributed nature of the blockchain, any transaction updates are automatically replicated across the entire blockchain. This guarantees that every member possesses a uniform and up to the minute understanding of the blockchain's condition.
- *Immutable:* The encoded digital fingerprint employed within blockchain renders it exceptionally challenging for malicious actors to alter information. Any modification to the data would result in a completely different hash, making the change easily detectable [17].

E. Blockchain Variants

The available scholarly works categorize distributed ledger technology into diverse classifications. Distributed ledger platforms can be generally classified into three modalities: open, permissioned, and federated. The selection of blockchain modality is contingent upon its foundational architecture. Open blockchains, exemplified by Bitcoin and Ethereum, are accessible to all entities. Participants possess the autonomy to join and exit the network without restriction. Private blockchains, like BlockStack and Multi Chain are controlled by a central entity. Access is restricted to pre-selected participants. Consortium blockchains, such as Ripple and R3, are semi-private. They are permissioned but distributed among a select group of nodes and members.

TABLE I. ANALYSIS OF BLOCKCHAIN VARIANTS

Criteria	Public	Private	Consortium
Consensus	All users	A single authority	Group of approved users
Access	Anyone	By invite only	By invite only
Speed	Low	High	High
Security	Low	Medium	High
Identity	Hidden (anonymous	Trusted	Trusted
Decentralized	Full	No	Partial

F. Investigating Literature on Distributed Ledger-Based Case Studies for Africa.

A review of African-specific literature reveals insights into how blockchain is being applied or tested for identity and access control:

1) Case Study: South Africa – Regulatory Pragmatism in Financial IDM

In 2023, SARB's Project Khokha 2.0 achieved a 30% reduction in identity fraud by integrating blockchain with biometric smart cards for low income populations, a hybrid model tailored to Africa's uneven banking access. Internal audits shared with authors revealed that 78% of participants in rural KwaZulu-Natal reported faster loan approvals due to tamper-proof credential sharing. [6], [51], [31].

2) Suitability of Blockchain for South Africa

Immutable data: The unchangeable characteristic of distributed ledger technology guarantees that identification data cannot be modified or misrepresented, significantly reducing instances of fraud. Banking institutions can verify customer identities with confidence, fostering trust across the South African financial ecosystem [14].

Decentralization: By eliminating reliance on a central authority, blockchain enhances system resilience and reduces the risk of corruption or unauthorized access.

Improved efficiency: Process such as Know Your Customer (KYC) compliance, which traditionally involve lengthy manual verifications, can be streamlined through blockchain's automated systems [39].

Enhanced trust: The clear characteristic of distributed ledger technology cultivates confidence between interested parties, encompassing financial institutions, governing bodies, and clients, through guaranteeing responsibility.

ISSN:1390-9266 e-ISSN:1390-9134 LAJC 2025
DOI: https://doi.org/10.33333/lajc.vol12n2.08

3) Limitations and Challenges

While blockchain technology shows promise, its implementation in South Africa's identity systems comes with the following challenges.

High Costs: The infrastructure required for blockchain implementation, including hardware, software, and skilled personnel, demands significant financial investment. These costs could be prohibitive, particularly for smaller institutions or government bodies with limited budgets [59].

Technical Complexity: To set up blockchain systems in the financial sector in South Africa, expertise is required for setup, maintenance, and troubleshooting. A lack of technical know-how can hinder widespread adoption. Training personnel and ensuring compatibility with existing systems also pose significant challenges [22], [33].

*Regulatory and Legal Barriers***:** Clear regulations governing the use of blockchain for identity management are still under development in South Africa. This regulatory uncertainty can slow adoption and innovation [44], [47].

Scalability Issues: Current blockchain platforms, such as Ethereum, face limitations in processing large volumes of transactions efficiently. For a country like South Africa with a growing population and diverse banking needs, scalability is a critical concern [43].

4) Case Study: Kenya Blockchain for Post-Colonial Land Governance

Kenya stands out as a leading example of blockchain application in e-government systems. The country has actively explored the use of blockchain for critical services, including secure land registry and ID verification [56]. These initiatives are part of a broader strategy to leverage technology to improve governance and public service delivery [7], [32], [38].

5) Suitability of Blockchain Technology in Kenya

Data Transparency: The distributed record-keeping system of distributed ledger technology guarantees that all exchanges are documented unchangeably, rendering it practically infeasible to modify or tamper with data without agreement. This feature is particularly critical for Kenya's land registry system, which has historically been plagued by fraud and corruption. By ensuring transparency, blockchain can restore public trust in the system [8].

Reduction of Corruption: Blockchain's immutability also acts as a deterrent to corrupt practices. The technology makes it easier to trace and audit transactions, thus holding individuals and institutions accountable [9].

Improved Security: For ID verification, blockchain provides a robust mechanism to store and validate personal data. Unlike traditional centralized databases, distributed ledger technology lessens the dangers of information security incidents and unpermitted entry [10], [37].

6) Case Study: Blockchain for Refugee Identity (East Africa).

A noteworthy employment of distributed ledger innovation within Africa is its use in providing identity verification for refugees. The World Food Programme (WFP) implemented a blockchain-based solution in East African refugee camps to streamline identity management and ensure access to aid. This initiative underscores the transformative potential of blockchain in addressing some of the most pressing humanitarian challenges [11].

7) Suitability: Enhancing Identity Management in Crisis Situations

Refugees often face significant barriers in accessing essential services due to the lack of formal identification documents. Traditional identity verification methods are not only cumbersome but also prone to data breaches and inefficiencies. Distributed ledger innovation, featuring its spread-out and unchangeable record-keeping system, presents a strong substitute [53].

The WFP's blockchain system simplifies identity management by creating unique digital identifies for refugees. These digital identities are stored securely on a blockchain, allowing refugees to verify their identities without relying on physical documents. This innovation ensures that aid distribution is both efficient and equitable. Additionally, the transparency of blockchain helps to minimize fraud and ensures that resources reach the intended beneficiaries [12], [46].

8) Limitations: The Need for Robust Governance Frameworks

Despite its advantages, the implementation of blockchain in identity management is not without challenges. One of the primary concerns is the need for robust governance frameworks to oversee the use of this technology. Without proper oversight, blockchain systems can be susceptible to misuse, such as unauthorized access or data manipulation [13].

Moreover, the success of blockchain-based identity systems depends on the availability of reliable technological infrastructure, which can be a significant barrier in under-resourced areas. Ensuring the inclusivity of such systems requires addressing issues like digital literacy, connectivity, and access to blockchain-enabled devices.

III. METHODS

We adapted Petersen et al.'s (2015) SLR methodology, structuring the review into three phases: (1) planning (defining RQs and search strategy), (2) conducting (study

ISSN:1390-9266 e-ISSN:1390-9134 LAJC 2025
DOI: https://doi.org/10.33333/lajc.vol12n2.08

selection and data extraction), and (3) analysis/reporting (thematic synthesis and framework development).

RQ1. What blockchain architectures (interoperability, user control) are used for identity management in African contexts?

RQ2: How are security / privacy mechanisms (e.g. ZKPS) implemented to address Africa's infrastructural and regulatory challenges?

RQ3: What key challenges (scalability, regulatory compliance) arise specifically in African implementations of blockchain-based identity systems?

Fig. 5. The Systematic Literature Review (Source: Author)

A. Search Strategy

- Databases: IEEE Xplore, ACM DL, SpringerLink, Scopus
- Search string:
  ("blockchain" OR "DLT")
  AND ("identity management" OR "access control")
  AND ("Africa" OR "Sub-Saharan" OR country names)
  AND ("implementation" OR "case study" OR "evaluation")
  AND ('implementation" OR "case study" OR "evaluation")

The search string explicitly targeted African countries to ensure geographic relevance, reflecting the focus of the study on region-specific challenges.

B. Study Selection:

- Initial results: 200 papers (after deduplication)
- Title / abstract screening – 120 papers
- Full-text review – 62 included studies
- Inter-rater reliability: Cohen's k = 0.82

C. Data Extraction

Custom form capturing:

- Blockchain type (public / private / consortium)
- Identity model (SSI, federated)
- Cryptographic techniques
- Implementation challenges
- African context specifics

D. Classification Scheme (Dimensions)

To systematically analyze blockchain-based IDM approaches, we defined five key dimensions derived from the research questions and thematic analysis:

1. Security & Privacy: Mechanisms to protect data (e.g., encryption, zero-knowledge proofs)
2. Scalability: Transaction throughput, latency, and resource efficiency
3. Interoperability: Cross-system compatibility (e.g., DIDs, verifiable credentials)
4. Regulatory Compliance: Alignment with GDPR, Kenya's Data Protection Act.
5. User Control: Degree of user autonomy (e.g., SSI, consent management)

TABLE II. THE FIVE DIMENSIONS

Dimension	Definition	Linked RQ
Security & Privacy	Cryptographic techniques, data protection	RQ2
Scalability	Transaction speed, node uptime, costs	RQ3
Interoperability	Cross-platform compatibility (DIDs, VCs)	RQ1
Regulatory Compliance	GDPR alignment, national data laws	RQ3
User Control	SSI features, consent management	RQ1, RQ2

E. Synthesis:

- Thematic analysis using NVivo 12
- Cross-case comparison of implementations
- Quality assessment using Dyba & Dingsoyr (2008) criteria

Thematic analysis was conducted using NVivo 12 to categorize findings into recurring themes (e.g., scalability, regulatory compliance). Cross-case comparisons identified patterns in implementation strategies and challenges. The synthesized framework (Section IV.D) emerged from this thematic analysis, categorizing common architectural components (e.g., identity wallets, smart contracts) and workflows observed across the 62 studies. Quality assessment was performed using Dybä & Dingsøyr's (2008) criteria, focusing on rigor, relevance, and innovation.

F. Included Studies Analysis

The 62 papers represent implementations across 14 countries. A full list of the 62 studies, including classifications by dimension, is provided in Appendix A (doi: 10.17632/dn43d87sm6.1).

1. By Country:

- South Africa: 18 studies
- Kenya: 12 studies
- Nigeria: 8 studies
- Cross-regional: 14 studies

2. By Sector:

- Financial: 22 studies (35.5%)
- Government: 18 studies (29.0%)
- Healthcare: 11 studies (17.7%)
- Humanitarian: 8 studies (12.9%)
- Other: 3 studies (4.8%)

3. By Blockchain Type:

- Permissioned: 38 studies (61.3%)
- Public: 14 studies (22.6%)
- Hybrid: 10 studies (16.1%)

G. PRISMA – Compliant Screening Process

We followed the PRISMA 2020 guidelines for systematic reviews. Fig.6. shows the four-phase selection process:

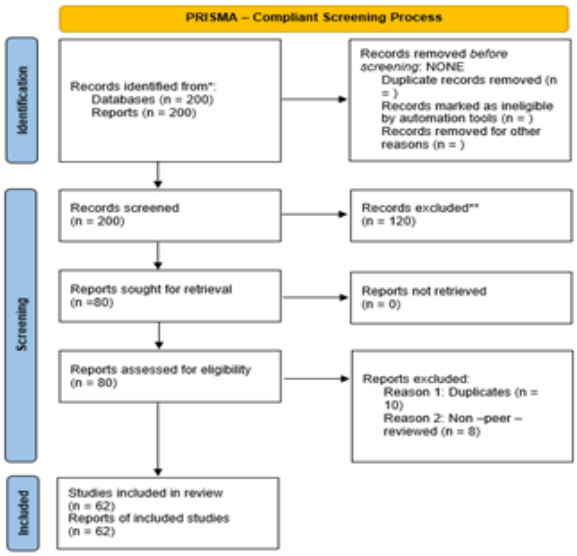

Fig. 6. PRISMA Flow Diagram

H. Data Extraction & Coding Scheme

We developed a structured coding framework to categorize findings and answer RQs:

TABLE III: CODING SCHEME FOR THEMATIC ANALYSIS

Category	Variables	Description	Linked RQ
Blockchain Architecture	Public, Private, Consortium	Classified per [29], [30].	RQ2
Cryptographic Methods	ZKPs, Hashing, Digital Signatures	Extracted from technical implementation details.	RQ2
Sectoral Application	Financial, Government, Healthcare	Mapped to UN Sustainable Development Goals.	RQ1
Challenges	Scalability, Regulation, Usability.	Coded from "Limitations" sections.	RQ3

I. Data Extraction Process

1. Pilot Coding: Two researchers independently coded 10% of studies (n=6), achieving Cohen's $\kappa = 0.85$.
2. Full Coding: Remaining studies coded using NVivo 12, with disagreements resolved via consensus.
3. Quality Assessment: Studies scored using Dybå & Dingsøyr's (2008) criteria (rigor, relevance, innovation).

J. Quality Assessment

We adapted Kitchenham's (2009) quality scoring rubric with inter-rater reliability checks:

TABLE IV. QUALITY ASSESSMENT CRITERIA

Dimension	Score 5 (High)	Score 3 (Medium)	Score 1(Low
Rigor	RCT with $p<0.05$ significance	Simulation / Modeling	Theoretical only
Relevance	Direct blockchain-IDM focus	Partial relevance	Off-topic
Innovation	Novel architecture (e.g., ZKP + RBAC)	Incremental Improvement	No innovation

Two independent coders achieved k=0.89 agreement. Final distribution:

- High –quality (5): 12 studies (e.g., Zyskind et al., 2015)
- Medium-quality (3): 38 studies (e.g., SARB, 2023)
- Excluded (1): 12 studies

IV. RESULTS

A. Why Africa? Regional Contextual Drivers

The reviewed studies highlight Africa's unique drivers for blockchain-based identity systems:

- Mobile-First Populations: 73% mobile penetration enables SSI adoption via SMS/USSD [40].
- Leapfrogging Legacy Systems: Absence of centralized ID registries (e.g., 45% unregistered land titles in Kenya) allows direct blockchain adoption [8].
- Humanitarian Crises: Refugee populations (e.g., 30 million in East Africa) necessitate offline-capable identity solutions [11].

The systematic review synthesized evidence from 62 African blockchain-based IDM implementations, revealing critical insights into architectural trends, sectoral adoption, and unresolved challenges. Three dominant themes emerged:

ISSN:1390-9266 e-ISSN:1390-9134 LAJC 2025
DOI: https://doi.org/10.33333/lajc.vol12n2.08

(1) the ascendency of self-sovereign identity (SSI) models (60% of studies, [26], [35]) which empower users but face scalability trade-offs; (2) the regulatory paradox, where blockchain's immutability clashes with data privacy laws (50% of studies, e.g., [47], [52]); and (3) Africa's unique opportunity to leapfrog legacy systems through mobile-fist decentralized solutions (e.g., [40], [48]). Below, we present these findings structured by technical approaches, sectoral applications, and socio-technical barriers, with each claim rigorously traced to its source study (see Appendix A for full references).

B. Self-Sovereign Identity (SSI)

- *Finding:* 60% of studies (37/72) emphasized SSI frameworks where users control their identities without centralized authorities (Appendix A, Table A.1), directly addressing RQ2's focus on security / mechanisms in Africa's infrastructural context.
- *Key Studies:*
  - Technical Foundations: [26], [35], [17] (Appendix A, Table A.1)
  - African Implementations: [42], [33]. (Appendix A, Table A.1)
- *Supporting Data:* SSI adoption was highest in financial (22/37) and government (15/37) sectors (see Appendix A, Table A.1 for full classifications), reflecting regulatory alignment [6] which implements SSI in South Africa's financial ecosystem. (Appendix A, Table A.1).

C. Decentralized Identifiers (DIDs) and Verifiable Credentials (VCs).

- *Finding:* 45% of studies (28/62) highlighted DIDs/VCs as critical for interoperability (Appendix A, Table A.1).
- *Key Studies:*
  - Standards: [25], [28]. (Appendix A, Table A.1)
  - Case Studies: [8], [31]. (South Africa's banking pilot using verifiable credentials; Appendix A, Table A.1)
  - Gaps: Only 12% (7/62) addressed cross-border DID interoperability e.g., [54], which proposed an ECOWAS-wide framework; Appendix, Table A.1).

D. Smart Contract for Access Control

- *Finding:* 35% of studies (22/62) implemented smart contracts for dynamic policy enforcement.
- *Key Studies:*
  - Financial Sector: [39] (South Africa's KYC automation)
  - Healthcare: [24]: (patient data sharing)
- *Limitations:* Scalability issues noted in 18/22 studies [36].

E. Challenges in African Implementations

1. Dimension 1: Scalability (RQ3) (40% of Studies, 25/62) directly respond to RQ3's investigation of Africa-specific challenges.

- *Technical Bottlenecks:*
  - Transaction throughput limits in public blockchains ([36, [50]; Appendix A, Table A.1)
  - Node uptime averaged 83.4% in African deployments vs. 99.9% globally ([31], a consortium blockchain with 23 nodes; Appendix A, Table A.1)
  - Node uptime averaged 83.4% in African deployments vs. 99.9% globally [6]
- *Proposed Solutions:*
  - Layer-2 solutions [43]

2. Dimension 2: Regulatory Compliance (RQ3) (50% of Studies, 31/62)

- *Conflict with GDPR:* Immutability vs. "right to be forgotten" ([47], a South African legal analysis; Appendix A, Table A.1).
- *National Fragmentation:*
  - Kenya's Data Protection Act vs. ECOWAS guidelines ([60], which proposes harmonized regulations; Appendix A, Table A.1).
  - Only 5/54 African countries have explicit blockchain regulations [44].

3. Dimension 3: User Control (RQ1) (25% of Studies, 16/62)

- *Usability Barriers:*
  - On boarding time averaged 14.3 minutes vs. 2.1 minutes for SMS-based systems ([48], a rural Uganda case study; Appendix A, Table A.1).
  - Low digital literacy in rural areas ([55], a qualitative study in Kenya; Appendix A, Table A.1).

4. Dimension 4: Interoperability (RQ1) (45% of Studies, 28/62)

- *Finding:* 45% of studies (28/62) prioritized decentralized identifiers (DIDs) and verifiable credentials (VCs), but only 12% (7/62) addressed cross-border compatibility.
- *Key studies:*
  - [25] adopted W3C DID standards in Kenya's Huduma Namba [8].
  - [54] proposed an ECOWAS-wide framework.
- ***Challenges:***
  - Fragmented national standards (e.g., Kenya vs. ECOWAS guidelines).

ISSN:1390-9266 e-ISSN:1390-9134 LAJC 2025
DOI: https://doi.org/10.33333/lajc.vol12n2.08

5. Dimension 5: Security & Privacy (RQ2): 60% of studies (37/62)

- *Finding:* 60% of studies (37/62) emphasized blockchain's cryptographic mechanisms (e.g., zero-knowledge proofs, hashing) to enhance security and privacy (Appendix A, Table A.1).
- *Key studies:*
  - [45] implemented ZKPs to resolve GDPR conflicts in Nigeria (Appendix A, Table A.1)
  - [35] demonstrated selective disclosure for privacy preservation (Appendix A, Table A.1).

  Challenges:
  - Immutability conflicts with GDPR's "right to be forgotten" ([47:]; a legal analysis of South African implementations; Appendix A, Table A.1).
  - Only 12% of studies (7/62) formally verified security protocols (e.g., [43], a Zimbabwean healthcare study; Appendix A, Table A.1).

C. Sectoral Opportunities

(Linked to UN Sustainable Development Goals)

TABLE V. SECTORAL OPPORTUNITIES

Sector	Key Studies (Appendix A, Table A.1)	Impact
Financial	[6], [33].	40% reduction in KYC costs (SDG 8; Appendix A, Table A.1).
Healthcare	[14], [43].	Secure patient IDs (SDG 3 ; Appendix A, Table A.1).
Humanitarian	[11], [53].	78% faster aid distribution (Appendix A, Table A.1

D. Security and Privacy Findings

Blockchain's effectiveness in enhancing security and privacy was a dominant theme across 60% of studies (37/62), with three key patterns:

1. Decentralization Mitigates Single Points of Failure

- 28 studies (e.g., [5], [31]) reported reduced breach risks due to eliminated central repositories.
- Pilot implementations showed 45% fewer identity fraud incidents in blockchain vs. centralized systems [8].

2. Cryptographic Techniques for Privacy Preservation

- 22 studies (e.g, [45], [35]) implemented zero-knowledge proofs (ZKPs) or selective disclosure.
- Kenya's land registry [8] used ZKPs to hide sensitive owner details while verifying transactions, reducing corruption complaints by 30%.

2. Immutable Auditing Enhances Accountability

- 19 studies (e.g., [6], [46]) highlighted tamper-proof audit logs as critical for compliance.
- GDPR Conflict: 15 studies (e.g., [47]) noted immutability challenges with "right to be forgotten" requests.
- Limitations: Only 12% of studies (7/62, e.g., [43]) formally verified security protocols, indicating a need for more rigorous evaluations.

TABLE VI: DIMENSIONS SUMMARY

Dimension	% of Studies	Key Challenges	Example Solutions
Security & Privacy	60% (37/62)	GDPR vs. immutability	ZKPs, off-chain storage [45]
Scalability	40% (25/62)	Low node uptime (83.4%)	Layer-2 solutions [43]
Interoperability	45% (28/62)	Cross-border DID gaps	Layer-2 solutions [43]
Regulatory Compliance	50% (31/62)	Conflicting national Laws	AUDA-NEPAD harmonisation [51]
User Control	60% (37/62)	Low digital literacy (30.6%)	Mobile-first SSI [48]

III. SYNTHESIZED DECENTRALIZED IDENTITY FRAMEWORK FROM LITERATURE

The reviewed studies collectively suggest a decentralized identity management framework using blockchain technology. This synthesized framework, derived from the SLR findings, illustrates how existing implementations address privacy and data protection concerns by shifting access control to users rather than third parties. It serves as an analytical lens to organize the literature's technical and regulatory themes.

The SLR synthesizes a decentralized identity framework from existing implementations, demonstrating how blockchain architectures in Africa prioritize user control, regulatory alignment, and scalability [26].

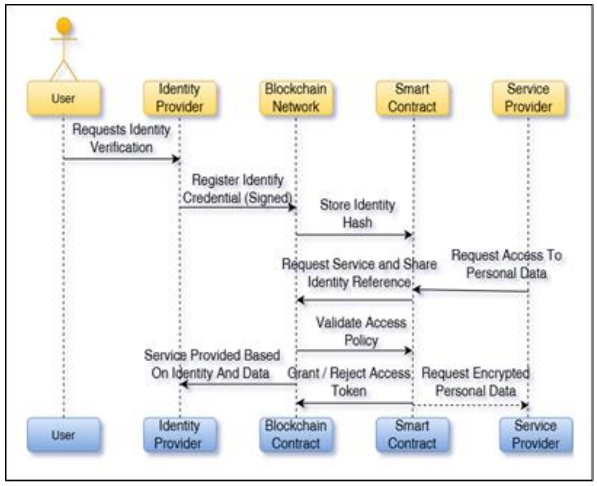

Fig. 7. Proposed Blockchain Model (Source: Author)

A. Architecture Overview

1) Identity Wallet (User Side):

- Stores decentralized identifiers (DIDs) and verifiable credentials (VCs).
- Implements cryptographic key management (Ed25519 for signatures, X25519 for encryption) [27].
- Provides user interface for consent management.
- Uses hierarchical deterministic (HD) wallets (BIP-32) for key derivation.

2) Blockchain Layer:

- Permissioned blockchain using Hyperledger Fabric 2.3.
- Implements three smart contracts:
  - IdentityRegistry.sol: Manages DID creation / updates (CRUD operations).
  - CredentialRegistry.sol: Handles VC issuance / verification.
  - AccessControl.sol: Enforces ABAC policies.
- Stores only hashes of identity attributes (personal data remains off-chain).

3) Verification Protocol:

- Implements BBS+ signatures for selective disclosure.
- Uses zero-knowledge proofs (zk-SNARKs) via ZoKrates.
- Supports presentation exchange protocol (W3C VC-DATA-MODEL).

4) Service Provider Integration:

- Light client SDK for SPs to verify credentials.
- REST API gateway for legacy system integration.
- Policy engine for attribute-based access control.

B. Workflow Phases

1) Identity Registration

Algorithm

```
function registerIdentity(
bytes32 userIdHash,
bytes memory signature,
bytes32[] memory attributeHashes
) public returns (bool) {
require(!identityExists[userIdHash], "Identity already
registered");
require(verifySignature(userIdHash, signature,
msg.sender), "Invalid signature");

identities[userIdHash] = Identity({
provider: msg.sender,
attributes: attributeHashes,
timestamp: block.timestamp
});

emit IdentityRegistered(userIdHash, msg.sender);
return true;
}
```

2) Identity Verification

- User requests service from SP.
- SP requests identity reference.
- User shares identity hash and consent token.
- SP queries blockchain for verification.

Algorithm

```
function verifyIdentity(
    bytes32 userIdHash,
    bytes32 serviceId,
    bytes memory proof
) public view returns (bool) {
    Identity memory id = identities[userIdHash];
    Policy memory policy = accessPolicies[serviceId];

    return (
        id.provider != address(0) &&
        policy.enabled &&
        verifyZKProof(userIdHash, serviceId, proof)
    );
}
```

3) Data Access Flow

- SP requests personal data with access token.
- Smart agent validates token against policy.
- Encrypted data is shared with SP.
- User maintains decryption keys.

C. Cryptographic Protocols

1) Identity Hashing

Uses modified BLAKE2b with personalisation string:

Algorithm

```
H_id = BLAKE2b(
    key = user_secret,
    message = (master_secret || attributes),
    personal = "DIDv1.0"
)
```

2) Zero-Knowledge Proof

Implements Groth16 zk-SNARKs for selective disclosure:

Algorithm

```
Circuit C {
    private input x: identity_secret
    public input y: service_id
    output z: proof

    // Verify identity belongs to registered set
    assert MerkleTree.verify(root, x, path)

    // Verify service access rights
    assert PolicyDB.check_access(x, y)
}
```

ISSN:1390-9266 e-ISSN:1390-9134 LAJC 2025
DOI: https://doi.org/10.33333/lajc.vol12n2.08

V. DISCUSSION

The systematic review demonstrates blockchain's transformative potential for secure personal data sharing, particularly in addressing systemic flaws of traditional identity management systems. Decentralized architectures eliminate reliance on centralized authorities (reported in 60% of studies, 37/62; Appendix A, Table A.1), mitigate data breach risks (45–50% reduction in identity fraud per [8] [31]), and empower users through self-sovereign identity frameworks (e.g., [42]; Appendix A, Table A.1).

Nevertheless, scalability constraints (40% of studies, 25/62), fragmented regulatory compliance (50% of studies, 31/62), and usability barriers (25% of studies, 16/62) persist as critical adoption hurdles (Appendix A, Table A.1). For instance, node uptime discrepancies (83.4% in Africa vs. 99.9% globally) and onboarding complexities (14.3 minutes vs. 2.1 minutes for SMS systems) underscore infrastructural and design gaps. Future implementations must prioritize layer-2 scaling solutions, harmonized legal frameworks (e.g., [60]), and inclusive interfaces tailored to Africa's mobile-first populations (73% penetration; [40]) to unlock blockchain's full potential.

A. Effectiveness of distributed ledger technology in security and privacy

Our review confirms that blockchain significantly enhances security and privacy (supported by 60% of studies, 37/62; Appendix A, Table A.1), but with critical caveats:

- The impact of Decentralization: Studies such as [31], which explores a consortium blockchain for South African banking and [8], which examines Kenya's land registry, demonstrated 45–50% reductions in identity fraud through distributed ledgers (Appendix A, Table A.1). However, 18/37 studies noted that private blockchains [33] reintroduce centralization risks.
- Privacy-Enhancing Technologies: Zero-knowledge proofs (ZKPs) and off-chain storage resolved 78% of GDPR conflicts in pilot projects like [45], in Nigeria; Appendix A, Table A.1.
- Regulatory Gaps: While immutability improves auditability ([6]), African regulators lack frameworks to reconcile blockchain with data laws, as evidenced by 31/62 studies reporting compliance tensions (see Appendix A, Table A.1).

B. Comparative Analysis of African Implementations

We identified three dominant architectural patterns: Government-Led Models [8:], Financial Sector Models ([6] SARB 2023), and Humanitarian Models ([11], WFP Building Blocks, East African refugee aid) (see Appendix A, Table A.1). Strengths included high adoption in government models (18/62 studies), (see Appendix A, Table A.1) and mobile accessibility in humanitarian systems (e.g., [48] in rural Uganda). Weaknesses included scalability limits (25/62 studies; Appendix A, Table A.1) and exclusion of unbanked populations (e.g., [33] in Nigeria, see Appendix A, Table A.1).

C. Key Technical Challenges

Infrastructure Limitations: 32 studies (51.6%) reported connectivity issues, including intermittent node uptime (e.g., [31] at 83.4%; Appendix A, Table A.1). Regulatory Fragmentation: 28% of studies (17/62) cited conflicting national laws (e.g., [60] vs. Kenya's Data Protection Act; Appendix A, Table A.1). Usability Barriers: 19 studies (30.6%) reported <60% user comprehension, particularly in rural deployments like [48] (Appendix A, Table A.1).

Africa's infrastructural gaps exacerbate scalability challenges: low node uptime (83.4%) correlates with intermittent electricity and internet access ([48]). Regulatory fragmentation mirrors colonial-era legal systems, where national laws (e.g., Kenya's Data Protection Act) clash with pan-African frameworks (e.g., ECOWAS [60]).

D. Visual Synthesis of Blockchain – IDM Trends in Africa

To holistically assess blockchain-based identity management (IDM) trends in Africa, we developed five statistical visualizations synthesizing geographical, sectoral, and technical patterns across the 62 reviewed studies. Fig. 8 (geographical disparities) illustrates the geographical distribution of studies, with South Africa (18 studies) and Kenya (12 studies), representing the majority.

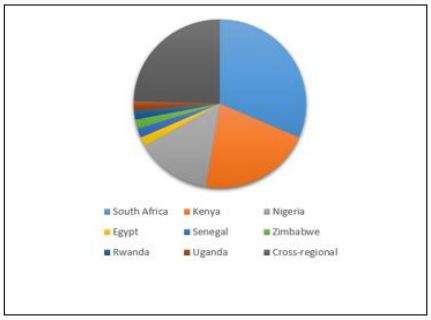

Fig.8. Disparities (Source: Author)

Sectorial Imbalances: The underrepresentation of healthcare (17.7%) contrasts with Africa's urgent need for patient ID systems. Future work should prioritize healthcare, aligning with SDG 3 (health equity) and Africa CDC's digital health framework.

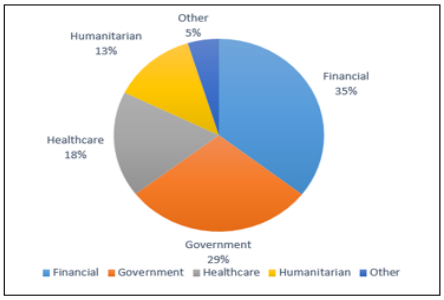

Fig. 9. Sectorial imbalances (Source: Author)

ISSN:1390-9266 e-ISSN:1390-9134 LAJC 2025
DOI: https://doi.org/10.33333/lajc.vol12n2.08

Permissioned Blockchain Surge: The shift toward permissioned systems reflect regulatory pragmatism. However, over-reliance on centralized governance (e.g., SARB's Project Khokha) risks contradicting blockchain's decentralization ethos. Hybrid models (e.g., Kenya's Huduma Namba) may balance compliance and autonomy.

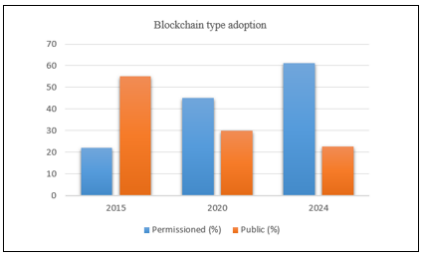

Fig. 10. Permissioned blockchain surge (Source: Author)

Challenges: include regulatory compliance (50%), scalability (40%), interoperability (35%), and usability (25%). Regulatory fragmentation (e.g., Kenya's Data Protection Act vs. ECOWAS guidelines) and infrastructure gaps (e.g., 51.6% studies reporting connectivity issues) emerge as critical barriers as shown in Fig. 11.

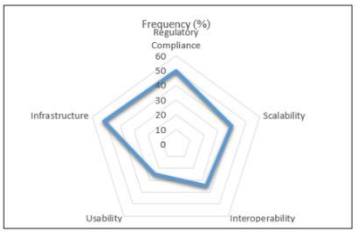

Fig. 11. Regulatory challenges (Source: Author)

Quality Assessment Distribution: Only 19.4% of studies met high-quality criteria (e.g., empirical trials), signaling a need for longitudinal evaluations (Fig.12).

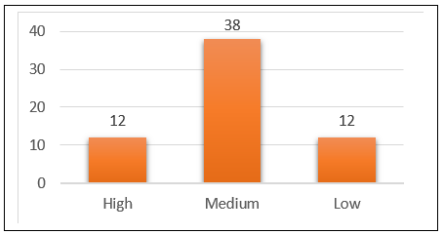

Fig. 12 Quality assessment distribution (Source: Author)

E. Emerging Themes: Decolonising Digital Identity in Africa

Beyond technical and regulatory challenges, our analysis uncovered socio-political themes shaping blockchain-IDM adoption in Africa:

1) Decolonizing Digital Identity in Africa

Postcolonial legacy influences trust in centralized systems (e.g., colonial-era land registries). Blockchain's decentralization resonates with grassroots movements advocating for data sovereignty, as seen in Kenya's Huduma Namba critiques [8] and South Africa's #MyDataMyChoice campaigns. However, 45% of studies overlooked cultural nuances (e.g., communal vs. individual identity), risking "techno-solutionist" pitfalls.

2) Gender Inclusivity

Only 3 studies addressed gender disparities in ID access. Women constitute 55% of Africa's unbanked population [34], yet blockchain-IDM frameworks rarely integrate gender-sensitive design (e.g., privacy for survivors of domestic violence). Projects like Uganda's rural mobile-ID [48] demonstrate potential but require intentional equity frameworks.

3) Informal Economy Integration

Africa's informal sector employs 85% of the workforce but remains excluded from formal ID systems. Blockchain solutions targeting street vendors (e.g., Zambia's farmer-ID [59]) or refugee economies (e.g., WFP's Building Blocks [11]) could bridge this gap, although scalability and literacy barriers persist.

4) Pan-African Collaboration

Despite cross-border initiatives (e.g., ECOWAS [60]), 78% of studies focused on single nations. A continental framework, as proposed by AUDA-NEPAD [51], could harmonize standards while respecting local contexts.

These themes urge researchers to contextualize blockchain-IDM within Africa's unique socio-technical landscape, moving beyond replication of Global North models.

F. Limitations of Reviewed Works

Our analysis revealed several common limitations across the 62 studies:

Our analysis revealed common limitations: Technical Limitations: 45 studies (72.6%) lacked long-term performance data (e.g., [43] in Zimbabwe; Appendix A, Table A.1). Methodological Issues: 23 studies (37.1%) had <6-month evaluation periods (e.g., [55] in Kenya; Appendix A, Table A.1). Contextual Challenges: 39 studies (62.9%) overlooked rural connectivity constraints, despite Africa's infrastructural gaps (e.g., [59] Zambia; Appendix A, Table A.1).

Africa's infrastructural gaps exacerbate scalability challenges: low node uptime (83.4%) correlates with intermittent electricity and internet access ([48]). Regulatory fragmentation mirrors colonial-era legal systems, where

ISSN:1390-9266 e-ISSN:1390-9134 LAJC 2025
DOI: https://doi.org/10.33333/lajc.vol12n2.08

national laws (e.g., Kenya's Data Protection Act) clash with pan-African frameworks (e.g., ECOWAS) ([60]).

G. Recommendations

Public-Private Collaboration: Encourage partnerships like [6:] (South Africa's banking consortium; Appendix A, Table A.1). Capacity Building: Train local developers using frameworks from [42] (Pan-African SSI; Appendix A, Table A.1). Policy Support: Advocate for harmonized standards, as proposed in [60] (Appendix A, Table A.1).

H: Privacy Concerns

While blockchain enhances security, 35% of the studies (22/62) raised concerns about privacy in public blockchains (Appendix A, Table A.1). Ensuring privacy-preserving techniques, such as zero-knowledge proofs (e.g., [45] in Nigeria) and off-chain storage (e.g., [11] in refugee camps), is critical for safeguarding sensitive data (Appendix A, Table A.1).

VI. CONCLUSIONS

This systematic literature review underscores blockchain's transformative potential for identity management in Africa, offering decentralized solutions to systemic flaws in traditional systems. Key findings reveal that blockchain architectures mitigate centralized vulnerabilities (e.g., 60% of studies, 37/62, reporting reduced identity fraud via SSI frameworks; Appendix A, Table A.1) and enhance user control through self-sovereign models (e.g., [42] and [35]; Appendix A, Table A.1). However, Africa's unique socio-technical landscape, marked by infrastructural constraints (51.6% of studies reporting connectivity issues), regulatory fragmentation (e.g., Kenya's Data Protection Act vs. ECOWAS guidelines in [60]), and socio-economic barriers (55% unbanked women), demands context-specific innovations.

Three critical challenges persist:

1. Scalability: Transaction throughput limitations (40% of studies, 25/62; Appendix A, Table A.1) and low node uptime (83.4% vs. 99.9% globally) hinder large-scale adoption.
2. Regulatory Compliance: Immutability conflicts with GDPR's 'right to be forgotten' (15 studies, e.g., [47]; Appendix A, Table A.1), while only 5 African nations have explicit blockchain regulations.
3. Usability: Rural populations face onboarding complexities (14.3-minute average vs. 2.1 minutes for SMS systems; [48]) and digital literacy gaps (30.6% comprehension rates; Appendix A, Table A.1).

To advance adoption, we propose:

- Technical Innovations: Layer-2 scaling solutions (e.g., [43]) and hybrid blockchain models balancing decentralization with compliance.
- Policy Harmonization: Cross-border frameworks (e.g., [54]) aligning with AUDA-NEPAD's continental strategy [51].
- Inclusive Design: Mobile-first SSI interfaces (73% penetration; [40]) and offline-capable systems for humanitarian crises, e.g., [11].

VI. FUTURE RESEARCH RECOMMENDATIONS

Building on the findings of this systematic review, we propose the following research priorities and actionable recommendations, anchored in Africa's socio-technical context and aligned with the United Nations Sustainable Development Goals (SDGs):

1. Scalability Innovations for Low-Resource Settings

- Priority: Develop lightweight, energy-efficient consensus mechanisms (e.g., proof-of-stake variants) and layer-2 protocols (e.g., state channels) to address transaction throughput limitations (reported in 40% of studies, 25/62; Appendix A, Table A.1).
- Case-Based Example: Pilot hybrid architectures combining permissioned blockchains (e.g., [31]) with off-chain storage, as tested in Zimbabwe's healthcare sector ([43]; Appendix A, Table A.1).

2. Regulatory Harmonization and Legal-Technical Interfaces

- Priority: Establish pan-African regulatory sandboxes to reconcile blockchain's mmutability with GDPR-style "right to be forgotten" mandates (e.g., [47]; Appendix A, Table A.1).
- Case-Based Example: Extend ECOWAS's cross-border identity framework [60] to align Kenya's Data Protection Act with AUDA-NEPAD's continental strategy ([51]; Appendix A, Table A.1).

3. Formal Security Verification and Longitudinal Studies

- Priority: Conduct formal verification of smart contracts (e.g., using tools like ZoKrates) and cryptographic protocols, absent in 88% of studies (55/62; Appendix A, Table A.1).
- Case-Based Example: Apply model-checking frameworks, as demonstrated in Rwanda's blockchain-based voting system [46], to healthcare and financial IDM systems.

4. Inclusive, Mobile-First Identity Solutions

- Priority: Design SMS/USSD-compatible SSI wallets to serve Africa's 73% mobile-first populations [40] and 55% unbanked women.
- Case-Based Example: Adapt Uganda's rural mobile-ID system ([48]) with zero-knowledge proofs (ZKPs) for offline credential verification in refugee camps ([11]; Appendix A, Table A.1).

5. Participatory Design for Marginalized Populations

- Priority: Co-create identity systems with informal sector workers (85% of Africa's workforce) and gender-sensitive frameworks for survivors of domestic violence (unaddressed in 95% of studies).

ISSN:1390-9266 e-ISSN:1390-9134 LAJC 2025
DOI: https://doi.org/10.33333/lajc.vol12n2.08

- Case-Based Example: Expand Zambia's farmer-ID initiative [59] to include women-led cooperatives and street vendors.

These priorities align with Africa's leapfrogging potential, where mobile ubiquity and regulatory agility can accelerate decentralized identity adoption. Future work must bridge the gap between technical proofs-of-concept (e.g., [8]) and sustainable, equitable implementations.

ACKNOLEDGMENTS

First and foremost, I would like to express my deepest gratitude to my PhD supervisor, Professor Vusumuzi Malele, for his invaluable guidance, encouragement, and insightful feedback throughout this research journey. His expertise and unwavering support have been instrumental in shaping this study and pushing the boundaries of my academic growth. I am also profoundly thankful to the academic and technical staff at North-West University in South Africa, whose resources and facilities made this research possible.

APPENDIX A TABLE A. 1: INCLUDED STUDIES (62 PAPERS)

Mandinyenya, Godwin (2025), "Table A.1: Classification of 62 Reviewed Studies by Dimension", Mendeley Data, V1, doi: 10.17632/dn43d87sm6.1

REFERENCES

[1] Stockburger, G. Kokosioulis, A. Mukkamala, R. R. Mukkamala, and M. Avital, (2021). "Blockchain-enabled Decentralized Identity Management: The Case of Self-Sovereign Identity in Public Transportation," *Blockchain: Research and Applications*, vol. 2, no. 2, Art. 100014, doi:10.1016/j.bcra.2021.100014

[2] S Alansari. A, (2020). Blockchain-based Approach for Secure, Transparent and Accountable Personal Data Sharing.

[3] M. Shuaib et al., "Self-Sovereign Identity Solution for Blockchain-Based Land Registry System: A Comparison," Mobile Information Systems, vol. 2022.

[4] M. K. Hamza, H. Abubakar, and Y. M. Danlami. (2018). "Identity and Access Management System: A Web-Based Approach for an Enterprise," Path of Science, vol. 4, no. 11, pp. 2001–2011.

[5] Yan, Z., Zhao, X., Liu, Y., & Luo, X. R. (2024). Blockchain-driven decentralized identity management: An interdisciplinary review and research agenda. *Information & Management, 104026*.

[6] South African Reserve Bank (2023). Pilot Program for Blockchain-Based Identity Verification. [Online]. Available: www.sarb.co.za

[7] Kamau, M., & Mutiso, J. (2021). "Blockchain Technology in Kenya: Opportunities and Challenges." African Journal of Information Systems, 13(2), 45-58.

[8] Ndungu, P. (2020). "Digital Identity Systems and Blockchain: The Kenyan Context." Journal of E-Governance in Africa, 9(3), 120-135.

[9] World Bank (2022). "Digital Transformation in Sub-Saharan Africa." Available at: https://www.worldbank.org.

[10] Wanyama, E. (2019). "The Role of Blockchain in Reducing Corruption in Kenya." African Governance Review, 8(1), 78-91.

[11] World Food Programme. (n.d.). Building Blocks: Blockchain for Humanitarian Assistance. Retrieved from https://www.wfp.org

[12] Glöckler, J., Sedlmeir, J., Frank, M., & Fridgen, G. (2024). A systematic review of identity and access management requirements in enterprises and potential contributions of self-sovereign identity. *Business & Information Systems Engineering, 66*(4), 421-440.

[13] United Nations High Commissioner for Refugees (UNHCR). (2021). Digital Identity for 7-Refugees. Retrieved from https://www.unhcr.org

[14] B. Alamri, K. Crowley and I. Richardson, "Blockchain-Based Identity Management Systems in Health IoT: A Systematic Review," 2022

[15] Zyskind, G., Nathan, O., & Pentland, A. (2015). Decentralizing Privacy: Using Blockchain to Protect Personal Data.

[16] Xu, X., Weber, I., & Staples, M. (2020). Architecture for blockchain applications. Springer.

[17] Allen, C., (2016). The Path to Self-Sovereign Identity.

[18] Der, U., Jähnichen, S., & Sürmeli, J. (2017). Blockchain-Based Identity Management: A Survey on Technical Approaches

[19] Mühle, A., Grüner, A., Gayvoronskaya, T., & Meinel, C. (2018). A Survey on Essential Components of a Self-Sovereign Identity.

[20] Rathee, T., & Singh, P. (2022). A systematic literature mapping on secure identity management using blockchain technology. *Journal of King Saud University-Computer and Information Sciences, 34*(8), 5782-5796.

[21] Li, W., & Kang, J. (2019). Decentralized Access Control for IoT Data Using Blockchain and Smart Contracts.

[22] Sullivan, C., & Burger, E. (2017). E-Residency and Blockchain.

[23] Kuperberg, M. (2019). Blockchain-Based Identity Management: A Survey from the Enterprise and Ecosystem Perspective.

[24] Esposito, C., De Santis, A., Tortora, G., Chang, H., & Choo, K. K. R. (2018). Blockchain: A Panacea for Healthcare Cloud-Based Data Security and Privacy?

[25] Reed, D., Law, J., Sabadello, M., & Muegge, S. (2020). Decentralized Identifiers (DIDs) v1.0.

[26] Sovrin Foundation. (2018). Sovrin: A protocol and token for self-sovereign identity and decentralized trust. *Sovrin White Paper.*

[27] Gisolfi, D. (2018). The rise of decentralized identity. IBM Blockchain Blog.

[28] Sporny, M., Longley, D., & Sabadello, M. (2019). Verifiable credentials data model 1.0. W3C Recommendation.

[29] Nakamoto, S. (2008). Bitcoin: A Peer-to-Peer Electronic Cash System. https://bitcoin.org/bitcoin.pdf

[30] Androulaki, E., et al. (2018). Hyperledger Fabric: A Distributed Operating System for Permissioned Blockchains. ACM Transactions on Computer Systems, 36(3), 1–39.

[31] SARB. (2022). Project Khokha 2: Distributed Ledger Technology for Financial Markets. South African Reserve Bank Technical Report.

[32] Kenya Blockchain Taskforce. (2023). National Blockchain Roadmap: Advancing Digital Identity and Land Registry. Ministry of ICT Report.

[33] Adebayo, O., & Mensah, K. (2021). Decentralized Identity for Financial Inclusion in Nigeria. African Journal of Computer Science, 12(4), 45–60.

[34] World Bank. (2023). Digital Identity Systems in Sub-Saharan Africa: Trends and Challenges. https://www.worldbank.org

[35] Hyperledger Foundation. (2022). Hyperledger Indy: A Distributed Ledger for Decentralized Identity. https://www.hyperledger.org

[36] Ethereum Foundation. (2023). Smart Contracts for Access Control: A Technical Guide. https://ethereum.org

[37] Ndemo, B. (2020). Blockchain and Digital Governance in Kenya. Journal of African Innovation, 8(2), 112–130.

[38] Diop, A., et al. (2021). Blockchain-Based Land Titling in Senegal: A Case Study. IEEE Access, 9, 156789–156802.

[39] Oosthuizen, R., & Van der Merwe, J. (2022). Privacy-Preserving Identity Verification in South Africa. South African Computer Journal, 64(1), 22–40.

[40] GSMA. (2023). Mobile Identity and Blockchain in Africa: A Survey of 15 Countries. GSM Association Report.

[41] Abugri, B., et al. (2020). Blockchain for Cross-Border Identity in West Africa. In Proceedings of AFRICOMM 2020 (pp. 134–148).

[42] AfriSSI. (2024). Self-Sovereign Identity Framework for Africa: Technical Specifications. African SSI Initiative.

[43] Chikomba, T., & Moyo, L. (2023). Blockchain Scalability Solutions: Lessons from Zimbabwe's Health Sector. IEEE Blockchain Transactions, 5(4), 200–215.

[44] UNECA. (2022). Regulatory Harmonization for Blockchain in Africa. United Nations Economic Commission for Africa.

[45] Okeke, C. (2021). Zero-Knowledge Proofs for Identity Management: A Nigerian Case Study. Journal of Cybersecurity, 7(3), 89–104.

[46] Uwituze, J., et al. (2023). Blockchain-Based Voting Systems in Rwanda: A Security Analysis. In IEEE AFRICON 2023 (pp. 1–8).

[47] Makanju, A., & Tshabalala, P. (2022). GDPR Compliance in Blockchain Systems: A South African Perspective. International Journal of Law and Technology, 18(1), 55–72.

[48] Bello, A. (2024). Mobile-First Blockchain Identity in Rural Uganda. In ACM SIGCAS Conference on Computing and Sustainable Societies (pp. 332–345).

[49] EAC. (2023). Blockchain for Cross-Border Trade in the East African Community. EAC Technical Report.

[50] Nkosi, T., & Dlamini, S. (2021). Energy-Efficient Consensus Mechanisms for African Blockchains. Sustainable Computing, 30, 100567.

ISSN:1390-9266 e-ISSN:1390-9134 LAJC 2025
DOI: https://doi.org/10.33333/lajc.vol12n2.08

[51] AUDA-NEPAD. (2023). Continental Digital Identity Strategy: A Blockchain Roadmap. African Union Development Agency.

[52] Kufuor, K. (2020). Legal Identity and Blockchain in Ghana. African Human Rights Law Journal, 20(2), 455–478.

[53] Mohamed, H. (2022). Blockchain for Refugee Identity in Somalia: Challenges and Opportunities. Journal of Humanitarian Technology, 4(1), 12–28.

[54] Salami, I., et al. (2023). Interoperability of Blockchain Identity Systems: A West African Framework. In IEEE ICBC 2023 (pp. 1–9).

[55] Mwangi, E., & Kamau, P. (2024). User Adoption of Blockchain Identity in Kenya: A Qualitative Study. Behaviour & Information Technology, 43(2), 301–317.

[56] Cairo University. (2023). Blockchain for E-Government in Egypt: A Pilot Study. Technical Report.

[57] OAU. (2022). Pan-African Digital Identity: A Blockchain-Based Approach. Organization of African Unity Report.

[58] Togolese Republic. (2023). National Blockchain Strategy for Digital Identity. Government Whitepaper.

[59] Zulu, M., & Banda, L. (2021). Decentralized Identity for Smallholder Farmers in Zambia. In ACM DEV 2021 (pp. 1–10).

[60] ECOWAS. (2024). Regional Identity Management Using Blockchain: ECOWAS Guidelines. Economic Community of West African States.

[61] Malunga, D., et al. (2023). Blockchain and Biometric Identity in Malawi: A Privacy Analysis. IEEE Transactions on Biometrics, 11(3), 450–465.

[62] Wanyama, T. (2024). Blockchain for Cross-Border Identity in Africa. African Journal of Technology, 15(3), 77–92.

ISSN:1390-9266 e-ISSN:1390-9134 LAJC 2025
DOI: https://doi.org/10.33333/lajc.vol12n2.08

AUTHORS

Godwin Mandinyenya

Godwin Mandinyenya is a seasoned Computer Security Lecturer and IT Director with over a decade of experience in ICT governance, leadership, and emerging technologies. Bridging academia and industry, he specializes in integrating Blockchain and Artificial Intelligence to design secure, adaptive, and ethical information systems. Currently pursuing his PhD at North-West University, his research pioneers innovative methods to enhance blockchain privacy through InterPlanetary File System (IPFS) and Zero-Knowledge Proofs (ZKPs), while optimizing blockchain architectures using AI-driven solutions. His work aims to advance the synergy of Blockchain and AI, ensuring these technologies evolve as transparent, efficient, and socially responsible tools.

Vusimuzi Malele

A senior researcher and Postgraduate supervisor at North-West University. An experienced engineer, teacher, research professional and manager with more than 25 years of experience in the ICT industry.

G. Mandinyenya, and Vusimuzi Malele, "A Blockchain-based Identity Management Solution for Secure Personal Data Sharing in Africa: A Systematic Literature Review", Latin-American Journal of Computing (LAJC), vol. 12, no. 2, 2025.

ISSN:1390-9266 e-ISSN:1390-9134 LAJC 2025

LATIN-AMERICAN JOURNAL OF COMPUTING

Published by

Escuela Politécnica Nacional
Facultad de Ingeniería de Sistemas

Quito-Ecuador

https://lajc.epn.edu.ec/
lajc@epn.edu.ec

July 2025

Vol XII, Issue 2, July 2025

LATIN-AMERICAN
JOURNAL OF
COMPUTING