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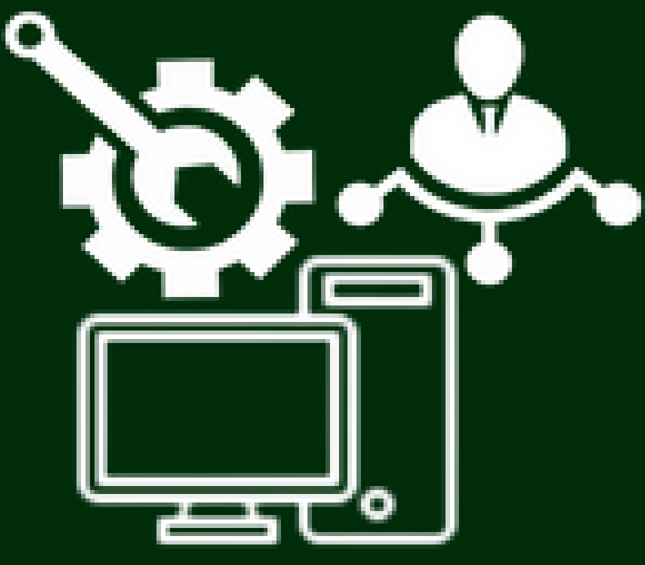

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Editorial Comments Volume 3 Issue 5

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Volume 3, Issue 5 of the *Journal of Computers, Mechanical, and Management* showcases an exciting array of research addressing significant technological, medical, financial, and educational challenges. The articles in this issue offer innovative solutions and frameworks that are poised to advance their respective fields while contributing to societal progress.

J. Jai Jaganath Babu *et al.* [1] investigate the critical issue of speckle noise in ultrasound imaging, a persistent challenge that compromises diagnostic accuracy. Their study introduces a hybrid despeckling method that combines Stick filters with Fourth-Order Partial Differential Equations (PDE), achieving a remarkable balance between noise reduction and edge preservation. Through an extensive evaluation using metrics such as the Peak Signal-to-Noise Ratio (PSNR) and the Structural Similarity Index (SSI), the hybrid method demonstrates superior performance compared to traditional filters. By enhancing image clarity in clinical scenarios, such as thyroid nodule analysis, this research provides a robust framework to improve diagnostic precision. The study also highlights the potential for optimizing these algorithms for real-time applications, paving the way for a larger clinical adoption.

In a comprehensive exploration of the role of the financial sector in promoting sustainability, Peehoo Jain *et al.* [2] delve into how FinTech innovations align with the United Nations' Sustainable Development Goals (SDGs). Their thematic analysis underscores the transformative potential of FinTech in fostering financial inclusion, enabling green finance, and advancing responsible investments. The study emphasizes the pivotal role of technologies such as blockchain, artificial intelligence, and InsurTech in enhancing transparency, resilience, and sustainability. By systematically linking FinTech advancements with specific SDGs, this research provides valuable insights for policymakers and industry stakeholders. It also identifies key challenges, such as regulatory constraints and scalability, and offers strategies for leveraging FinTech as a catalyst for sustainable development.

Nilakshman Sooriyaperakasam *et al.* [3] present a comparative analysis of random forest (RF) and logistic regression (LR) models to predict heart attack risk. Their study addresses critical gaps in current research by focusing on model interpretability and the challenges posed by imbalanced medical datasets. While both RF and LR demonstrate comparable accuracy, the authors highlight their complementary strengths: RF's ability to capture non-linear relationships and LR's efficiency in handling linear correlations and interpretability. This work not only advances the application of machine learning in healthcare but also emphasizes the importance of tailored approaches to optimize predictive performance in clinical settings.

D. Linett Sophia *et al.* [4] examines the transformative potential of virtual reality (VR) and augmented reality (AR) in education. Their mini-review highlights how these technologies foster immersive and interactive learning environments, making abstract concepts more accessible and engaging. By integrating VR and AR into curricula, educators can address diverse learning needs and create inclusive educational experiences. The article also discusses barriers to adoption, such as high costs and technical challenges, and proposes solutions, including open source tools and professional training for educators. This work underscores the importance of strategic planning and cross-sector collaboration in harnessing the full potential of VR and AR to revolutionize education.

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The research presented in this issue reflects the journal's commitment to addressing pressing global challenges through interdisciplinary approaches. From improving medical diagnostics and financial sustainability to advancing machine learning and educational technologies, these articles demonstrate the power of innovation to drive progress. The authors thank the authors for their invaluable contributions and the reviewers for their critical insights. We invite readers to explore this issue, which offers a wealth of knowledge and inspiration for researchers, practitioners, and policymakers alike.

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Hybrid Despeckling for Ultrasound Images Using Sticks Filter and Fourth-Order PDE for Enhanced Diagnostic Precision

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Abstract

Speckle noise in ultrasound imaging poses significant challenges by degrading image quality and affecting diagnostic precision. This study evaluates and compares the performance of established despeckling algorithms, including Lee, Kuan, Frost, Non-Local Means, and PMAD filters, as well as advanced techniques such as Fourth-Order Partial Differential Equations (PDEs) and a novel hybrid method combining Sticks filters with Fourth-Order PDE. Quantitative assessment was performed using metrics such as Peak Signal-to-Noise Ratio (PSNR), Mean Squared Error (MSE), Equivalent Number of Looks (ENL), Structural Similarity Index (SSI), Signal-to-Mean Power Index (SMPI), and computational efficiency. Among the evaluated methods, the Lee filter achieved the highest PSNR of 25.05 dB, demonstrating effective noise suppression while preserving the details of the image. The combination of Sticks and Fourth-Order PDE achieved the highest ENL of 0.0331, indicating superior smoothing in homogeneous regions and enhanced contrast. While PMAD exhibited superior speckle suppression with a minimal MSE of 886.49, it introduced slight blurring, compromising structural details. Visual inspections revealed that the hybrid Sticks and Fourth-Order PDE approach delivered exceptional edge preservation and contrast enhancement, outperforming other filters in clinical scenarios such as thyroid nodule analysis. The results demonstrate that the proposed hybrid method addresses critical trade-offs between noise suppression and detail preservation, offering a robust framework to improve the diagnostic utility of ultrasound images. Future research could explore optimizing these algorithms for real-time applications, enabling broader clinical adoption.

Keywords: Speckle Noise Reduction; Ultrasound Image Processing; Partial Differential Equations; Edge Preservation; Thyroid Diagnosis

1. Introduction

Ultrasound imaging is widely recognized as a non-invasive, cost-effective, and radiation-free diagnostic tool, particularly valuable for the detection and evaluation of thyroid disorders [1, 2]. However, the intrinsic presence of speckle noise, which originates from backscattered ultrasound signals, severely degrades image quality, complicating diagnosis and feature extraction [3, 4]. Over the years, numerous despeckling algorithms have been proposed to mitigate this issue. Traditional approaches, such as the Lee filter [5–8] and the Kuan filter [5, 9–12], utilize local statistical measures to reduce noise while attempting to preserve image details. The Frost filter introduces a spatially adaptive kernel to achieve similar objectives, while Non-local means focus on patch-level comparisons to retain finer structural details [13–15]. Several authors [16–19] have used advanced techniques such as anisotropic diffusion and its speckle-specific adaptations to offer selective smoothing mechanisms to preserve edges while minimizing noise. Recent developments in fourth-order partial differential equations (PDEs) have further enhanced despeckling by leveraging higher-order curvature information to retain image fidelity [20–24].

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Despite these advancements, many existing methods suffer from trade-offs between noise suppression, edge preservation, and computational efficiency, limiting their applicability in clinical settings [25–27]. This study addresses these gaps by proposing a hybrid approach combining Sticks filters with Fourth-Order PDE, designed to enhance edge clarity and contrast while minimizing speckle noise. The novelty lies in the synergy of these techniques, which offer superior performance in quantitative metrics and visual inspection. By systematically evaluating the proposed method against established filters, this work provides a robust framework to improve diagnostic precision in ultrasound imaging.

2. Despeckling Filters

Speckle noise in ultrasound images is modeled as multiplicative noise superimposed on the original signal [28]. The observed image $y(x, y)$ is expressed as:

$$y(x, y) = I(x, y) \cdot n(x, y), \tag{1}$$

where $I(x, y)$ is the noise-free image and $n(x, y)$ represents the multiplicative noise. Additive noise, although present, has minimal impact compared to the multiplicative component.

2.1. The Lee Filter

The Lee filter takes advantage of local statistical measures, such as mean and variance, to reduce speckle noise. It uses the Equivalent Number of Looks (ENL) to estimate noise variance and control smoothing [7, 29]. The reconstructed image is calculated as:

$$\hat{I}(x, y) = W(x, y) \cdot I(x, y) + [1 - W(x, y)] \cdot \bar{I}(x, y), \tag{2}$$

where $W(x, y)$ is the weighting function defined as:

$$W(x, y) = 1 - \frac{C_n^2}{C_I^2(x, y)}. \tag{3}$$

Here, $C_I(x, y)$ is the coefficient of variation for the intensity of the image and C_n is the coefficient of variation of noise.

2.2. The Kuan Filter

The Kuan filter transforms the multiplicative noise model into an additive noise model using local statistics. The image reconstruction is similar to the Lee filter [30], but the weighting function is modified as:

$$W(x, y) = \frac{1 - \frac{C_n^2}{C_I^2(x,y)}}{1 + C_n^2}. \tag{4}$$

This modification enhances noise reduction while preserving the details of the image. The least mean square error (LMSE) criterion assesses the filter's effectiveness.

2.3. The Frost Filter

The Frost filter estimates the original image by convolving the noisy image with a spatially adaptive kernel [31]. The reconstructed image is given as:

$$\hat{I}(x, y) = I(x, y) * m(x, y), \tag{5}$$

where $m(x, y)$ is the kernel defined as:

$$m(x, y) = k \cdot \exp\left(-\frac{C_I^2(x_0, y_0)}{(x, y)^2}\right). \tag{6}$$

Here, k is a normalization constant, $C_I(x_0, y_0)$ is the local coefficient of variation, and (x, y) denotes the distance within the kernel window. The filter preserves edges while reducing speckle noise.

2.4. The Non-Local Means Filter

The Non-Local Means (NLM) filter replaces pixel-level comparisons with patch-level comparisons. Calculate the intensity in a pixel as the weighted mean of intensities across the image [32]:

$$\hat{I}(x) = \sum_{j \in \Omega} w(x, x_j) \cdot I(x_j), \tag{7}$$

where $w(x, x_j)$ is the weight assigned to the pixel x_j, based on the similarity between the patches around x and x_j. This approach effectively suppresses speckle noise while retaining fine details.

2.5. Perona-Malik Anisotropic Diffusion

Anisotropic diffusion, proposed by Perona and Malik, smooths the images selectively to preserve the edges [33, 34]. The diffusion process is governed by:

$$\frac{\partial I(x, y; t)}{\partial t} = \nabla \cdot [C(\nabla I(x, y; t)) \cdot \nabla I(x, y; t)], \tag{8}$$

where ∇ and $\nabla\cdot$ denote the gradient and divergence operators, respectively, and $C(\cdot)$ is the diffusion coefficient, defined as:

$$C(x) = \exp\left(-\frac{x}{k}\right), \tag{9}$$

With k as the edge threshold parameter. This method achieves noise reduction while preserving structural details.

2.6. Speckle Reduction Anisotropic Diffusion

Yu and Acton proposed a variation of anisotropic diffusion tailored to ultrasound images to specifically address speckle noise [35]. The diffusion equation is given by:

$$\frac{\partial I(x, y; t)}{\partial t} = \nabla \cdot [q(x, y; t) \cdot \nabla I(x, y; t)], \tag{10}$$

where $q(x, y; t)$ is the instantaneous coefficient of variation, the diffusion rate adapts based on speckle characteristics. This approach reduces speckle noise while maintaining the integrity of the edges and features of the image.

2.7. Fourth-Order Partial Differential Equation

Using fourth-order partial differential equations, a model based on the L_2-curvature gradient. The evolution of the image is governed by:

$$\frac{\partial I(x, y; t)}{\partial t} = -\nabla^4 I(x, y; t) + \nabla \cdot [C(\nabla I(x, y; t)) \cdot \nabla I(x, y; t)], \tag{11}$$

where ∇ represents the biharmonic operator (Laplacian squared), and $C(\cdot)$ is the diffusion coefficient defined as:

$$C(x) = \exp\left(-\frac{\|\nabla I(x, y)\|}{k}\right). \tag{12}$$

Here, k controls the sensitivity to intensity gradients. The fourth-order PDE approach excels in retaining edges while suppressing noise, offering a significant improvement over second-order methods.

2.8. Cascading Uniform Stick Filter and Fourth-Order Partial Differential Equation

The stick filter, proposed by Czerwinski et al. [36], enhances the edge information while reducing the speckle noise. The filter operates by applying a bank of stick-shaped masks in multiple orientations, computing the average intensity for each orientation, and replacing the pixel value with the maximum average. The process is mathematically represented as:

$$g(x, y) = \max_{i=1,\ldots,N} \left[f(x, y) * s_i(x, y)\right], \tag{13}$$

where $f(x, y)$ is the input image, $s_i(x, y)$ represents the i-th stick mask, and $g(x, y)$ is the filtered output. The filtered image is smoothed using a fourth-order partial differential equation for enhanced despeckling and edge preservation. The combined approach minimizes noise while retaining structural details critical for diagnostic accuracy.

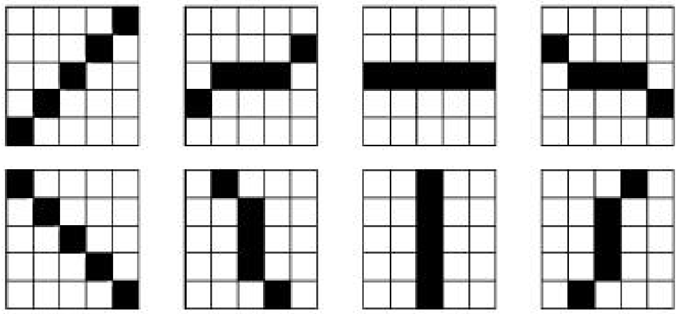

Figure 1: Illustration of stick filter orientations. Each stick mask represents a possible line direction for segmentation.

3. Performance Evaluation Measure

A set of quantitative performance metrics was employed to assess the effectiveness of speckle reduction metrics to evaluate the filter's ability to suppress speckle noise and preserve visual detail and linear structures. While some tests focus on noise reduction, others examine the retention of fine-grained image details. Conflicting results can arise, as a filter that excels in noise suppression may compromise detail preservation. For this study, a speckle-contaminated sample image was used to evaluate filter performance based on the following criteria: Mean, Mean Squared Error (MSE), Peak Signal-to-Noise Ratio (PSNR), Equivalent Number of Looks (ENL), Structural Similarity Index (SSI), Signal-to-Mean Power Index (SMPI), and Elapsed Time (ET). These metrics are defined as $I(x, y)$: Original image and $Y(x, y)$: Denoised image. In addition, a visual quality inspection was conducted to complement the quantitative analysis, ensuring a comprehensive evaluation of the filter's effectiveness.

4. Results and Discussion

Various despeckling techniques' performance was evaluated using synthetic and real-world ultrasound images. The study incorporated a comprehensive assessment based on quantitative metrics, visual inspection, and diagnostic relevance. Quantitative evaluation included metrics such as mean square error (MSE), peak signal-to-noise ratio (PSNR), equivalent number of looks (ENL), structural similarity index (SSI), signal-to-mean power index (SMPI) and elapsed time (ET). Each metric highlights a specific aspect of the filter's effectiveness, ranging from noise suppression to computational efficiency. For example, lower MSE values signify better denoising, while higher PSNR values indicate superior image clarity. ENL measures the smoothness of homogeneous regions and SSI assesses the structural similarity to the original image. The computational cost of the algorithms was captured through elapsed time.

As summarized in Table 1, the quantitative results reveal interesting insights. The Lee filter achieved the highest PSNR, demonstrating its capacity to suppress speckle noise effectively while preserving fine image details. In contrast, the combination of Sticks and Fourth-Order Partial Differential Equations (PDE) produced the highest ENL, reflecting its ability to smooth homogeneous regions while maintaining edge integrity. Fourth-order PDE performed exceptionally well in preserving the mean intensity of the image, underscoring its robustness in retaining image fidelity. While PMAD exhibited superior speckle suppression, it introduced slight blurring, compromising finer structural detail retention. Non-local means achieved high structural similarity scores but at the expense of significant computational overhead, rendering it less feasible for real-time applications. Visual inspection further corroborated the quantitative findings.

Table 1: Performance Metrics for Despeckling Filters

Filter	**Mean**	**MSE**	**PSNR (dB)**	**ENL**	**SSI**	**ET (s)**
Lee	110.72	202.44	25.05	0.0456	0.9038	0.2431
Frost	110.84	408.43	22.04	0.0452	0.9082	11.30
Kuan	110.27	267.41	23.90	0.0473	0.8877	19.87
Non-Local Means	108.85	387.56	22.30	0.0437	0.9235	99.13
PMAD	110.73	886.49	17.07	0.0506	0.8585	0.96
Fourth-Order PDE	110.73	1721.28	16.00	0.0399	1.2296	5.14
Sticks + PDE	128.08	2461.20	14.23	0.0331	1.3499	5.65

The results of applying despeckling filters to synthetic and real-world images are shown in Figures 2 and 3, respectively. The Lee filter provided a balanced trade-off between noise suppression and preservation of structural detail, as evident in Figures 2(c) and 3(b). However, while moderately effective in reducing noise, the Frost filter struggled to retain edge details, particularly in heterogeneous regions. Non-local means demonstrated impressive detail preservation, but their high computational cost limits its practical application. The combination of Sticks and Fourth-Order PDE stood out, delivering exceptional contrast enhancement and edge preservation, making it particularly suitable for clinical scenarios requiring high diagnostic precision.

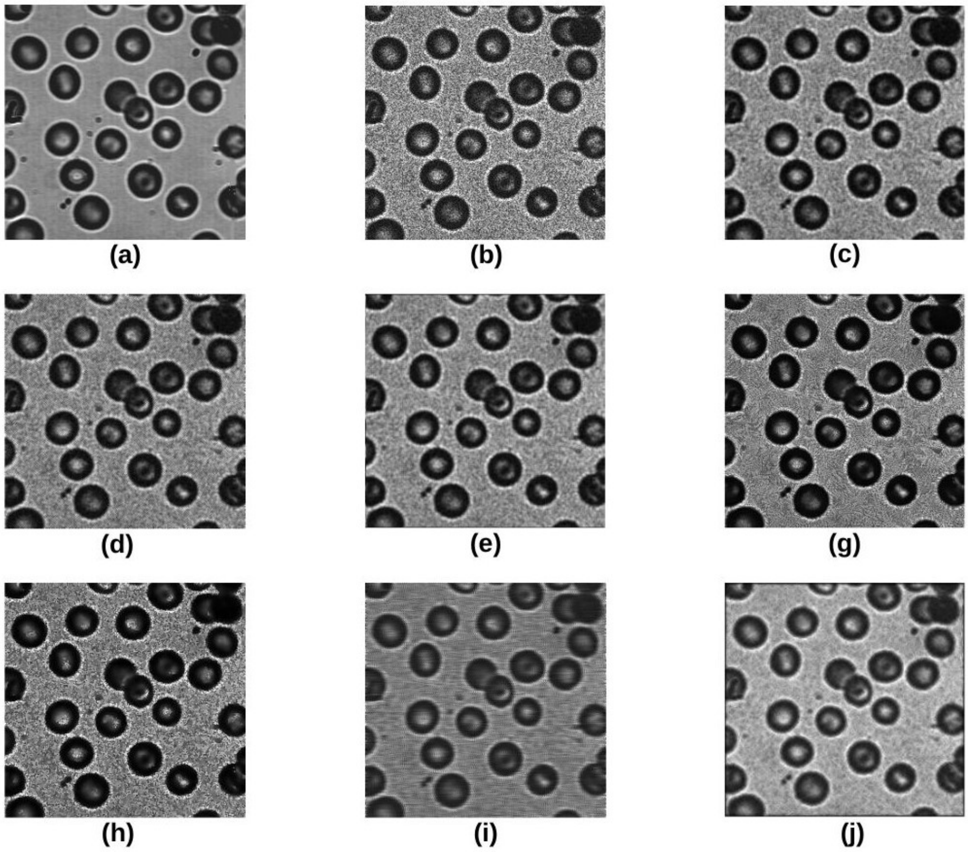

Figure 2: Despeckling results on a blood cell image with 10% speckle noise. (a) Original image, (b) Noisy image, (c) Lee filter, (d) Frost filter, (e) Kuan filter, (f) Non-Local Means filter, (g) PMAD filter, (h) Fourth-Order PDE filter, (i) Sticks combined with Fourth-Order PDE filter.

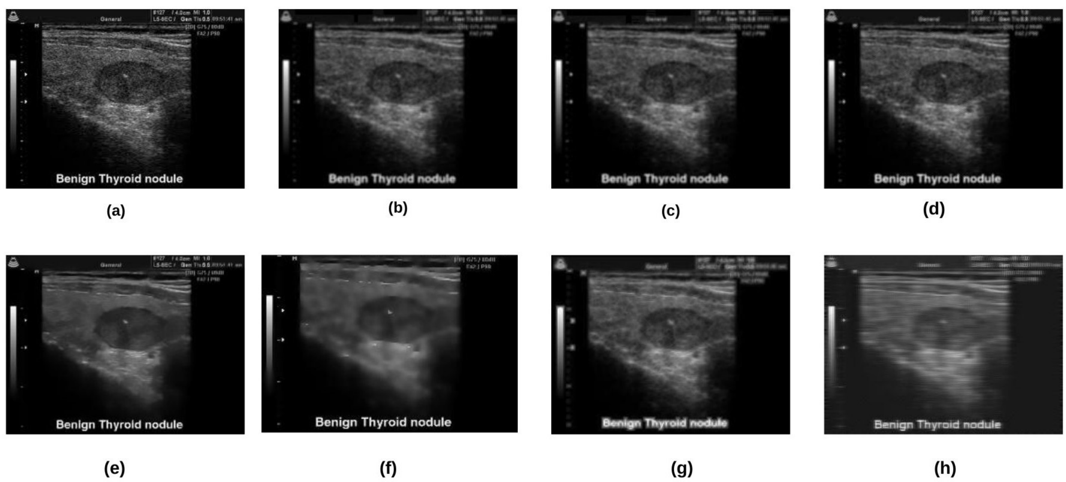

Figure 3: Despeckling results on ultrasound thyroid nodular images. (a) Original image, (b) Lee filter, (c) Frost filter, (d) Kuan filter, (e) Non-Local Means filter, (f) PMAD filter, (g) Fourth-Order PDE filter, (h) Sticks + Fourth-Order PDE filter.

The analysis highlights critical trade-offs between computational efficiency, noise suppression, and structural detail preservation. Filters like PMAD and Fourth-Order PDE, while computationally efficient, require careful parameter tuning to achieve an optimal balance between smoothing and edge retention. However, the combination of Sticks and Fourth-Order PDE demonstrated superior performance in enhancing structural clarity, albeit at a slightly higher computational cost. These trade-offs underscore the need to align the choice of the despeckling algorithm with the application's specific requirements. In the context of clinical relevance, effective reduction in despeckle significantly increases the diagnostic utility of ultrasound images. The findings suggest that while the Lee filter is well suited for general-purpose denoising, Sticks and Fourth-Order PDE offer unparalleled advantages in applications demanding high contrast and precise edge delineation, such as thyroid nodule analysis. This makes the latter an excellent choice for scenarios where accurate diagnosis relies heavily on image quality and structural clarity.

5. Conclusion

This study analyzed several despeckling techniques, combining quantitative metrics and visual evaluation to assess their performance in reducing speckle noise in ultrasound images. Filters such as Lee, Frost, Kuan, Non-Local Means, and PMAD demonstrated their efficacy in suppressing noise. However, this often came at the expense of edge preservation and structural detail retention, particularly in cases of significant noise reduction. Advanced techniques, including Fourth-Order Partial Differential Equations (PDEs) and their combinations, performed better in balancing noise suppression and edge preservation. While Fourth-Order PDEs excel in maintaining image fidelity by preserving edges, their lower PSNR values indicate a trade-off in overall noise reduction performance. Sticks and Fourth-Order PDE emerged as the most effective strategy among the evaluated filters. This method achieved remarkable results in reducing speckle noise, improving edge clarity, and improving image contrast. These attributes make it especially suitable for clinical applications such as thyroid ultrasound imaging, where diagnostic precision is critical. Future work could focus on optimizing the parameters of these algorithms to further improve their computational efficiency and adapt them for clinical use in real time. Additionally, exploring hybrid approaches that integrate the strengths of multiple filters may yield even better results in detail preservation and definition.

Declaration of Competing Interests

The authors declare no known competing financial interests or personal relationships.

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Author Contributions

J. Jai Jaganath Babu: Conceptualization, Supervision, Data Analysis, Writing – Review and Editing; **M. Rohith**: Methodology, Validation, Investigation, Writing – Original Draft; **L. S. Monish Krishnan and L. S. Monish Krishnan**: Software, Visualization, Investigation

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The Role of FinTech in Sustainability and United Nations' Sustainable Development Goals

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Abstract

This study investigates the role of FinTech (Financial Technology) in promoting sustainability and advancing the Sustainable Development Goals (SDGs) of the United Nations. It examines how FinTech innovations in financial inclusion, digital payments, and green finance contribute to economic and environmental sustainability. The research employs a comprehensive literature review and thematic analysis, using NVivo and the Orange Data Mining Tool, to identify key themes and analyze data from 77 scholarly articles, industry reports, and case studies on FinTech applications related to sustainability. The study finds that FinTech significantly supports SDGs through improved financial inclusion, empowering under-banked populations, and facilitating sustainable investments and green finance initiatives that address climate challenges. Blockchain and InsurTech also contribute to transparency and resilience, promoting responsible production and inclusive economic growth. This research provides valuable information for policymakers, financial institutions, and technology innovators on aligning FinTech with sustainability goals. It highlights the critical role of regulatory support and cross-sector collaboration in maximizing FinTech's potential to drive sustainable development. This study addresses a gap in current research by systematically connecting FinTech innovations with specific SDGs, providing a structured framework to clarify FinTech's role in advancing sustainable development goals.

Keywords: FinTech; Sustainable Development Goals; Responsible Investment; Green Technology Adoption; Climate Finance

1. Introduction

Financial technology (FinTech) has significantly transformed the financial sector, redefining how services are delivered, accessed, and used [1]. Simultaneously, the global community confronts pressing sustainability challenges, which the United Nations seeks to address through the Sustainable Development Goals (SDGs). These goals include eradicating poverty, achieving gender equality, promoting sustainable energy and promoting responsible consumption and production [2]. The intersection of FinTech and sustainability presents a unique opportunity to leverage technology to advance sustainable development. Through innovations such as blockchain, artificial intelligence, and mobile applications, FinTech can enhance financial inclusion, mobilize climate finance, encourage responsible investments, and promote the adoption of green technologies [3]. This integration can drive progress toward the SDGs with greater inclusivity and efficiency. Despite the recognized potential of FinTech to promote sustainability, further research is essential to elucidate the specific pathways through which it contributes to the SDGs. The evolving nature of both fields necessitates a closer examination of the challenges, constraints, and ethical considerations involved in applying FinTech to sustainable development.

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For example, mobile payment systems and peer-to-peer lending platforms have empowered underserved communities by providing access to credit and facilitating economic participation, thus supporting financial inclusion and reducing inequalities [4]. Similarly, blockchain technology improves transparency in financial transactions, promoting responsible consumption and production practices [5]. This study explores the role of FinTech in advancing the SDGs, with a particular focus on financial inclusion, sustainable investments, climate finance, and the adoption of green technologies. Reviewing the relevant literature, theoretical frameworks, and empirical evidence aims to provide actionable insights for policymakers, financial institutions, and FinTech innovators. Figure 1 illustrates the SDGs, which serve as the cornerstone of this exploration. The research seeks to highlight the potential of FinTech as a catalyst for sustainable development while addressing the broader implications of using technology to tackle global challenges. Through this effort, the study aspires to bridge the gap between FinTech and sustainability, guiding stakeholders to harness FinTech advancements to accelerate progress toward the SDGs.

Figure 1: The UN Sustainable Development Goals [6].

2. Literature Review

The convergence of FinTech, sustainability, and the Sustainable Development Goals (SDGs) of the United Nations provides a powerful framework to address global challenges [1]. FinTech, through innovative applications in financial services, fosters sustainability by promoting financial inclusion, equitable resource distribution, and environmentally conscious practices. Arner et al. [7] identify three ways in which FinTech advances the progress of the SDGs: improving financial resources for sustainable projects, optimizing resource use, and providing targeted support for specific SDGs. Using technologies such as artificial intelligence, big data, and cloud platforms, the private sector drives sustainability by improving resource efficiency, simplifying operations, and reducing costs [8–10]. These innovations deliver significant environmental and social impacts across sectors, including agriculture and green project financing [11]. Major corporations increasingly support sustainability, underscoring the critical role of technology-driven initiatives. Companies such as Amazon, Google, Alibaba, and Tencent demonstrate how global reach and modern technologies contribute to the SDGs [8]. FinTech promotes financial inclusion, sustainable investments, and digital payment innovations, directly impacting economic stability and poverty reduction [12–14]. Financial inclusion is particularly transformative as it empowers marginalized communities and promotes resilience through improved access to credit and financial services [15, 16]. Enhanced financial literacy complements these efforts, promoting societal stability and supporting education, health, and small business growth [17, 7]. Sustainable investments, increasingly aligned with environmental, social, and governance (ESG) criteria, bridge financial returns with broader societal benefits. By integrating investment strategies with the SDGs, stakeholders address the challenges of inequality, poverty, and climate, fostering accountability in financial markets [18, 19].

CleanTech and microfinance illustrate FinTech's capacity to promote sustainability by driving innovation in health services, creating employment opportunities, and supporting environmental conservation efforts [20, 21]. However, the pace of sustainable investment remains inadequate to achieve the SDGs by 2030, highlighting the need for further innovation in green finance mechanisms [22, 23]. Digital payments demonstrate FinTech's ability to drive socioeconomic progress by increasing access to financial services, improving efficiency, and reducing transaction costs [6, 24]. These platforms expand services to include savings, tax payments and micro-loans, addressing health, education, and poverty alleviation [25, 23]. Digital payments also empower underserved populations, particularly women, by improving access to resources [13, 26]. Blockchain and distributed ledger technologies (DLT) enable secure and transparent transactions, thereby advancing SDG priorities such as poverty alleviation, educational access through digital records, and food security through supply chain optimization [27, 28]. The applications span healthcare, sustainable tourism, and governance, emphasizing accountability and inclusion [29, 30].

InsurTech, another innovation in FinTech, revolutionizes insurance by facilitating risk assessment and resilience through parametric disaster coverage and incentivized green behaviors [31, 32]. Using AI and IoT, InsurTech drives economic growth and equity [33, 34]. Artificial intelligence (AI) and data analytics enable FinTech to support sustainable agriculture, climate action, and resource management. AI improves decision-making and fraud detection, while real-time analytics drive sustainable practices [35, 36]. RegTech focuses on regulatory compliance, improving governance, transparency, and stability [37, 38]. These technologies streamline processes and align financial systems with sustainability goals. Green finance facilitates investments in renewable energy, sustainable infrastructure, and agriculture, which are crucial to achieving the SDGs [39–41]. Instruments like green bonds and sustainability-linked loans integrate environmental goals with economic resilience, fostering multi-stakeholder collaborations [42, 43]. However, challenges in scaling and integrating emerging solutions like AI and blockchain persist, particularly in regulatory and developing contexts [22]. The literature highlights FinTech's transformative potential in advancing the SDGs while emphasizing the need for robust frameworks to address scalability, regulatory barriers, and regional disparities. Comparative regional studies and focused research on integration mechanisms could unlock FinTech's full potential, guiding its contributions to sustainable global growth.

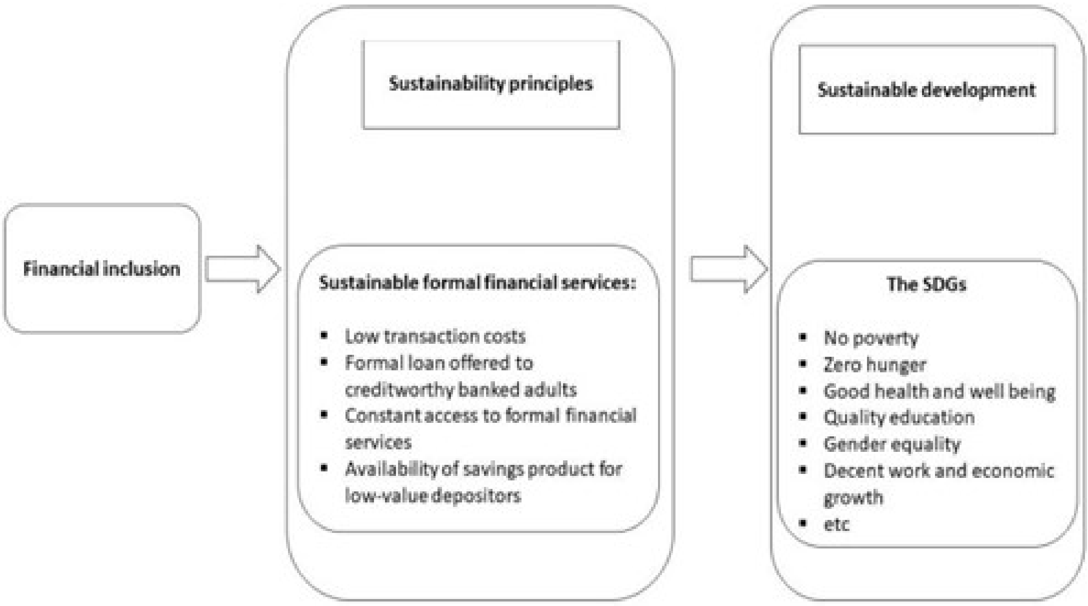

Figure 2: The link between financial inclusion, sustainability, and sustainable development [44].

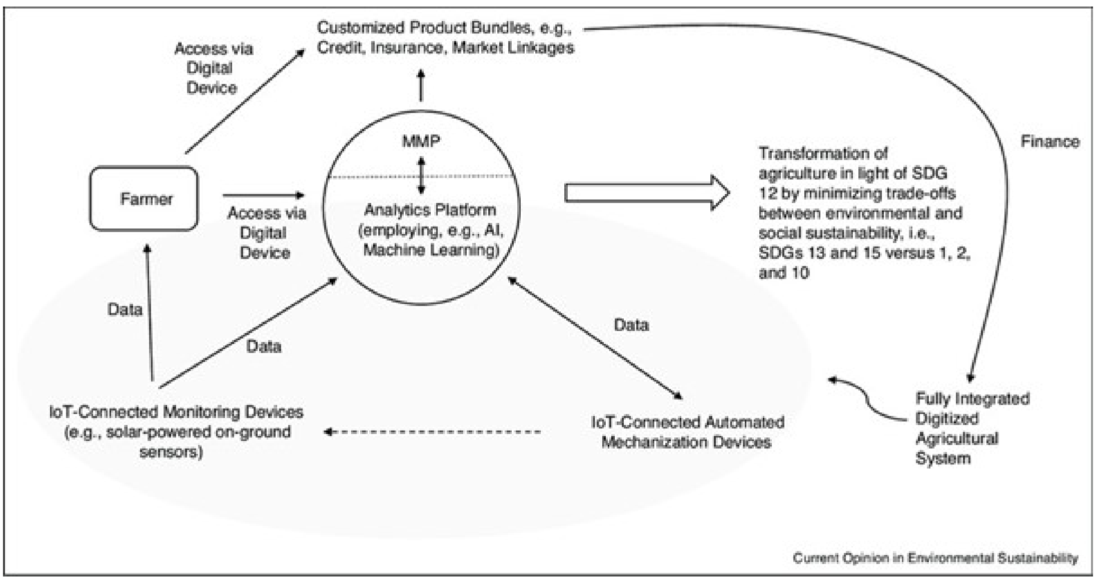

Figure 3: Interoperability between mobile money platforms and integrated digitized agricultural systems [11].

3. Methods

This study uses a comprehensive literature review combined with a thematic analysis to investigate the role of FinTech in advancing sustainability and supporting the Sustainable Development Goals (SDGs) of the United Nations. By synthesizing a wide range of scholarly sources, including academic articles, case studies, and industry reports, the research consolidates existing knowledge on the intersection of FinTech and sustainable development. Data were collected from reputable academic databases and publications, with Google Scholar, peer-reviewed articles, and institutional reports as primary sources. Search terms such as "FinTech AND Sustainability", "Digital Payments AND UN SDGs", "Blockchain AND Sustainability" and "AI AND Sustainable Development" were used to ensure alignment with the focus of the study. To maintain relevance, the scope was limited to publications in English from the last decade, reflecting recent trends and innovations. After initial filtering, 77 articles were processed using Orange Data Mining Tool and NVivo 14 for further analysis. The study adopts a qualitative exploratory approach appropriate for understanding the emerging role of FinTech in sustainable development. This method facilitates the integration of diverse perspectives and the identification of patterns and themes across various sectors. Braun and Clarke's thematic analysis framework guided the organization and interpretation of the data, enabling the identification of recurring trends in the contributions of FinTech to the SDGs. The SDGs of the United Nations provided a core analytical framework, aligning FinTech applications with specific goals such as financial inclusion, climate action, and responsible consumption. NVivo 14 was used for thematic coding, while the Orange Data Mining Tool enabled clustering and visualization, offering insights into relationships between identified themes. Data preprocessing, including filtering and cleaning, ensured consistency and reliability across sources, while visualizations such as word clouds and cluster diagrams facilitated a comprehensive understanding of FinTech's role in promoting sustainability.

4. Results and Findings

This study demonstrates how FinTech technologies contribute to sustainable development by directly advancing the United Nations Sustainable Development Goals (SDGs). Key impact areas include financial inclusion, sustainable investing, digital payments, blockchain technology, InsurTech, data analytics, artificial intelligence, regulatory technology, and green finance. These advancements, driven by financial innovation, present opportunities to build a more equitable and resilient global society, with stakeholder engagement critical to progress. Financial inclusion facilitated by FinTech platforms has become a cornerstone of global development, offering solutions to alleviate poverty and economic growth and improve socioeconomic resilience. For example, socioeconomic platforms such as Kenya's M-Pesa have significantly improved financial access, lifting approximately 2% of the population out of poverty. M-Pesa alone accounts for more than 50%

Digital payments have significantly boosted economic stability, especially in emerging markets. During the COVID-19 pandemic, digital payment platforms provided a lifeline to small businesses, ensuring the continuity of transactions despite lockdowns. In India, the usage of digital payments increased by more than 70% on certain platforms during this period, contributing an estimated 1.5% to the country's GDP by 2023. This underscores FinTech's role in fostering economic resilience, supporting employment, and driving growth in alignment with SDGs, promoting decent work and economic progress. Blockchain technology further advances sustainability by emphasizing transparency and accountability. Blockchain-powered supply chain solutions like IBM's Food Trust system allow businesses and consumers to trace product origins, ensuring ethical sourcing and reducing waste. Companies utilizing this technology have reported operational cost reductions exceeding 20%, thereby supporting SDGs related to responsible production and consumption. Table 1 presents the themes and subthemes identified through thematic analysis using NVivo 14. It highlights FinTech's multidimensional impact on sustainability, categorizing banking, mobile payments, climate action, economic development, innovation, and sustainable finance. These findings provide a comprehensive perspective on how FinTech technologies intersect with sustainable development. This breakdown of the themes highlights the central role of sustainability, digital infrastructure, and innovation in FinTech, showcasing how these areas contribute to advancing the SDGs. For instance, the prominence of "Digital Payments" and "Green Finance" underscores FinTech's crucial role in expanding financial inclusion and channeling investments into environmentally responsible initiatives. Simultaneously, themes such as "Climate Action" and "Economic Development" illustrate FinTech's broader impact on fostering economic resilience and promoting environmental sustainability. InsurTech, which leverages mobile technology, is pivotal in extending access to healthcare and financial security. In emerging economies, mobile platforms offer underserved populations affordable health and life insurance, increasing resilience and economic stability. InsurTech now serves millions, providing essential risk coverage that aligns with SDG goals related to health and well-being, economic resilience, and climate adaptation. Data analytics and artificial intelligence further revolutionize FinTech's capacity to tackle industry challenges. These technologies improve risk assessment, fraud detection, personalized consumer services, and regulatory compliance. By fostering social justice, human rights, and innovation, they contribute significantly to achieving the SDG goals. RegTech, for example, streamlines ESG compliance through automated processes, enhancing transparency and accountability. This approach strengthens governance and aligns financial systems with the SDGs related to responsible consumption, climate action, and good governance.

Table 1: Key Themes and Sub-Themes in FinTech and Sustainable Development Identified Through NVivo 14 Analysis

Theme	**Sub-Theme**	**Reference Count**	**Reference Weight (%)**
Banking, Mobile Payments and Digital Infrastructure	Payment Services	6	2.92
	Digital Payment Infrastructure	4	1.28
	Digital Payments	4	1.29
	Banking Industry	8	0.92
	Green Banks	5	1.73
	Mobile Banking	8	2.4
	Online Banking	5	1.78
	Sustainable Banking	5	1.35
	Digital Currency	15	7.26
	Digital Economy	8	1.78
	Digital Identities	11	2.67
	Digital Platforms	7	1.25
	Digital Revolution	7	1.42
	Digital Technologies	18	3.98
	Digital Infrastructure	6	1.78
	Financial Infrastructure	5	1.47
	Infrastructure Projects	7	1.45
	Mobile Money Platforms	4	1.06
	Mobile Payments	13	4.37
	Mobile Technology	10	2.11
Climate Action	Climate Action	5	1.49
	Climate Crisis	4	0.5
	Climate Change	21	7.67
	Global Climate Stability	4	1.19
Economic Development	Developing Economies	17	3.46
	Financial Development	8	1.39
	RegTech Developments	6	1.24
	Sustainable Development	40	12.18
	Technological Developments	19	5.8
	Digital Economy	8	1.78
	Emerging Economies	9	1.53
	Sustainable Economy	5	0.79
FinTech Applications	FinTech Applications	5	1.95
	FinTech Enterprises	3	1.58
	FinTech Growth	4	0.91
	FinTech Innovation	8	1.92
	FinTech Products	5	0.7
Innovation	Digital Innovation	5	1.3
	FinTech Innovation	8	1.92
	Product Innovation	5	1.07
	Technological Innovation	19	4.23
Sustainable Development	Green Economy	6	1.71
	Digital Innovation	5	1.3
	Sustainable Development	40	12.18

Figure 4 presents the word cloud generated using the Orange Data Mining Tool, where terms such as "sustainability", "technology", "digital," and "green finance" emerge as dominant themes. This visualization underscores the study's emphasis on sustainable development and FinTech's critical role in addressing global challenges. Figure 5 provides a hierarchical clustering of these terms, visually grouping related topics to demonstrate the interconnections between FinTech's contributions to sustainability.

Figure 4: Word Cloud using Orange Data Mining Tool

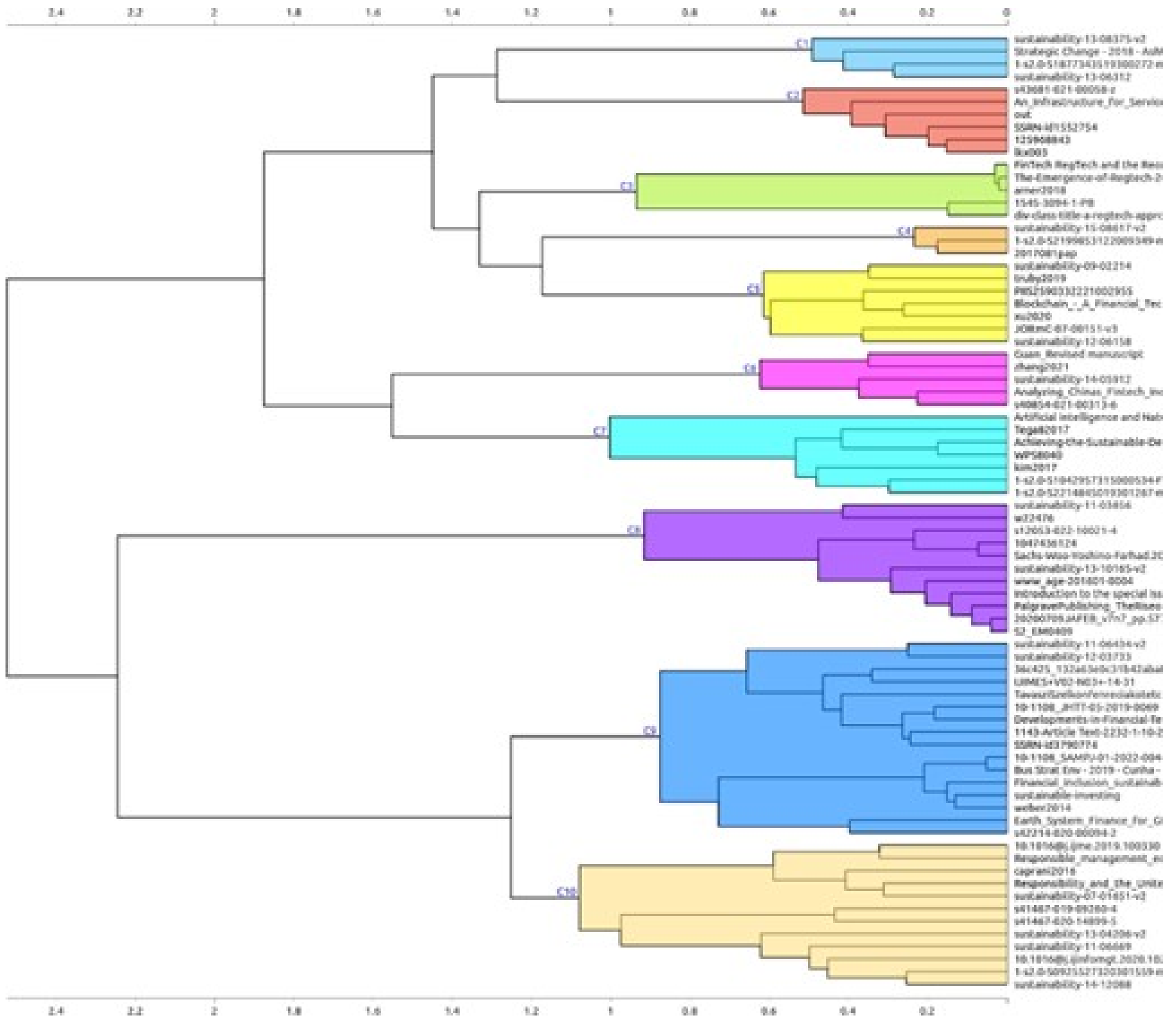

Figure 5: Hierarchical Clustering using Orange Data Mining Tool

The findings confirm that integrating FinTech into sustainable finance provides a robust and scalable platform to achieve the SDGs. As FinTech continues to evolve, its influence on economic and environmental sustainability will expand, underscoring the need for coordinated efforts between businesses, governments, and financial institutions. Such collaboration is essential for unlocking FinTech's full potential to create a sustainable and inclusive global future.

5. Conclusion

This study highlights FinTech's transformative potential in advancing the Sustainable Development Goals (SDGs) through innovations in financial inclusion, sustainable investing, digital payments, blockchain technology, InsurTech, data analytics, artificial intelligence (AI), RegTech, and green finance. These subdomains of FinTech have shown significant potential to improve economic and environmental sustainability by improving financial accessibility, promoting responsible investing, increasing transparency, and enabling secure digital transactions. Using thematic analysis, this research provides critical insights into how FinTech can catalyze progress toward a more inclusive and sustainable future. It guides policymakers, financial institutions, and technology providers in aligning FinTech innovations with global sustainability goals. The findings contribute to the existing literature by offering a comprehensive understanding of FinTech's impact on specific SDGs and emphasizing the importance of stakeholder collaboration to maximize its potential for sustainable development. For policymakers, the study underscores the importance of fostering FinTech advancements, prioritizing inclusivity and environmental responsibility. Provides a framework for financial institutions and technology providers to innovate responsibly, creating long-term social value while adhering to sustainability standards. Although this study lays a foundational understanding of the role of FinTech in achieving the SDGs, several areas remain for future research. Hybrid methodological approaches could provide deeper insights, such as combining grounded theory with thematic analysis. Integrating qualitative and quantitative methodologies, such as sentiment or cluster analysis, could enhance the analytical depth and understanding of FinTech's contributions. Further exploration of emerging applications such as decentralized finance (DeFi), digital identity verification, and green cryptocurrencies could reveal new opportunities to advance the SDGs. Longitudinal studies are needed to examine the long-term effects of FinTech on economic resilience, environmental sustainability, and social equity, offering a more comprehensive view of its sustained benefits. Another potential area for methodological enhancement is improving the rigor of thematic analysis by adopting standardized coding systems or software-based validation techniques. Quantitative metrics, such as financial inclusion indicators or environmental impact assessments, can supplement qualitative findings, providing a more holistic view of FinTech's role in sustainable development.

Future research should also explore collaborative models involving governments, financial institutions, technology corporations, and non-profits to realize the potential of FinTech for sustainable development fully. Identifying best practices for cross-sector partnerships could promote a unified approach to achieving the SDGs, ensuring that the impact of FinTech is extensive and inclusive. In conclusion, this study underscores the revolutionary role of FinTech in driving sustainable development but emphasizes the need for more research to explore emerging trends, evaluate long-term impacts, and develop robust methodologies. These directions for future research will deepen our understanding of the contributions of FinTech to the SDGs and its ongoing role in building a sustainable, inclusive, and prosperous future.

Declaration of Competing Interests

The authors declare that they have no known competing financial interests or personal relationships.

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Author Contributions

Peehoo Jain: Methodology, Validation, Writing – Original Draft; **Priya Gupta**: Conceptualization, Data Analysis, Writing – Review and Editing; **Bhawna**: Software, Visualization, Investigation

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Comparative Analysis of Random Forest and Logistic Regression for Heart Attack Risk Prediction

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Abstract

Cardiovascular diseases, particularly heart attacks, are leading causes of global mortality, highlighting the need for enhanced early detection and intervention strategies. This study evaluates the effectiveness of two machine learning algorithmsRandom Forest (RF) and Logistic Regression (LR)in predicting heart attack risk using diverse patient data sets. The focus is on uncovering subtle patterns and risk factors that traditional methods may overlook, while also assessing the accuracy and performance of both models. A critical aspect of the study is the interpretability of these algorithms, addressing a significant gap in current research. Additionally, the issue of dataset imbalance, which is prevalent in medical data, is examined, and solutions are proposed to improve model reliability in real-world applications. These findings contribute to the discourse on optimizing machine learning in healthcare, advocating for tailored approaches that balance predictive power with interpretability. By analyzing the strengths and weaknesses of RF and LR in heart attack prediction, this study aims to provide valuable insights for clinicians and researchers, ultimately enhancing decision-making processes in cardiovascular care and interventions.

Keywords: Machine Learning; Heart Attack Prediction; Random Forest; Logistic Regression; Interpretability

1. Introduction

Cardiovascular diseases, including heart attacks, represent a major public health concern throughout the world, contributing to substantial morbidity and mortality [1]. Despite advances in medical science, early detection and prediction of heart attacks remain a challenge, with delays often leading to life-threatening complications [2]. Detecting individuals at risk early could significantly improve outcomes by enabling prompt intervention [3, 4]. In this context, machine learning techniques offer a promising avenue to enhance predictive accuracy in heart attack detection [5]. These models can process large, complex datasets to uncover subtle patterns that traditional statistical methods might overlook [6]. Several studies have applied machine learning to heart disease prediction, exploring various algorithms from Random Forest (RF) to Logistic Regression (LR) models [7]. However, this study distinguishes itself by providing a direct comparative analysis of the RF and LR models, focusing on interpretability and performance evaluation in real world contexts. Furthermore, unlike previous studies that often overlook the implications of unbalanced datasets or do not address the interpretability of the model in a comprehensive way [8], the present research underscores these challenges, offering novel insights into optimizing predictive performance.

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2. Related Works

This section provides an overview of the key findings and methodologies employed in previous research related to the application of machine learning models for the prediction of heart attacks. Ruby Hasan (2021) [9] conducted a comparative analysis of various machine learning algorithms to predict heart disease using patient medical data. The study evaluated models including K-Nearest Neighbors (KNN), Decision Trees, Gaussian Naïve Bayes, Logistic Regression, and Random Forest. Each algorithm was assessed based on its ability to predict heart disease effectively, and the analysis highlighted the strengths and limitations of each approach. The findings demonstrated the potential of machine learning tools to enable early detection of heart disease, thus facilitating timely interventions. This work underscores the importance of selecting appropriate algorithms and optimizing models for medical data to improve predictive accuracy and reliability. Abdellati et al. (2022) [10] introduced a supervised infinite feature selection method combined with an improved weighted random forest algorithm to address class imbalance and high-dimensional data challenges in heart disease detection. This approach demonstrated superior performance compared to traditional methods, highlighting the potential of advanced feature selection and ensemble learning techniques in medical diagnostics. Pathan et al. (2022) [11] focused on the application of machine learning models for the prediction of heart disease, highlighting the importance of data pre-processing and model optimization. The study underscored that integrating domain knowledge with machine learning approaches can significantly improve predictive outcomes, thus aiding in early diagnosis and treatment planning. Zhaozhao Xu et al. (2020) address the challenges of imbalanced medical data classification with a hybrid sampling algorithm called RFMSE, which integrates Misclassification-Oriented SMOTE (M-SMOTE) and Edited Nearest Neighbor (ENN) techniques with Random Forest (RF). Unlike traditional methods that solely rely on static imbalance rates, RFMSE dynamically updates sampling rates based on RF's misclassification rates. The hybrid approach enhances minority class recognition by combining over-sampling to generate synthetic samples and under-sampling to remove noise from majority class data. Experimental results on ten UCI datasets demonstrate RFMSE's superiority over classical algorithms, achieving notable improvements in F-value and Matthews Correlation Coefficient (MCC). This method also effectively balances time complexity and classification performance, making it highly suitable for medical applications like missed abortion prediction [6]. Lingyu Li and Zhi-Ping Liu (2022) [12] proposed a connected network-regularized logistic regression (CNet-RLR) model for feature selection in high-dimensional datasets, particularly focusing on genomic data. The model uniquely integrates Lasso penalties for sparsity, graph Laplacians for smoothness, and network connectivity constraints to ensure features form connected subnetworks. The model achieves efficient and interpretable feature selection by reformulating the Lasso penalty into a convex optimization problem and employing an interior-point algorithm. Empirical validation using synthetic and real-world cancer genomics datasets demonstrated superior classification accuracy and feature interpretability compared to existing models like Lasso-RLR and Elastic Net. This work highlights the importance of embedding domain-specific network structures into feature selection algorithms to enhance their practical utility. These recent advancements in heart attack prediction research have emphasized the integration of RF and LR models with complementary techniques such as deep learning, ensemble learning, and feature engineering. At the same time, its also noted that, efforts have been directed towards addressing real-world challenges such as data imbalance, model interpretability, and scalability.

3. Methods

3.1. ML models

The selection of machine learning models in this study was guided by the dataset's characteristics, including its size, feature space, and complexity of relationships among variables. Random Forest (RF) and Logistic Regression (LR) were chosen as the primary models for evaluation due to their complementary strengths in predictive modeling and interoperability. The random forest is an ensemble learning method that creates multiple decision trees during training and predicts the most common class. It effectively captures complex, non-linear relationships in data, making it ideal for medical datasets. Furthermore, it is resistant to over-fitting, especially with smaller datasets, as it averages predictions from various trees to reduce variance [13]. Logistic regression is an efficient statistical method for binary classification, particularly suited for large datasets. Its linear nature allows it to scale effectively with the size of the data, making it ideal for real-time predictions and high-dimensional applications. In addition, it provides clear information on feature-target relationships, which is vital for interpretability in medical contexts [14]. The combination of these two models promises to provide a comprehensive analysis, balancing the interpretability and simplicity of Logistic Regression with the robustness and flexibility of Random Forest. Thus, the dual approach ensures that the study findings are both practically relevant and grounded in methodologically sound modeling strategies.

3.2. Data collection and analysis

The dataset consisted of 303 samples with 14 features, sourced from Kaggle's "Heart Attack Analysis & Prediction Dataset" (`https://www.kaggle.com/datasets/sonialikhan/heart-attack-analysis-and-prediction-dataset`) as described in Table 1.

The entire model data curation, model preparation, and classification were done in Jupiter Notebook IDE. The feature selection was performed later using Pearson's correlation analysis to identify features with the strongest linear relationships to the target variable. This method was chosen for its simplicity and effectiveness in identifying predictive characteristics in datasets where linear relationships may play a significant role [15].

3.3. Data preprocessing

Data preprocessing was performed to address missing values and prepare the dataset for machine learning models. Missing values were identified but not imputed intentionally to simulate real-world scenarios where complete data may not always be available. This approach allows the models to handle incomplete datasets, reflecting practical clinical applications. Additionally, normalization was applied to continuous features to ensure that they were on comparable scales, improving model performance and stability.

3.4. Model training and validation

The dataset was split into training and testing sets, with 80% of the samples used for training and 20% reserved for testing. Both RF and LR models were trained on the preprocessed dataset, and their performance was evaluated using metrics such as accuracy, precision, recall, and F1 score. These metrics were selected to provide a comprehensive evaluation of the models, especially given the potential class imbalance in the dataset.

Table 1: Feature selection for ML training

Feature	**Description**
age	The age of the patient in years.
sex	The gender of the patient (1 = male, 0 = female).
cp	The chest pain type experienced by the patient (0 = typical angina, 1 = atypical angina, 2 = non-anginal pain, 3 = asymptomatic).
trtbps	The resting blood pressure of the patient in mm Hg.
chol	The cholesterol level of the patient in mg/dl.
fbs	The fasting blood sugar level of the patient (1 = fasting blood sugar > 120 mg/dl, 0 = otherwise).
restecg	The resting electrocardiographic results (0 = normal, 1 = having ST-T wave abnormality, 2 = showing probable or definite left ventricular hypertrophy).
thalachh	The maximum heart rate achieved by the patient.
exng	Exercise-induced angina (1 = yes, 0 = no).
oldpeak	The ST depression induced by exercise relative to rest.
slp	The slope of the peak exercise ST segment (1 = upsloping, 2 = flat, 3 = downsloping).
caa	The number of major vessels (0-3) colored by fluoroscopy.
thall	The thallium stress test result (1 = normal, 2 = fixed defect, 3 = reversible defect).
output	The diagnosis of heart disease (1 = presence of heart disease, 0 = absence of heart disease).

4. Results and Discussion

The implementation of Pearson correlation analysis reduced the initial 13 features to 7, focusing on those with the highest correlation coefficients, as shown in Table 2. For instance, features like `cp` (chest pain type) and `exng` (exercise-induced angina) demonstrated the highest correlations, with coefficients of 0.432 and 0.436, respectively.

The results of this study indicate that both the Random Forest (RF) and Logistic Regression (LR) models achieved comparable test accuracy rates of 86%. Despite the higher training accuracy of RF 100%, its test performance did not exceed that of LR, suggesting the possibility of overfitting. This section delves into the potential reasons for this similarity, examines additional performance metrics, and evaluates the models' real-world applicability.

Table 2: Pearson coefficient analysis for selected features.

Feature	Pearson Coefficient
cp	0.432080
thalachh	0.419955
exng	0.435601
oldpeak	0.429146
slp	0.343940
caa	0.408992
thall	0.343106

Several factors may explain the comparable performance of RF and LR models:

- **Feature Selection Overlap**: Pearson's correlation analysis identified features (`cp`, `exng`, etc.) that were highly predictive for both models. This shared feature space may have led to similar predictive outcomes.
- **Dataset Characteristics**: With only 303 samples, the limited size of the dataset may have restricted RFs ability to take advantage of its complexity advantages over LR. Furthermore, the linear relationships in the dataset between certain features and the target variable may have favored the simpler modeling approach of LR.
- **Class Balance**: Although the dataset exhibited some imbalance, both models likely handled it effectively due to their inherent robustness and the moderate size of the dataset.
- **Noise and Missing Data**: The intentional decision not to impute missing values may have influenced both models similarly, as they had to learn patterns from incomplete data.

4.1. Evaluation Using Additional Metrics

Relying solely on accuracy as a performance metric can mask a model's limitations, particularly in the context of imbalanced datasets. To provide a more comprehensive evaluation, metrics such as precision, recall, F1 score, and ROC-AUC were calculated (Table 3).

Table 3: Performance metrics for RF and LR models.

Metric	Random Forest	Logistic Regression
Precision	0.88	0.87
Recall	0.84	0.85
F1-Score	0.86	0.86
ROC-AUC	0.90	0.89

Both models demonstrated high precision and recall values, indicating their effectiveness in identifying positive cases while minimizing false positives. The F1 scores reinforce their balanced performance in precision and recall, and the ROC-AUC values highlight their strong ability to distinguish between classes. These results further support the robustness of both models in heart attack prediction.

4.2. Real-World Implications and Limitations

The findings emphasize the importance of thorough feature selection and preprocessing when working with clinical datasets. LRs simplicity and interpretability make it an attractive option for real-time applications where computational efficiency is critical. RF, with its ability to capture non-linear relationships, may excel in scenarios with larger datasets or more complex interactions. However, the observed similarity in performance highlights the need for advanced feature engineering or hybrid modeling approaches to fully utilize RFs capabilities. The primary limitation of this study is the small size of the data set, which can restrict generalizability. Additionally, while metrics like the F1-score and ROC-AUC provide a broader evaluation, future studies should explore calibration metrics to assess model reliability and confidence in predictions.

5. Conclusion

In conclusion, this study evaluated the performance of Random Forest (RF) and Logistic Regression (LR) models for heart attack prediction, utilizing a dataset of 303 samples with 14 features. Both models achieved comparable test accuracy rates of 86%, with RF showing higher training accuracy. This highlights RF's ability to capture non-linear relationships and LR's simplicity and interpretability. The findings emphasize the importance of considering the characteristics of the dataset and the modeling requirements when selecting machine learning algorithms for medical applications. While accuracy was the primary evaluation metric, additional metrics such as precision, recall, F1-score, and ROC-AUC provided a more comprehensive assessment of model performance, confirming the effectiveness of both RF and LR in identifying heart attack risks. For future research, there are several avenues to explore. Researchers should consider evaluating more advanced algorithms, such as gradient boosting machines and neural networks, to see if they can outperform RF and LR. Techniques to address class imbalance, like oversampling or synthetic data generation, could enhance model performance. Additionally, incorporating advanced feature selection methods and expanding the dataset size and diversity will improve the generalizability of the findings. Finally, integrating RF and LR with other approaches, such as deep learning or ensemble techniques, may further enhance predictive accuracy and interpretability. By pursuing these strategies, future work can optimize the predictive capabilities of machine learning models, advancing their clinical utility in heart attack prevention and management.

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The Role of Virtual and Augmented Reality in Enhancing Educational Experiences: A Mini-Review

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Abstract

This mini-review explores the role of virtual reality (VR) and augmented reality (AR) in transforming education by making learning interactive, engaging and accessible. VR enhances comprehension by simplifying complex concepts, while AR creates immersive environments that foster critical thinking and retention. These technologies address diverse learning needs, making education more inclusive. However, their adoption faces challenges such as high costs, technical barriers, and skill gaps among educators. This article discusses strategies to overcome these obstacles, including the use of open source tools, improving infrastructure, and providing professional training. Future research should focus on affordable AR solutions, inclusive design, and evaluation of the long-term impact of these technologies. VR and AR are poised to become integral tools for modern education, creating dynamic and learner-centric environments.

Keywords: Virtual Reality; Augmented Reality; Educational Technology; Immersive Learning; Inclusive Design

1. Introduction

The rapid evolution of technology has revolutionized various sectors, and education is no exception [1]. Among the many advances, virtual reality (VR) and augmented reality (AR) stand out for their ability to create engaging and interactive learning experiences [2, 3]. These tools cater to diverse learning preferences by combining visual, auditory, and kinesthetic elements, transforming the traditional classroom into a dynamic and inclusive space [4]. VR simplifies abstract or complex topics through vivid and interactive visuals, while AR bridges the gap between theory and practice by superimposing digital content onto the real world, enabling learners to experience concepts in context [5]. Despite the critical role of traditional teaching methods, their limitations, such as static content and a one-size-fits-all approach, often hinder deeper understanding, especially in complex subjects such as science, engineering and history [6, 7]. VR addresses these gaps by visualizing intricate processes, such as molecular interactions or historical reconstructions, making them easier to comprehend [8, 9]. Similarly, AR introduces immersive simulations that provide real-world relevance, such as virtual laboratories or historical site tours, fostering critical thinking and retention [10]. The educational benefits of VR and AR extend beyond engagement. Research shows that these technologies improve cognitive load management, improve long-term retention, and facilitate personalized learning experiences. Moreover, they offer opportunities to address diverse learning needs, including those of visual and kinesthetic learners, while making education accessible to students in remote or resource-constrained environments [11, 12]. This mini-review explores the transformative potential of VR and AR in education. It delves into their applications, highlights evidence of their effectiveness, and addresses challenges in their adoption, such as high costs and technological barriers. By synthesizing current research and real-world examples, this review aims to provide insight into the role of these technologies in shaping an equitable and impactful educational future.

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2. Core Concepts and Definitions

Virtual reality (VR) and augmented reality (AR) are transformative technologies that have redefined education delivery, offering new ways to present information and engage learners. Understanding their definitions, scope, and underlying principles is crucial to understanding their role in improving educational experiences. Virtual reality (VR) is a computer-generated environment that immerses users in interactive experiences, creating a sensation of presence in a virtual world. Utilizing head-mounted displays and motion tracking, VR delivers vivid visuals, spatial audio, and tactile feedback. Since its development in the 1960s, VR has advanced significantly with devices such as the Oculus Rift and HTC VIVE. It is now commonly used in healthcare, education, and corporate training, including applications such as surgical simulations and virtual classrooms. Companies like IKEA and Tata Motors use VR to boost efficiency and enhance customer engagement, emphasizing its growing importance in various industries [13, 14].

Augmented Reality (AR) overlays digital elements onto the physical world, enhancing real-time interaction through devices like smartphones and AR glasses. Coined in 1992 by Thomas Caudell, AR enriches reality by integrating virtual content into real-world settings, unlike virtual reality, which creates entirely synthetic environments. Widely applied in fields such as medicine, education, retail and manufacturing, AR aids in surgical visualization, immersive learning, and predictive maintenance tasks. While challenges like interoperability and hardware optimization remain, ongoing advances drive its adoption across industries, particularly in Industry 4.0 [15–17].

While both technologies focus on enhancing engagement, they differ in scope and application. Augmented Reality (AR) integrates digital elements into the physical world, overlaying information without isolating users from their real surroundings, while Virtual Reality (VR) creates fully immersive synthetic environments, replacing real-world stimuli entirely. AR enhances real-world interactions, making it more suitable for practical applications such as virtual trials, whereas VR offers deep immersion, ideal for simulated experiences like virtual tours. AR typically provides lower immersion but greater accessibility than VR, which requires specialized equipment for complete immersion of the user [18, 19].

Augmented and Virtual Reality in Education

Augmented Reality (AR) and Virtual Reality (VR) are undoubtedly transforming education by providing immersive and interactive experiences that traditional methods cannot achieve. AR overlays digital elements such as text, images, and 3D objects on the physical world, improving real-world settings, while VR creates entirely synthetic environments that immerse users in simulated realities [20, 21]. These technologies enable students to visualize abstract concepts, engage in interactive simulations, and participate in virtual field trips to enhance engagement and comprehension in various disciplines [22]. In K-12 education, AR and VR have proven effective in making complex scientific concepts accessible. For example, AR applications have been used to illustrate the effects of magnetic fields or simulate Earth's movement around the Sun, providing vivid demonstrations that improve understanding and retention [22, 23]. Similarly, VR environments allow students to explore microscopic objects or celestial phenomena, offering hands-on virtual experiences without the risks or costs associated with real-world experimentation [23]. Higher education has benefited significantly from these technologies, particularly engineering, medicine, and vocational training. VR enables medical students to practice surgical procedures in safe, controlled environments, while AR helps visualize anatomical structures. In engineering education, VR facilitates immersive simulations for design and prototyping, fostering the development of practical skills [21, 24]. In addition, vocational training programs utilize AR and VR to provide real-world simulations, such as engine repair or automation tasks, allowing trainees to practice repeatedly without additional costs [25]. Despite their transformative potential, AR and VR face challenges such as high costs, limited accessibility, and lack of comprehensive training for educators. However, advances in mobile technology, wearable devices and open-source platforms address these barriers, making these technologies increasingly accessible for widespread adoption [24]. To maximize their educational impact, integrating AR and VR into curricula requires strategic planning, teacher training, and a robust technical infrastructure [23, 25]. Several tools and technologies facilitate the creation of VR and AR content. Table 1 summarizes key technical tools used in educational applications, describing their features and benefits.

3. Challenges and Strategies for Implementation

While animation and augmented reality (AR) have immense potential to transform education, their implementation faces significant financial, technological, and pedagogical challenges. Developing high-quality animations and AR applications requires substantial investment in tools, software, and skilled professionals. While offering advanced capabilities, tools like Blender and Autodesk Maya often prove resource-intensive for underfunded institutions. Furthermore, the cost of AR-enabled devices and robust Internet infrastructure further exacerbates disparities in access, particularly in underserved regions. Educators also face a skill gap in the effective use of these technologies. Many tools require technical expertise, and without adequate training or support, educators may struggle to integrate animation and AR into curricula or adapt content to diverse classroom needs. In addition, ensuring inclusivity poses additional challenges.

Table 1: Technical tools used and their features.

Reference	Tools	Description	Features	Benefits
[26]	Pencil-2D	Pencil-2D is an open-source animation/drawing software for creating 2D animations. It's simple and intuitive, making it a great tool for beginners.	Raster and vector workflow, minimalistic design for ease of use, lightweight and fast, cross-platform support.	2D Hand-Drawn Animation
[27]	Blender 3D	Blender is a free and open-source 3D creation suite that supports the entirety of the 3D pipeline, including modeling, animation, simulation, rendering, compositing, and motion tracking.	Comprehensive 3D modeling and sculpting tools, advanced animation and rigging capabilities, real-time viewport preview with EEVEE engine, extensive add-ons and scriptability with Python.	3D Modeling, Animation, and Rendering.
[28]	Adobe Animate	Adobe Animate is used for creating vector graphics and animations. It supports a wide range of formats and allows for interactive content development.	Vector drawing tool, timeline and frame-by-frame animation, HTML5, Canvas, and WebGL support, integration with other Adobe Creative Cloud apps.	2D Vector Animation and Interactive Content.
[29, 30]	Autodesk Maya	Autodesk Maya is a leading 3D animation software for creating interactive 3D applications, including video games, animated films, TV series, and visual effects.	Comprehensive 3D modeling tools, advanced rigging and skinning options, high-quality rendering with Arnold integration, extensive animation tools and motion graphics capabilities.	3D Character Animation and Visual Effects.
[31, 32]	Moho	Moho, formerly known as Anime Studio, is a complete 2D animation software designed for professionals looking to create complex animations.	Bone rigging system, frame-by-frame animation, smart bones and dynamics, 3D object import and manipulation.	2D Cutout Animation.
[33]	Synfig Studio	Synfig Studio is free, open-source 2D animation software designed to create high-quality animation with fewer resources.	Vector-based artwork creation, a bone system for cutout animation, support for bitmap artwork, powerful layer system for complex animations.	2D Vector Animation and Tweening.

Designing accessible content that incorporates features like subtitles, audio narration, and adaptive interfaces requires significant time and resources, which can limit broader adoption. To address these barriers, open source tools such as Blender and Synfig Studio can mitigate cost concerns while maintaining quality. Partnerships with technology companies and non-profits can also facilitate access to proprietary tools and devices through grants or subsidies. Bridging the skill gap requires targeted professional development, including workshops, online tutorials, and modular training programs tailored to specific educational goals. Improving accessibility involves adopting cloud-based AR solutions compatible with widely available devices like smartphones and tablets. Community-driven initiatives, such as device sharing programs, can further reduce access inequities. Prioritizing inclusivity in content design, with features that accommodate diverse learning needs, ensures that these tools benefit all students. Collaborative efforts among educators, developers, and policymakers will be critical to overcoming these challenges and unlocking the full potential of animation and AR to create dynamic, inclusive, and impactful learning environments.

4. Conclusion and Future Directions

Integrating animation and augmented reality (AR) in education offers immense promise to enhance learning experiences. These technologies simplify complex concepts, engage learners, and provide immersive hands-on opportunities for skill development. Tools like Blender, Adobe Animate, and ARKit have already demonstrated their ability to revolutionize traditional teaching methods by making education more interactive and accessible. However, challenges such as high costs, skill gaps, and inclusivity barriers must be addressed to ensure equitable access to these innovations. Open source solutions, collaborative partnerships, and targeted professional development can mitigate these challenges and pave the way for wider adoption. Looking ahead, advancements in artificial intelligence (AI), extended reality (XR), and gamification are poised to enhance animation and AR's educational potential. AI-powered tools could enable the adaptation of real-time content to individual learners' needs, while XR could integrate virtual and augmented realities for even more immersive learning environments. Collaboration among educators, technologists, and policymakers will ensure that these technologies are implemented effectively and equitably. In conclusion, animation and AR have the potential to reinvent education by creating dynamic, interactive, and inclusive learning environments. By addressing current barriers and embracing emerging innovations, these tools can empower students to thrive in an increasingly complex and technology-driven world.

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The authors declare no known competing financial interests or personal relationships.

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