A Systematic Review of Energy-Efficient Fog Computing in Smart Healthcare

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Abstract: Internet Of Medical Things (IoMT) When combined with Fog Computing, is used to revise smart healthcare systems by sanctioning low-latency, secure, and energy-aware services. Traditional methods like cloud-based infrastructure that suffer from delay and bandwidth, fog architecture brings computation near to the medical devices, so that ensuring faster response times in critical applications such as emergency care, remote monitoring, and telesurgery. This survey methodically reviews more than 30 associate papers studies published between 2020 to 2025, focusing on mainly six domains like fog-cloud integration, blockchain and quantum-enabled security frameworks, AI-driven service placement, federated learning, real-time monitoring, and energy-efficient fog designs. A PRISMA based approach was adopted to ensure transparency in paper selection, tracked by a detailed taxonomy and comparative analysis of latency, scalability, privacy, and energy efficiency across current models. In comparison with past surveys that primarily focus on cloud-fog architecture or general IoT applications, this work individually integrates quantum security, lightweight blockchain protocols, and federated learning approaches into healthcare context. Key research challenges are analysed including interoperability, sustainability, legal compliance, and trust alongside a future roadmap highlighting 6G enabled healthcare, digital twins, and green fog systems. This study targets to provide researchers and practitioners with a comprehensive reference for advancing fog-enabled smart healthcare solutions.

Keywords: Fog Computing, Internet of Medical Things (IoMT), Smart Healthcare, Low Latency, Security, Service Placement, Real-Time Monitoring, Energy Efficiency.

I. INTRODUCTION

The quick use of the Internet of Medical Things (IoMT) has changed healthcare systems by sanctioning endless patient monitoring, real-time diagnostics, and personalized treatment delivery. These applications require ultra-low latency, high reliability, and secure data handling , which is hard to achieve using traditional cloud-centric models due to their centralized nature congestion issues[1],[2].

To solve this problem, fog computing has come up as an intermediary paradigm that decentralizes computation by placing intelligence closer to IoMT devices. This distributed approach actually improves responsiveness, reduces bandwidth overhead, and enables localized decision-making in life-critical scenarios such as telemedicine, remote surgery, and emergency care [3],[4],[5],[6].

While various review studies [7], [8] have inspected fog computing in healthcare, they mainly focus on general IoT-fog architecture or cloud assisted frameworks, with limited emphasis on security,energy efficiency, and next-generation technologies. Moreover, recent advances such as federated learning, blockchain for medical data governance, and quantum cryptography remain uncharted in many surveys.

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II. BACKGROUND CONCEPTS

A. Fog Computing and Cloud Integration

Fog computing expands the cloud paradigm by decentralizing computation near to IoT devices, typically via local gateways or micro data centers. This facilitates decreased response time and supports mission-critical healthcare applications such as real-time ECG analysis, telemedicine, and smart ambulances [1], [4], [9]. Many hybrid modes have been proposed that leverage both cloud scalability and fog responsiveness, allowing resource-intensive analytics to occur in the cloud white time sensitive tasks are processed at the fog layer [10], [11].

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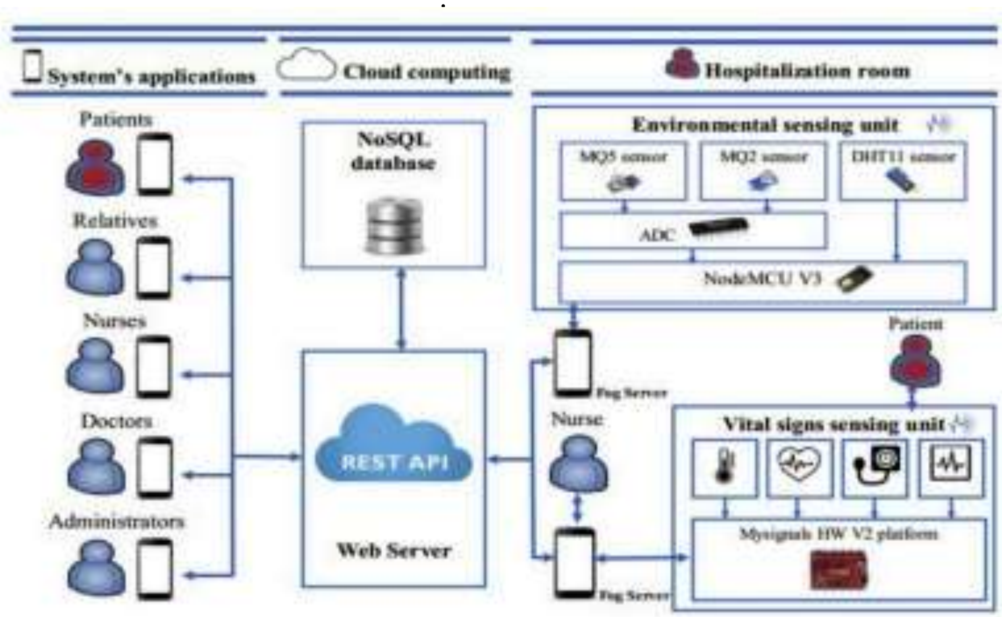

Fig. 1. End-to-end architecture of IoMT-based healthcare system with Fog and Cloud integration [1]

B. Internet of Medical Things (IoMT)

IoMT connects to the ecosystem of interconnected medical sensors, wearable devices, and healthcare systems that generate continuous data streams [2], [5]. These systems need fast, secure, and reliable communication, often involving multiple network hops and computing layers. Typical IoMT architectures carry device-level sensing, fog-based local computation, cloud-level data gathering and user-level interfaces or dashboard [3], [12]. Protocols that are used for managing IoMT cover SDN-based routing [13], QoS-aware scheduling [14], and service placement methods tailored for healthcare needs [15].

III. SURVEY METHODOLOGY

To plan a complete review of fog computing applications in smart healthcare, we chose more than 30 peer-reviewed articles published from 2020 to 2025 from top indexing databases including IEEE Xplore, Springer, Elsevier, MDPI, and ACM Digital Library. The search prompt includes “Fog computing in Healthcare”, “IoMT with Fog”, “Service Placement in Fog”, “Secure Fog Architecture”, and “Energy-efficient Fog Computing”.

The consecutive inclusion criteria were used:

1. Papers majorly addressing healthcare use cases of fog computing or IoMT
2. Addition offering or evaluating architectures, algorithm, or security models
3. Peer-reviewed full-text papers with experimental results or models
4. Publication from reputed Scopus-indexed journals and conferences

Papers were not included if they:

1. Focused on general IoT/fog without healthcare emphasis
2. Lacked clear evaluation metrics or system architecture
3. Were review-only papers without original frameworks

Each paper was manually considered for its architectural design, optimization technique, quality-of-service (QoS) focus, and relevance to medical sketches such as remote monitoring, real-time diagnostics, or emergency care. In terms of core focus areas, we classified the literature into mainly six categories as described below

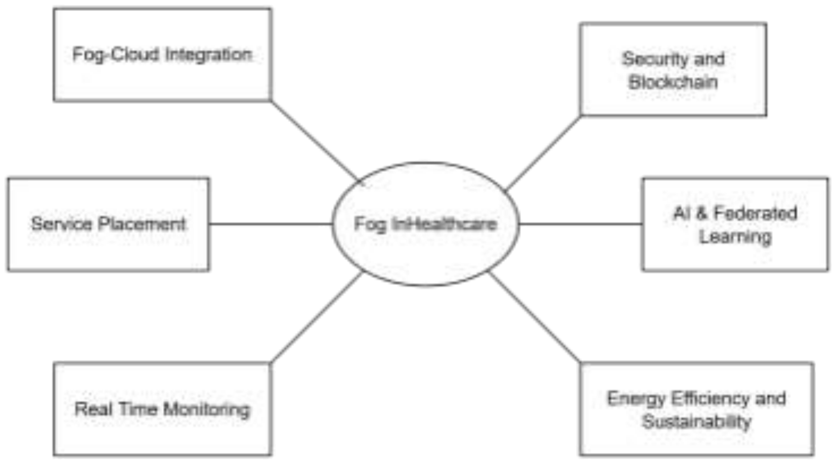

Fig. 2: Taxonomy of Fog Computing in Smart Healthcare

Fig. 2 depicts a high-level taxonomy of key research domains in fog computing for smart healthcare, centered on six core areas. Fog-Cloud Integration emphasizes hybrid architectures that balance latency and scalability, while Security and Blockchain focuses on privacy-preserving frameworks for sensitive medical data. AI & Federated Learning represents intelligent, decentralized analytics, and Service Placement addresses optimal allocation of computational tasks across fog nodes. Finally, Real-Time Monitoring and Energy Efficiency & Sustainability highlight continuous patient data processing and low-power fog designs essential for long-term, reliable healthcare deployments.

IV. LITERATURE CLASSIFICATION

A. Fog-cloud Integration in Healthcare

Fog-cloud integration set up real-time responsiveness in healthcare systems by distributing computation across edge, fog and cloud layers. Sharma and Gupta [1] popularized a hybrid architecture for home healthcare monitoring that advantages fog nodes for low-latency analysis. Gupta and Das [6] suggested a patient-centric computational health system focusing real-time cloud support.

Moreover, Shah [10] abstracted the interoperability and latency challenges faced during IoT-fog-cloud transitions, while Qureshi and Ali [7] addressed cost-performance trade-offs in fog environments.

B. Security and Blockchain in IoMT

Privacy and security are most crucial in healthcare, given the sensitive data of patients. Patel and Mehta [2] recommended key security challenges and proposed lightweight encryption protocols for IoMT environments. Shah [10] discussed fog assisted privacy layers that bridge cloud-fog interactions.

Quantum-inspired healthcare systems by Kim and Singh [6] offers secure wearable frameworks by implementing fog and quantum cryptography principles. Blockchain mixture was explored in other works for distributed access control and audit trials [5], [13].

C. Optimization of Service Placement

Effectual service placement boosts latency, reliability and resource usage. Deshmukh et al. [12] designed a TLBO-based method for placing healthcare service in fog layers. Mahajan and Bose [14] enhanced service deployment through JAYA-GA hybrid metaheuristics.

Das [13] proposed Qos-aware fog node placement mechanisms using dynamic IoT metrics. Various works indicate scalability-aware fog placements using multi-objective algorithms [15], [27], [28].

D. AI and Learning Models

AI-driven methods boost flexibility in fog networks. Roy et al. [3] provided federated learning to approve real-time system disruption detection in Industry 4.0, reducing latency and improving fault tolerance. Sharma and Arora [4] combined SDN and fog for smart decision-making in IoT Healthcare.

Appearing tendency also point to serverless AI models [24], reinforcement learning for fog orchestration, and learning-based energy schedulers [10], [22].

E. Real-Time Monitoring and Embedded Systems

Real-time healthcare needs embedded intelligence at the edge. Joshi and Zhang [9] surveyed embedded monitoring device that work with fog nodes for ECG, oxygen, and glucose tracking. Das [13] demonstrated remote pain monitoring using fog supported sensors.

Roy et al. [3] and Singh [6] designed fog-assisted emergency systems for continuous patient surveillance with ultra-low delay.

F. Energy Efficiency and Sustainability

Energy-aware fog designs aim to minimize power usage without sacrificing QoS. Wang and Kumar [22] conducted a broad survey on energy-saving strategies in fog systems. Qureshi and Ali [7] addressed energy-throughput optimization in smart hospital IoT frameworks.

Kim and Singh [6] incorporated quantum-efficient routing in wearable fog-assisted systems. CDN placement techniques proposed by Sharma et al. [29] reduced redundant transmissions, improving sustainability.

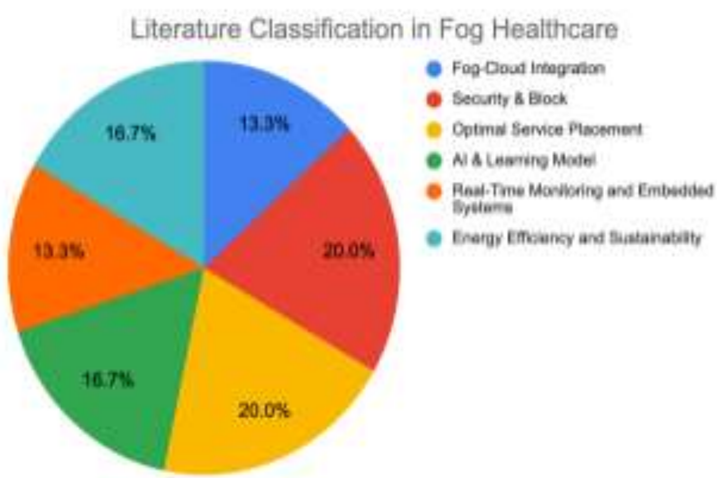

Fig. 3. Literature Classification in Fog Healthcare

Figure 3 presents the distribution of research focus areas in fog computing healthcare literature, categorized into six primary domains. The analysis reveals that Fog-Cloud Integration and Security & Block technologies each represent the largest research segments at 20%, highlighting the dual emphasis on hybrid architectures and data protection in healthcare fog systems. AI & Learning Models and Optimal Service Placement each account for 16.7% of the literature, demonstrating significant attention to intelligent systems and resource optimization strategies. The remaining research is distributed between Real-Time Monitoring and Embedded Systems (13.3%) and Energy Efficiency and Sustainability (13.3%), indicating comprehensive coverage of both foundational IoT infrastructure and environmental considerations in fog healthcare deployments.

TABLE 1:
COMPARISON OF KEY FOG-BASED HEALTHCARE RESEARCH PAPERS

Paper	**Focus Area**	**Optimization Technique**	**Latency Improved**	**Security Enhanced**	**Energy Efficiency**
Ijaz [1]	Fog–Cloud Integration	Heuristic Architecture	Yes	Moderate	Moderate
Al Khatib [2]	IoMT Security	Lightweight Encryption	Moderate	Yes	Low
Roy [3]	Federated Learning	Federated Learning	High	Moderate	Moderate
Sarkar [4]	SDN-Based Fog	SDN Control Flow	Yes	Moderate	Low
Song [6]	Quantum Secure Wearable IoT	Quantum-Inspired Scheduling	High	Yes	High
Ahmed [7]	Energy Optimization	Priority-based Allocation	Moderate	Moderate	High
Baskar [12]	Service Placement (TLBO)	TLBO	Yes	Low	Moderate
Singh [14]	Fog Node Placement (JAYA-GA)	JAYA-GA Hybrid	Yes	Moderate	Moderate
Baranwal [13]	QoS-aware Node Placement	Modified TOPSIS	Yes	High	Moderate

Table 1 compares key fog-based healthcare studies in terms of focus area, optimization technique, and performance outcomes. Approaches such as heuristic architectures, lightweight encryption, federated learning, and SDN control flow mainly improve latency and security, while priority-based allocation and TLBO focus on energy optimization and service placement. Quantum-inspired scheduling shows high efficiency across all metrics, whereas node placement strategies (JAYA-GA, TOPSIS) provide balanced improvements. The analysis reveals that individual methods optimize specific goals, highlighting the need for integrated frameworks to achieve holistic performance.

V. RESEARCH CHALLENGES IN FOG-BASED SMART HEALTHCARE

Despite the rapid adoption of fog computing in healthcare, several critical challenges hinder its full-scale implementation. These issues span across architectural, operational, and ethical dimensions.

1. Latency and Real-Time Responsiveness

Many healthcare applications, such as remote surgeries, continuous monitoring, and emergency care, demand ultra-low latency. However, latency control is still a challenge due to dynamic network traffic and heterogeneous fog node capabilities [1], [3]. Federated learning models attempt to mitigate this [3], but require high-quality edge nodes with GPU support.

2. Service Placement and Load Balancing

Efficient service placement plays a key role in maintaining responsiveness and reliability. Placing computation services too far from users increases latency; placing them too close may overload fog nodes [12], [14], [27]. Multi-objective metaheuristics like TLBO [12] and JAYA–GA [14] improve placement, but balancing performance and energy consumption remains complex.

3. Energy Efficiency and Sustainability

Most fog devices operate on limited energy budgets, making energy-aware scheduling and load distribution essential. Energy efficient strategies like dynamic scheduling [22] and green routing [10] have been proposed. However, sustaining long-term deployments in hospitals and rural areas still poses a challenge [7].

4. Security and Data Privacy

IoMT devices generate highly sensitive patient data. Ensuring secure transmission and access control is mandatory under regulations like HIPAA. Existing encryption schemes [2] and fog-assisted privacy models [10] reduce risks but struggle to support real-time authentication and fine-grained access control.

Blockchain [5] and quantum-inspired frameworks [6] offer advanced security solutions, though their integration into lightweight fog environments is still evolving.

5. Scalability and Resource Management

As the quantity of medical gadgets that are connected increases, maintaining system scalability without compromising performance is a challenge. Resource bottlenecks can lead to packet drops, service denial, or device failures. Dynamic orchestration using SDN [4] and serverless resource models [24] are under exploration.

6. Interoperability and Standardization

Fog deployments vary in protocols, middleware, and service APIs. Lack of standardization in healthcare-focused fog implementations causes integration issues. Studies emphasize the need for unified fog-healthcare standards [10], [17] and vendor-agnostic deployment frameworks.

7. Reliability and Fault Tolerance

In life-critical systems, even brief fog node failures can endanger patient health. While backup services and replication models have been suggested, real-time failover mechanisms in fog–cloud systems are not yet mature [6], [18].

8. Ethics, Trust, and Legal Concerns

Patient data distribution over decentralized fog networks raises legal and ethical concerns. Issues include cross-border data transfer,trust in fog service providers, and patient consent mechanisms. Emerging literature explores data governance in distributed medical platforms [25].

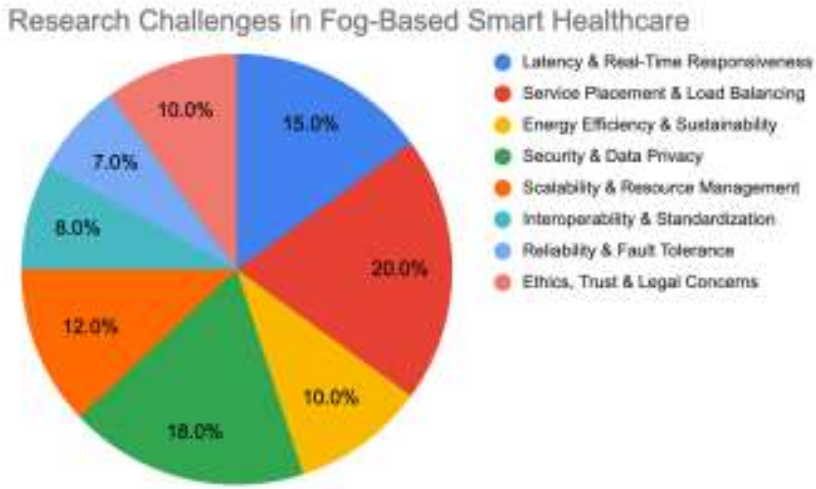

Fig. 4. Research Challenges in Fog-Based Smart Healthcare

Figure 4 illustrates the distribution of key research challenges in fog-based smart healthcare systems, with Service Placement & Load Balancing representing the largest challenge at 20% of research focus. Security & Data Privacy concerns account for 18% of the literature, highlighting critical issues around protecting sensitive patient data in distributed fog environments. Latency & Real-Time Responsiveness (15%) and Energy Efficiency & Sustainability (12%) represent significant operational challenges, while Scalability & Resource Management (10%) and Interoperability & Standardization (8%) address system integration issues. The remaining challenges include Reliability & Fault Tolerance (7%) and Ethics, Trust & Legal Concerns (10%), emphasizing the comprehensive nature of barriers facing fog healthcare deployment.

Fig. 5. Research Challenges by Publishers (2020-2025)

Figure 5 presents the distribution of fog computing research challenges across major academic publishers from 2020-2025, with Springer leading publication output at approximately 2,000 papers, followed by ScienceDirect and ACM with around 1,300 and 1,000 publications respectively. IEEE demonstrates significant research focus on Latency and Real-Time Responsiveness and Service Placement & Load Balancing, while Springer shows relatively balanced coverage across all seven challenge categories including Security and Data Privacy, Energy Efficiency, and Scalability. MDPI contributes the smallest volume with around 600 publications, primarily focusing on Interoperability & Standardization and Reliability & Fault Tolerance challenges. The data reveals that Security and Data Privacy and Service Placement & Load Balancing consistently receive the highest research attention across all publishers, indicating these as the most critical challenges in fog based smart healthcare systems.

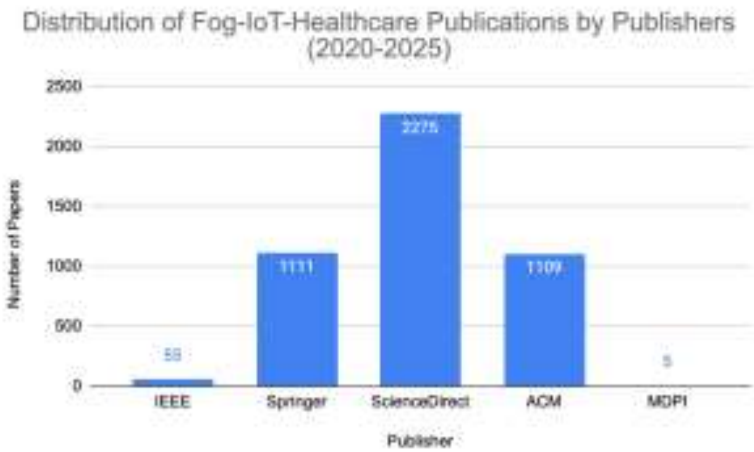

Fig. 6. Distribution of Fog-IoT-Healthcare Publication by Publishers (2020-2025)

Figure 6 illustrates the distribution of fog-IoT healthcare publications across major academic publishers from 2020-2025, with ScienceDirect dominating the research landscape with 2,275 publications, representing the largest contribution to fog computing healthcare literature. Springer follows as the second-largest publisher with 1,111 publications, while ACM contributes 1,100 publications, demonstrating significant academic interest in fog-enabled healthcare systems across these platforms. IEEE shows the smallest contribution with only 66 publications, and MDPI contributes merely 5 publications, indicating concentrated research efforts among the top three publishers. This distribution reflects the growing emphasis on fog computing applications in healthcare IoT systems, particularly in areas such as real-time patient monitoring, data processing optimization, and healthcare service quality enhancement.

CONCLUSION AND FUTURE WORK

In summary, fog computing has updated traditional cloud-centric healthcare by decentralizing computation to edge-proximate fog nodes, enabling ultra-low latency, enhanced security, and energy-efficient operation essential for critical applications such as emergency care, remote monitoring, and telesurgery. Through a PRISMA-based review of more than 30 peer-reviewed papers published between 2020 to 2025, this survey categorizes research into mainly six domains like fog-cloud integration, blockchain and quantum-enabled security, AI-driven service placement, federated learning, real-time monitoring, and energy

efficient fog design and evaluates each for latency, scalability, privacy, and sustainability. While hybrid architectures and robust security frameworks dominate current efforts, advances in AI and optimization techniques are empowering adaptive, resource aware fog platforms. Remaining challenges include interoperability, fault tolerance and ethical governance.

Future work should prioritize the Improvement of High speed connectivity to achieve garnished bandwidth and ultra-reliable low-latency communication for healthcare IoT systems. The integration of digital twin technologies can enable real-time simulation and personalized patient monitoring, advancing predictive healthcare. Emphasis must also be placed on creating standardized and green fog infrastructures that promote sustainability through energy-efficient designs, renewable energy integration, and context-aware resource management. Moreover, future research should focus on improving energy-efficient fog computing through nature inspired algorithms, AI-driven energy optimization, and hybrid fog-cloud task orchestration to support scalable, long-term healthcare deployments. Addressing these areas will facilitate the realization of truly resilient, ubiquitous smart healthcare ecosystems that meet the demands of next-generation medical services globally.

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