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TOPICAL REVIEW

Internet of Things-Based Fuzzy Systems for Medical Applications: A Review

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ABSTRACT The integration of IoT with fuzzy logic provides innovative solutions for various medical applications. IoT enables seamless connectivity between medical devices, real-time monitoring, and data collection. Fuzzy logic has the ability to handle uncertainty and imprecision, thereby enhancing decision-making, medical diagnosis, and treatment. By combining IoT with fuzzy logic, medical providers can develop an intelligent system that improves the quality of healthcare systems. Moreover, the integration of IoT with fuzzy logic enables healthcare providers with powerful predictive analytics capabilities, enabling early detection of diseases and proactive interventions. Several research papers in the literature have investigated the use of IoT with fuzzy logic in medical applications. This review focuses on the use of IoT with fuzzy logic in medical applications. The contributions of this paper are to review the current state of the literature and the potential direction of the medical application of fuzzy system with IoT, and propose a novel scheme that combines Generative Artificial Intelligence (GAI) such as ChatGPT with a fuzzy-based IoT framework. The benefits, challenges, power management, and privacy are also discussed in this paper. The publications are classified according to the type of medical applications. In addition, they are classified according to the type of fuzzy logic used into four categories. We present this review to show the current status in this field. We used Scopus and Google Scholar databases as the basis for presenting this review. The number of publications, number of citations, and other information are discussed to show the achievements in this field. The related research is examined, compared, and classified, focusing on the advantages, challenges, and future research areas.

INDEX TERMS Fuzzy logic, healthcare, medical applications, Internet of Things, wearable device.

I. INTRODUCTION

The convergence of technology and medicine has opened the door to significant advances in healthcare. Among these developments, the combination of fuzzy logic and the Internet of Things (IoT) is a promising new force to revolutionize patient care. The IoT in healthcare is a network of interconnected devices that collect and exchange medical data. These devices include wearable sensors, implantable devices, and medical equipment [1], [2], [3], [4]. This article examines the medical applications of integrating fuzzy systems with the IoT and illustrates their current capabilities and future prospects. The first study on this model was conducted in 2016 [5]. A fuzzy logic-based home healthcare monitoring system was presented to assist the elderly people. A new fuzzy logic-based scheme was developed, with a set of rules governed by medical guidelines. In the same year, the authors of [6] proposed a two-stage fuzzy logic approach. Initially, the user's current activity is monitored and the system provides information related to heart rate. Several studies have been presented, which can be classified into the following categories:

a) Chronic Disease Management [7], [8], [9], [10], in which IoT sensors can track heart rate, blood sugar, and

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temperature. Fuzzy logic can be used to analyze these data and generate alerts regarding possible issues. A fuzzy system may consider factors such as patient age and medical history when explaining slightly elevated blood sugar levels. These studies provide good solutions for modern healthcare requirements as the integration of IoT and fuzzy logic with machine learning gives great potential to improve disease monitoring and diagnosis. However, further study is needed to address practical implementation and ethical considerations.

b) Remote Patient Monitoring [11], [12], where IoT devices can monitor patients in remote locations. Fuzzy logic can be used to interpret the sensor data and identify subtle changes that may indicate worsening conditions. This allows early intervention and improved patient outcomes.

These papers present important applications for the integration of IoT and fuzzy logic in healthcare. They show the potential for improving diagnosis, monitoring and decision-making particularly in chronic disease management and telemedicine support. A practical test is recommended to ensure the effectiveness of the proposed methods.

c) Decision Support Systems [7], [13], in which fuzzy logic can be combined in medical devices to provide decision support for healthcare providers. For example, a fuzzy system may analyze blood pressure readings and suggest medication adjustments based on the current patient condition and medical history. The two papers present patient care management systems, especially in the case of chronic diseases and urgent health state such as COVID-19, using the integration of the IoT and fuzzy logic. It is preferable to benefit from the feedback of healthcare providers and patients to improve the proposed systems and ensure that the actual needs are met.

d) Data Aggregation and Analysis [14] in which fuzzy logic can help optimize data collection and analysis at the edge nodes. This reduces the processing load and ensures that critical data are prioritized for transmission.

Other studies on medical applications consider different cases, like data security and privacy [15], and reduce the processing time by implementing the fuzzy system using a field-programmable gate array (FPGA) [16]. In addition, some studies have considered reducing the energy consumption and increasing the lifetime of devices and sensors [17].

From our first look at the research and studies related to the subject, we found that the idea started in 2016 with simple work, then works developed and took various forms with the passage of time. The proposed works evolved from mere monitoring and measurement to advanced works include data analysis and decision-making. The work continued in its simple form until 2021 and 2022, where more advanced works appeared that used concepts such as machine learning to support and develop the proposed systems, as well as the use of advanced technologies and methods to maintain information security and increase execution capacity and reduce energy consumption. There is no doubt that the combination of fuzzy logic with the internet of things has promising and great prospects in advanced applications, in monitoring and managing the work of health institutions and assisting in analysis and diagnosing diseases and treatment, and we expect a lot of development in this field, especially with the tremendous progress made in artificial intelligence.

The concept of fuzzy logic, inspired by human reasoning and decision-making processes, represents a significant shift from the traditional binary logic. It has been used in many applications, such as classification, control, and robotics [18], [19], [20], [21], [22], [23], and can handle imprecise data, incorporate expert knowledge into decision-making processes, and modelling of complex relationships between variables. This makes fuzzy logic particularly well suited for analyzing and interpreting real-world medical data collected through IoT devices. The merging of fuzzy systems and the IoT generates a new track of intelligent healthcare systems that have capabilities similar to human cognition. By integrating fuzzy logic into IoT frameworks, medical devices can correctly interpret and analyze data. This enables healthcare providers to enhance diagnostic accuracy and treatment efficiency. The increase interests in this paradigm encourage us to provide this review. The purpose of this review is to explore and categorize the current state of research on medical applications of IoT and fuzzy logic and to propose a new scheme that combine Generative Artificial Intelligence with in the fuzzy based IoT framework. To the our knowledge, there is no review study on the use of IoT with fuzzy systems in medical applications. The review in [24] presents the fuzzy logic-based systems for the diagnosis of various diseases. It focuses on different fuzzy models adopted in healthcare systems. The work in [25] presents a survey of IoT based edge- intelligent health care. The article in [26] aims to identify, compare, and categorize the present related studies. The article in [27] provides a review of works on IoT-based healthcare systems. The work in [28] presents a detailed study on IoT adoption in healthcare, focusing on sensor types and communication schemes. While our review focuses on using IoT with fuzzy systems for medical applications. The review will categorize the current state of researches based on application and on type of fuzzy system used. It also propose a new intelligent scheme based on using Generative AI (GAI).

We believe that this paper will provide good ideas for those interested in this field for their future work. The aim is to give review on existing works in IoT with fuzzy system for medical applications. In order to attain this aim, a search has been made for documents with (''internet of thing'' OR IoT) AND fuzzy AND (healthcare OR ''medical applications'') terms was made on Scopus database and Google Scholar. To obtain more related documents, the search also consider terms like ''patients monitoring'', OR ''diseases diagnosis'' OR prediction for the years from 2016 to 2024.

The main contributions of this review are:

1. Explore, study, and categorize the current state of researches on using IoT with fuzzy system for medical applications.

2. Develop a novel intelligent scheme based on using GAI with the fuzzy based IoT framework for healthcare.
3. Classify the researches according to the type of application, and then according to the type of fuzzy system.
4. Identify the benefits and challenges and propose solutions to address the challenges.
5. Suggest ideas for future works.

The rest of the paper is arranged as follows: Section II presents the methodology and statistical results. Section III presents the basic concept of integrating fuzzy logic with IoT for medical applications. Section IV describes medical application examples. In section V the developed scheme is presented. A literature review is presented in section VI. A discussion is presented in Section VII. Finally, the conclusions are presented in Section VIII.

II. METHODOLOGY AND STATISTICAL RESULTS

We followed the PRISMA systematic review process to identify studies and narrow down the results for this review. The review process includes three consecutive steps, namely identification, screening, and eligibility testing. In the first step, papers were identified through Google Scholar and Scopus database searches. We carry out a search for all publications with the strings (''Internet of things'' OR IoT) AND Fuzzy AND (Healthcare OR ''medical applications'' OR ''patients monitoring'' OR prediction OR ''diseases diagnosis'') in the title of the document, in the years from 2016 to 2024.

The number was 104, including 46 from Google Scholar and 58 from Scopus database search. In the second step, duplicate and non-matching papers were removed, after this step, 72 papers were selected. Then, in the final step, which is the eligibility testing step, we removed papers that were not related to our topic, where the remaining 60 papers were included in the review.

The tables and figures in this part were prepared based on the results of the search on Scopus database. The number of published documents up to September 18, 2024 was 58. Figure 1 shows the number of documents published each year since 2016. Figure 2 shows the citations number. (no citation in the years before 2018).

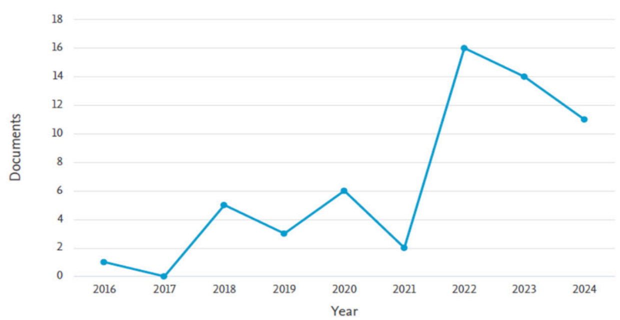

FIGURE 1. The number of documents against year.

Table 1. Shows the number of papers for each journal for the first 10 top sources.

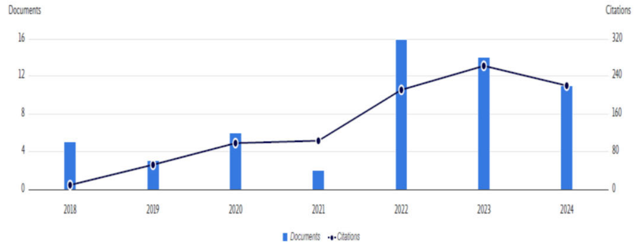

FIGURE 2. The citations number against year.

TABLE 1. Documents per source.

Source	Documents
IEEE Internet Of Things Journal	3
Journal of Intelligent And Fuzzy systems	2
Journal Of Supercomputing	2
Scientific Reports	2
Advances In Intelligent Systems And Computing	1
Applied Sciences Switzerland	1
Cluster Computing	1
Computer Communications	1
Computers In Biology And Medicine	1
Computers Materials And continua	1

Figure 3 shows the number of documents per country, and Figure 4 presents the number of documents per affiliation. Figure 5 shows document by type.

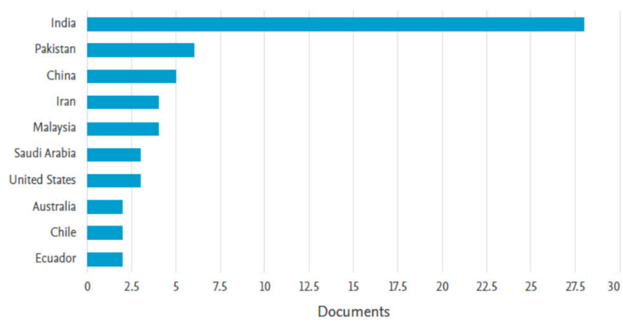

FIGURE 3. Documents number per country.

Figure 1 shows that the search terms first appeared in a publication in the year 2016. Notably, the number of related publications remained relatively modest until 2022, at which there was a significant jump, with the number rising from 5 at 2020 and 1 at 2021 to 16 at 2022 so the path of development is promising. From Figure 2 which shows the number of citations per year. In 2016, the first publication on the search terms emerged, with its first citation appearing in 2018. The number of citation per year remained low. In 2022 the number of citations becomes 211 and 262 in 2023. This large jump in the number of citations is likely due to rising interest in newly developed systems. Since 2022, a notable increase is observed, with large growth from 2016 to 2023, likely due to

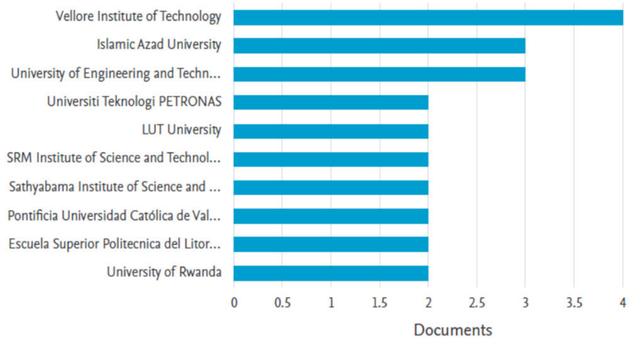

FIGURE 4. The number of documents per affiliation.

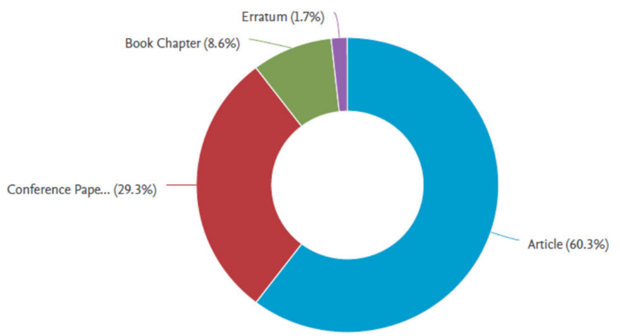

FIGURE 5. Documents by type.

rising interest in newly developed systems. The total citations from 2016-2023 is 955, trend suggests that the total citations in 2024 will significantly exceed previous years, likely due to rising interest in newly developed fuzzy based IoT systems. Results indicates that the total citations in 2024 will significantly exceed previous years, indicating an increased scholarly interest in the subject.

The documents are published in a high impact journals, as shown in Table 1. that includes the ten journals that most publish these documents. The most publishing journal is the journal ''IEEE Internet of Things Journal'', which is known to be an excellent, Q1 journal. Figure 3 shows the distribution of published documents by country. It shows that the list includes many different countries. By observing Figure 4 which displays the names of the universities and scientific institutes to which the researchers belong, it appears that they are reputable, international scientific institutions. From this, we conclude that this research topic has attracted the attention of many researchers from universities and scientific institutes in different countries, and the global scientific community has become interested in this topic. We attribute this to the development of internet technology and artificial intelligence and the desire to enter the world of automation in all life activities such as smart cities, smart hospitals, and others.

III. INTEGRATING FUZZY LOGIC WITH IoT

The integration of the two technological domains of fuzzy systems with IoT in healthcare leads to unique capabilities that contribute to a complete system. Essentially, fuzzy logic enables the modeling and reasoning of imprecise, uncertain, and incomplete information, simulating humans when dealing with ambiguity [29], [30], [31], [32]. The IoT includes a network of interconnected devices with sensors, actuators, and communication modules, providing a seamless exchange of data and enabling real-time monitoring and control.

A. INTERNET OF THINGS

IoT is a network of interconnected devices with sensors, actuators, and communication modules, allowing them to collect, transmit, and exchange data with minimal human involvement. These devices have many applications like monitoring, automation, and healthcare. Figure 6 shows the applications of IoT [33]. The IoT can connects the digital and real-world applications through real-time data acquisition and analysis. Data from sensors are collected and transmitted to servers or cloud form platforms for processing, analysis, and storage and may perform actions through actuators based on sensor data [34].

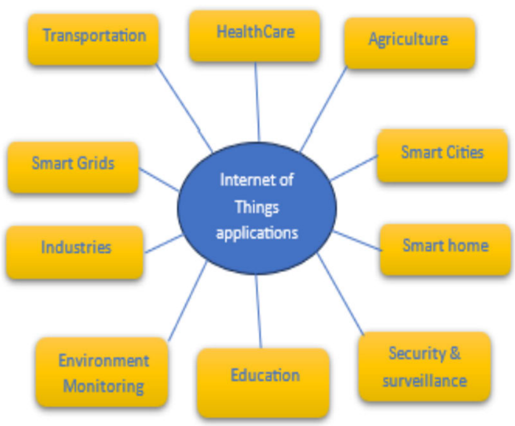

FIGURE 6. Application of internet of things [33].

The IoT includes connectivity and scalability for seamless integration and communication between heterogeneous devices and systems. IoT devices can form network connections and exchange data over short or long distances, enabling remote monitoring and control tasks through wireless communication protocols, like Wi-Fi, Zigbee, Bluetooth, and cellular networks. IoT standards and protocols like MQTT, CoAP, and HTTP allow interoperability between devices and platforms, thereby ensuring compatibility and integration [35]. Fog computing is used to solve cloud computing restrictions and avoid the difficulties associated with IoT applications. Fog computing bridges edge users and cloud [36].

Moreover, IoT architectures encompass edge-computing paradigms, wherein data processing and analysis are performed near the data source at the edge of the network. Edge computing allows real-time data processing suitable for healthcare, where rapid decision making is required [37]. The major components of IoT-based smart healthcare systems are shown in Figure 7 [38].

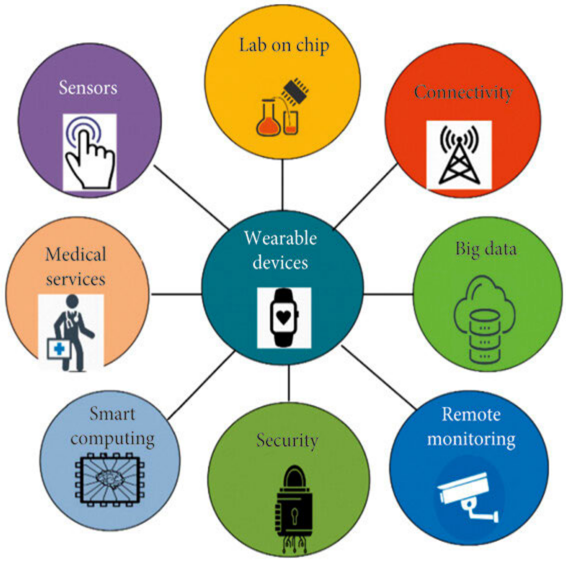

FIGURE 7. Typical components of IoT based smart healthcare [38].

B. FUZZY SYSTEM AND MEDICAL APPLICATIONS

Fuzzy logic differs from conventional binary logic because it accommodates imprecision, uncertainty, and ambiguity. In healthcare systems, fuzzy logic provides a powerful framework for interpreting complex medical information in healthcare systems. The basic concept in medical applications of fuzzy systems lies in their ability to simulate human-like reasoning and decision-making in the medical field. Conventional medical decision-making processes experience difficulties in handling the uncertainty and variability in clinical data, leading to challenges in diagnosis and treatment planning. Fuzzy systems can handle imprecise and uncertain medical data and solve these problems [30].

Fuzzy systems use linguistic variables and fuzzy rules to represent the uncertainty and ambiguity present in medical data and to determine the relationships between the input variables (patient symptoms and laboratory results) and output variables (diagnoses and recommendations) [31]. Figure 8 shows the structure of the fuzz system. Fuzzy systems can handle imprecise and incomplete information, and operate effectively in situations where data are uncertain or ambiguous. This makes fuzzy systems more suitable for medical applications such as medical diagnosis and patient monitoring [32]. In many works type2 fuzzy logic (T2FL) is considered, which is proposed to better represent the uncertainty [39]. The membership value for each element of a T2F set is a fuzzy set in [0, 1], which captures more information regarding the described item. T2F sets are used in cases where it is difficult to determine the exact and specific membership function of a fuzzy set [40]. T2 fuzzy sets can model uncertainties in a situation where it is impossible for T1 fuzzy set [40], [41]. Figure 9 shows the structure of T2F system.

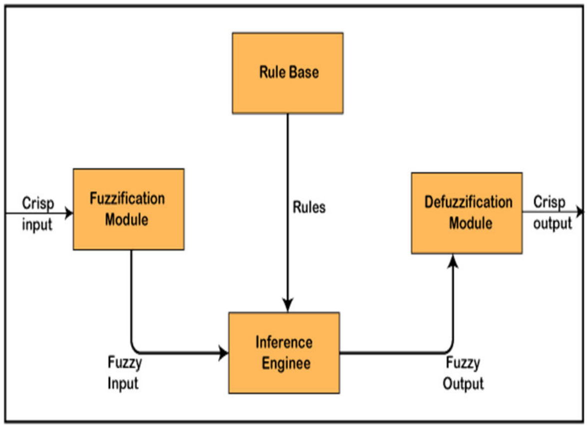

FIGURE 8. The structure of fuzzy system.

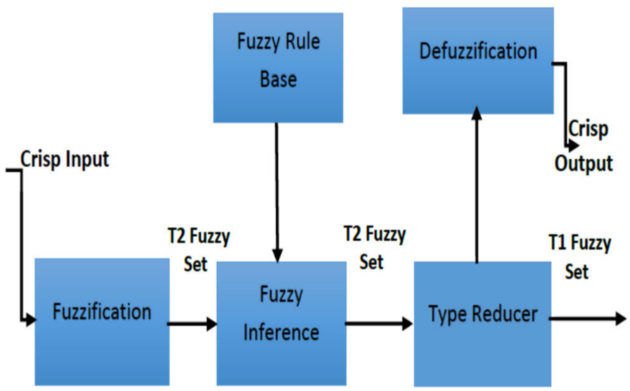

FIGURE 9. The structure of T2F system.

IV. MEDICAL APPLICATIONS EXAMPLES

The integration of fuzzy systems with IoT results in a new track of healthcare systems that have capabilities similar to humans, and enables the modeling and reasoning of imprecise and uncertain information in a manner similar to that of humans in dealing with ambiguity. The following two examples (case study) illustrate two different applications:

A. MEDICAL DIAGNOSIS AND MONITORING EXAMPLE

This example demonstrates how fuzzy logic and IoT can be combined to enable real-time medical diagnosis and monitoring, thereby providing valuable insights and alerts to both patients and healthcare providers. Consider the case of a patient wearing a health monitoring device equipped with four sensors: blood pressure, temperature, heart rate, and oxygen saturation sensors. Continuous data on the patient signs were collected using these sensors. IoT devices continuously receive patient data and send them to a central server or a cloud-based system for analysis. Fuzzy logic was used to analyze the received medical data. Fuzzy logic can assign a degree of membership to various categories based on a patient's signs. The degree of membership reflects the degree to which a patient's signs match the typical patterns associated with different health conditions. A fuzzy rule-based system can be designed using a set of rules based on medical knowledge [2], [5]. For example, a rule may take the form if the blood pressure is low and the heart rate is high then there is a high possibility of being in state of dehydration. Based on the concept and results of the fuzzy rule-based system, the IoT scheme can provide real-time diagnosis or alerts to the patient or healthcare providers and monitor the patient's state, so that it can adjust the analysis and advice based on the current condition of the patient.

B. PLANNING EXAMPLE

Fuzzy logic with an IoT scheme can be adopted in healthcare treatment planning to enhance patient results and decision making. Consider the case of a diabetic patient using a smart insulin pump, and assume that diabetic patients need insulin therapy to manage their blood sugar levels. Normally, insulin doses are computed on the basis of fixed rules and measurements. With a fuzzy-based IoT scheme, the pump can be connected to several sensors that continuously collect real-time data on the condition of the patient. The fuzzy system can analyze data and generate certain insulin dosage recommendations. By continuously adjusting insulin dosages based on real-time data and fuzzy logic reasoning, a smart insulin pump can optimize glycemic control, while minimizing the risk of low blood sugar levels and other complications. Moreover, IoT enables remote monitoring by healthcare providers, allowing them to intervene or adjust treatment plans as needed based on insights derived from continuous data streams [12], [15], [42]. Thus, the combination of fuzzy logic and the IoT enhances treatment planning in diabetes care by providing personalized, adaptive, and data-driven approaches to insulin therapy.

V. GENERATIVE AI-BASED FUZZY SYSTEM WITH IoT FOR HEALTHCARE

Generative AI has emerged as a significant mean that contributes to the evolution of the healthcare setting [43], [44], [45]. It plays a crucial role in increasing the efficiency of healthcare providers. This technology provides basic information about symptoms, and treatments, it plays an important role in determining the type of disease.

In this section, we propose an advanced healthcare system that integrates (Generative Artificial Intelligence) GAI, fuzzy logic, and the IoT. It can be used for real-time data collection, adaptive learning, and intelligent decision making to improve patient care and operational efficiency of healthcare system. This system uses IoT devices to collect health data, applies fuzzy logic to make decisions, and uses generative AI to predict outcomes and generate actionable insights. The GAI Assists healthcare providers by generating recommendations for diagnostics and treatments based on fuzzy logic evaluations and patient history. A generative AI-based fuzzy healthcare system utilizing IoT offers a new approach to modern medicine. By combining advanced technologies, it enhances patient outcomes, optimizes care delivery, and addresses the complexities of healthcare decision-making. This integration holds the potential to strongly improve the healthcare aspect into more efficient model.

In this advanced approach, fuzzy system handles uncertainty and imprecision in patient data, enables a more human-like reasoning process for diagnoses and treatment plans, and incorporates expert knowledge to evaluate patient conditions through fuzzy rules. On the hand GAI analyzes data patterns to creates a personalized treatment programs based on individual health data, patient history, genetic factors and the result of the fuzzy system to support professionals in decision-making. In fact, GAI has become an essential component of the IoT healthcare framework.

VI. RELATED WORKS

Many medical application schemes have been proposed that integrate IoT with fuzzy logic. In this part, a review of medical applications based on fuzzy logic with the IoT is presented. The publications are classified into four categories: using type1 fuzzy logic, using type2 fuzzy logic(T2FL), using fuzzy neural networks, and using fuzzy system with machine learning techniques and optimization algorithms. We found in the literature, works that use fuzzy logic with several machine learning methods like Support Vector Machine (SVM), Random Forest (RF), and Neural network(NN). Other works use fuzzy logic and optimization algorithms like Genetic Algorithm (GA), Particle Swam Optimization (PSO). The latest innovative technologies were considered in this study. The contribution would be highlighted with a discussion of the limitations of related works. This work aims to show the advantages and challenges of merging the IoT with fuzzy logic for medical applications.

It is noticed that one study used a type1 fuzzy ontology, and two works used type 2 fuzzy ontology. Fuzzy ontology is an extension of the traditional ontology that incorporates the principles of fuzzy logic to handle uncertainty and vagueness in knowledge representation [46], [47], [48]. The first study was included in the type1 fuzzy group and the other two were in the type2 fuzzy group. Also one study used the intuitionistic fuzzy sets which have been found to be useful to deal with vagueness or lack in the information available [49]. It was included in the type1 fuzzy group.

A. TYPE 1 FUZZY SYSTEM WITH INTERNET OF THINGS

Many articles consider to present medical applications of IoT with fuzzy system.

In [5], the authors presented an in-home healthcare-monitoring system. The main idea is to use several sensors at home to enable controlled care of elderly patients. The data scheme, which use fuzzy system, is based on medical instructions. The developed work Assists independence for elderly individuals while guarantee care provider monitoring.

It uses several sensors for better monitoring. Also using fuzzy system allows for adjustable care advices. However, the effectiveness of the system depends on the reliability of sensors and it may need more testing to check the efficiency of the system in different environments. In [6], the authors presented a fuzzy logic approach for monitoring users' routine activities. The current activity of the user is monitored, and the system provides information regarding the heart rate. The study in [42] tested the appropriateness of a hierarchal fuzzy system for classifying data. It considers a test case to predict the disease spread. Different cases are created to examine the efficiency of the proposed system. Different case studies are considered to test the efficiency of the presented method. The idea of using hierarchal fuzzy in this approach may solve the complexity problem. This study addresses the challenges that arise from the rapid proliferation of healthcare IoT devices, which generate large amounts of data, leading to network bottlenecks and increased latency. In [50] a fuzzy based fog computing architecture is proposed that integrates healthcare IoT with cloud systems. The fuzzy data packet allocation algorithm aims to optimize data transmission, ensuring the delivery of patient health information to healthcare providers. The proposed system takes into account the critical issues of time and data movement in healthcare IoT networks. It uses fuzzy with fog computing to optimize real-time data processing and transmission. However, the implementation complexity may pose challenges in practical applications. Additional experimental tests are needed to evaluate the performance of the developed algorithm.

The study in [51] presented a conceptual scheme for a smart home with electronic health support using IoT and fuzzy logic, which receives inputs from sensors and produces outputs to support sick or aged people efficiently. The implementation of this work in smart homes may give more efficiency in healthcare support. A study in [52] presented a healthcare system for elderly people using a fuzzy system to evaluate stress and physical health. This system can save lives by providing timely medical assistance. The work needs more experimental test.

This study in [53] presents a fuzzy system for diagnosing stress levels using temperature sensors, galvanic skin response, and heart rate. The data are processed and displayed online. Out of a total of 15 participants, 80% were diagnosed with stable stress levels, indicating the effectiveness of the system in monitoring stress. This system provides a practical tool for assessing stress. However, its dependence on a small sample size may limit its applicability in wider application. Further research would validate the effectiveness of the system.

The study in [16] proposed a fuzzy classifier to accurately determine the pathological conditions of a disease. The classifier was implemented using an FPGA to reduce the execution time. The use of FPGA increases the efficiency but the implementation difficulty may pose challenges in practical adoption. Further testing is required to check the performance in different environments. In [17], a fuzzy logic-based clustering technique for internet of medical things applications was proposed to reduce energy consumption. Simulation results validated the proposed system. The article in [54] considers the stabilizing electronic-loyalty to healthcare services in the area of IoT. It evaluates electronic-loyalty among 29 experts using the fuzzy analytical hierarchy process, finding that electronic loyalty, satisfaction, and information privacy are crucial factors, exceeding perceived benefit and personal innovation outweighing perceived benefit and personal innovation. In general, the work highlights the significance of IoT in healthcare. Authors discussed the main factors influencing electronic loyalty, emphasizing the ultimate need for privacy and satisfaction in electronic health services. The study in [55] considered the enhancement of IoT capability in healthcare based on the utilization of fuzzy techniques, reducing costs with advance treatment outcome. The implementation of the proposed method may face challenges in real-world application. Further test is needed to support theoretical results. The work in [56] presented a system that measures heartbeat and analyzes the measured data using an Arduino-based analyzer to determine whether the heart is normal or damaged. The proposed method is useful in early detection. Authors in [57] develops a data aggregation method based on using fuzzy logic for IoT healthcare, aiming to improve network life time. Results show good improvement. It outperformed other works by 5–20%. The study presented an efficient aggregation method, enhancing IoT healthcare applications, but it may need additional validation. In [58], the authors presented an intelligent classifier for disease prediction using a fuzzy system. It uses cloud and IoT based databases. The study in [59] presents a system for monitoring patients' vital signs. The system cleans environments and measures parameters like oxygen saturation and temperature using IR sensors and fuzzy logic. The data is processed and displayed online, facilitating health monitoring and reducing disease transmission risks. The developed system considers public health challenges, especially during pandemics. It offers a practical solution for remote health monitoring, enhancing patient safety and care efficiency. This approach may significantly aid patient care. The article in [60] introduces a fuzzy logic-based privacy-aware algorithm designed to protect sensitive healthcare information. It addresses the risks of privacy opening due to multiple sensitive attributes in patient data. Experimental results indicate that the model significantly reduces information loss while maintaining query accuracy compared to existing solutions. The proposed algorithm is crucial for ensuring patient privacy. Its effectiveness in balancing data benefit and privacy protection makes it a valuable tool for safeguarding health information. The work in [61] proposes an IoT-based approach designed to enhance the Algerian healthcare system response to COVID-19. It emphasizes early detection and resource management through a semantic web system that accommodates data heterogeneity. Fuzzy ontology helps manage fuzzy medical data. The system shows effectiveness in managing health crises. The integration of IoT into public health management could revolutionize pandemic response strategies. This approach not only addresses COVID-19, but is also adaptable to future health crises. The work in [62] introduces a new remote healthcare system utilizing IoT and fuzzy systems to enhance data analysis efficiency. The method achieves a 12% accuracy improvement, 56% faster analysis, and reduces energy consumption by 54%. This study addresses significant challenges in remote healthcare, particularly in developing countries The method effectively enhances data processing and energy efficiency, making it a valuable contribution to the field. The promising experimental results demonstrate its potential impact on stress detection and overall healthcare decision-making. However, further validation in diverse real-world scenarios would enhance its applicability and robustness. Overall, the research offers a significant advancement in remote healthcare analytics.

The study in [63] presents a Chronic Kidney Disease (CKD) monitoring system for early detection of cardiovascular disease and anemia using fuzzy logic. The model is simulated in MATLAB and Simulink, receiving and processing ECG and PPG inputs to determine heart rate and blood oxygen saturation, achieving results within normal ranges. The system, implemented on an ESP8266 microcontroller, demonstrated 100% accuracy in detecting patient status and 99% accuracy compared to a commercial pulse oximeter. The work addresses early health monitoring of CKD patients, using fuzzy logic with IoT for real-time data analysis. The high accuracy rates in both simulation and real-time implementation indicate the reliability of the model. In general, the study provides a valuable approach to improve patient monitoring and care in chronic diseases.

The work in [11] aims to demonstrate a disease diagnosis scheme that uses the IoT and a fuzzy system to diagnose different diseases. It combines sign tracking with fuzzy logic for disease diagnosis. The system may need additional clinical testing. In [64], the authors presented a rule-based fuzzy system with IoT for elderly patients with cardiac issues. Medical treatment depends on data, like blood pressure, blood sugar, and cholesterol levels. The health care expert receives an alarm only when emergency medical treatment is wanted. Results show that the presented method use 8 times less power than the normal method.

In [65], an IoT-based monitoring system was proposed and implemented using fuzzy logic and a microcontroller for patient-health monitoring. The developed system can be used to help elderly individuals and patients with chronic disease. However, it may need further verification by conducting a number of practical tests under different conditions. The article in [66] presents a system that combines IoT and fuzzy logic for monitoring and diagnosing cardiac arrhythmias in COVID-19 patients. It employs advanced sensors and cloud computing to make possible remote healthcare. The algorithm achieved almost 100% accuracy in ECG data analysis. The system addresses critical healthcare needs, particularly for isolated patients, through automating diagnosis. The ability of the system to work effectively without direct physician collaboration can improve patient outcomes during health crises.

The work in [67] develops an IoT- based cloud- fuzzy expert system to evaluate the level of severity of COVID-19 patients. The system uses data from wearable devices to monitor health every five minutes, and to notify families and doctors if conditions become worse. The system offers a proactive approach to patient monitoring. However, its effectiveness depends on the availability of wearable devices and data privacy considerations, which need precise attention. The work in [68] introduces an IoT and cloud-based framework that uses self-assessment data and hesitant Intuitionistic Fuzzy Set (IFS) techniques in the COVID-19 pandemic to predict infection risk. This approach benefits from technology to enhance pandemic response through data-driven risk assessment. The integration of IoT and cloud solutions could improve tracking and early intervention. However, the implementation challenges and data privacy concerns need to be addressed for wider acceptance. The suggested approach in [69] adopts IoT and fuzzy logic to collect and analyze health data from COVID-19 patients using wearable sensors. The fuzzy classifier aids in data fusion, enabling real-time monitoring and decision-making. Experimental results show that this method outperforms traditional algorithms in accuracy. This method enhances remote healthcare monitoring during the pandemic. The superiority of the system over traditional models indicates that it has good abilities for applications in urgent medical settings. In [7], an IoT-based intelligent system was presented for monitoring, diagnosing, and treating patients. This study presents an IoT- based fuzzy system for monitoring and treatment of COVID-19 patients, using Arduino. The system effectively combines IoT and fuzzy logic, providing timely healthcare solutions. The use of real-time data enhances patient monitoring, though it may face difficulties in practical situation. Table 2 shows a comparison of the methods and techniques using T1 fuzzy system.

B. TYPE 2 FUZZY SYSTEM WITH INTERNET OF THINGS

Medical data often contain inherent uncertainties owing to factors such as variability in patient conditions, imprecision and noise in measurements, and ambiguity in diagnostic criteria. T2FL, with its ability to model uncertainty not only in the data but also in the membership functions, can effectively handle and represent these uncertainties. T2F sets allow the modeling of more complex and higher levels of uncertainty by introducing a secondary level of uncertainty into the membership function itself.

The research in [70] introduces T2FL based recommendation system in IoT-based healthcare to monitor patients and recommend appropriate diets with specific foods and medications. The proposed system determines the patient's risk factor values and health status through wearable sensors and then recommends diabetes-specific prescriptions. The proposed system increased the accuracy of predicting patient conditions and the accuracy of drug and nutritional recommendations. Cloud services are adopted to save and retrieve data for further study and analysis. An experiment is also being conducted on patient data sets and the results of the experiment show that the work presented is effective in improving patient data and providing appropriate recommendations to patients. There is no doubt that using the cloud has an impact on increasing the speed of implementing the required calculations and improving performance, but to ensure reliability we need to conduct more tests to verify the validity of the results. In [71], a new data-fusion model based on T2FL using the dumpster – Shafer theory was developed to produce a correct information and properly derive the result. The simulation with a dataset of heart disease and diabetes showed that the proposed method outperforms existing schemes based on T1FL in terms of decision accuracy. The simulation results showed good performance compared to existing schemes. The work in [13] presents a healthcare recommendation system using IoT-based T2 fuzzy ontology, targeting the management of chronic diabetes. The system monitors patients' physiological data using wearable sensors and recommends specific dietary and medication regimens. By integrating T2FL and ontology, the system enhances the prediction accuracy and recommendation precision. Experimental results illustrate that the developed system is efficient in finding patient risk factors and diabetes prescriptions. The experimental show good performance. The proposed system combines fuzzy logic and ontology to enhance the accuracy of health assessments and recommendations and uses wearable and smart devices technologies in patient care. However, relying on accurate sensor data may affect the results if the sensor performance is inconsistent. Further validation with a diverse patient population is needed to ensure generalizability. The study in [72] deals with the evaluation of medical devices in the healthcare industry using real options analysis combined with T2FL. Since medical devices require significant investment, this method addresses uncertainty during the evaluation process. This study addresses critical investment decisions in medical technology with uncertainty. It uses T2FL to effectively handle ambiguity. It provides a practical application and sensitivity analysis, which enhances the clarity of the decision-making process, but the approach may need to be validated using different healthcare settings for broader application. Potential limitations in data availability may affect the robustness of the analysis. By calculating the probabilistic mean and variance, the study applies the approach to a real healthcare situation, helping organizations determine the timing of their investments.

The study in [73] proposes an IoT-enabled smart healthcare system utilizing T2FL to monitor patient stretchers in remote areas. This system aims to address issues with immovable stretchers by employing fuzzy controller and sensors to enhance monitoring accuracy and reliability. Experimental results illustrate that the developed scheme is more reliable to produce a good monitoring applications through the T2FL.

The authors of [74] investigated the applicability of IoT with T2FL in healthcare systems. The authors proposed a new system for monitoring patients with diabetes using wearable sensors. The experimental results illustrate the effectiveness of the presented system. The T2FL scheme solve limitations in healthcare monitoring system. It provides a promising solution in real-time, enhancing care for chronic disease patients. The work in [75] presents an AI-driven IoT system that adjusts anesthesia depth during surgery. The system uses an adaptive T2 fuzzy systems to enhance control robustness and precision in drug delivery. The system permits for remote adjustments and performs effectively across several patient models. The combination of AI and IoT marks a significant development in anesthesia management, ensuring patient safety and operational efficiency. The adaptability property in the system makes it a valuable tool in modern surgical practices, although real-world trials are needed for validation. Table 3 shows a comparison of the methods and techniques using T2 fuzzy system.

C. FUZZY NEURAL NETWORK WITH INTERNET OF THINGS

A fuzzy neural network, also known as a neuro-fuzzy system, integrates the strengths of neural networks and fuzzy logic. The combined structure incorporates fuzzy logic into a neural network architecture. This allowed them to process the real-world data. Fuzzy neural networks have multiple layers, including an input layer, fuzzification layer, rule-based layer, defuzzification layer, and output layer. Figure 10 shows the structure of a two-input two-rule fuzzy neural network. The work in [76] presented the design of an intelligent system based on IoT and a neuro fuzzy self-learning model. The system monitors patients and supports medical experts in the diagnosis of diseases. The system produced an alert signal for any abnormality. Learning ability enhances decisions regarding disease diagnosis. The system facilitates timely communication between patients and healthcare providers and aims to reduce costs in monitoring. Further validation and testing is needed to ensure reliability in diverse environments.

The study in [77] presents a cloud and IoT- based mobile healthcare system for monitoring and diagnosing serious diseases, especially diabetes. It holds the data from IoT devices and uses a fuzzy rule-based neural classifier to predict the disease. Using data from real health records, the system demonstrates improved performance compared to existing systems in diagnosing the severity of diabetes. The proposed system integrates cloud computing and IoT for effective health monitoring and disease diagnosis. The fuzzy rule-based neural classifier enhances the prediction accuracy. However, further validation under diverse conditions is needed to ensure robustness.

The work in [78] discusses the importance of data delivery and acquisition in Internet of Medical Things (IoMT) systems, considering the issue of missing data that impacts performance. It proposes a dynamic Adaptive Network-based Fuzzy Inference System (ANFIS) for estimating missing values, using complete and incomplete datasets. Results show a 5% performance improvement using Genetic Algorithm (GA) and ANFIS and 3% using Particle Swarm Optimization (PSO) and ANFIS. The study significantly contributes to enhancing data quality in IoMT applications. Additional study on real-world implementations is required.

The paper in [8] proposes a model that uses mobile IoT and cloud storage to predict and assess disease severity. It uses a fuzzy neural classifier, which enhances prediction accuracy compared to existing systems. The model uses a standard dataset with real-time data from hospitals, ensuring secure data access and efficient processing. The results indicate significant improvements in real-time prediction capabilities. The proposed approach combines advanced techniques to improve disease prediction accuracy and uses real-time data, which improves performance. Cloud integration also provides secure data management while reducing cost. However, the complexity of the developed fuzzy neural classifier may pose implementation challenges.

The study in [38] introduced an intelligent healthcare system based on IoT and Fuzzy Neural Networks. The system was developed for people in remote areas to determine whether they were suffering from a serious health problem and were treated by contacting nearby hospitals. It aims to bridge critical healthcare gaps in remote areas, enhancing accessibility. Supporting improved efficiency and lowering costs. Timely diagnosis and support can be provided, potentially saving lives. Technology-based dependence may be restricted by lack of infrastructure in remote areas. Further validation is needed to ensure the system is effective in diverse scenarios. The work in [79] is related to the classification of diseases by utilizing image processing at a secure cloud using the extended zigzag image encryption. A fuzzy convolutional neural network is utilized for image classification. The decoded images are adopted to classify cancer levels in different layers of training. The results are then transmitted to the related doctors and patients for treatment purpose. Here, the training is done using the standard dataset. The results exhibit good performance compared to other methods and can be used for diagnosis of medical images. The method is useful in diagnosis and treatment of disease in a secure way due to using cloud technology for storing and processing data.

In [15], the authors proposed a system for secure disease prediction in healthcare using fog computing and a block chain. It focuses on diabetes and heart disease. Patient health data are collected and stored in a block chain. The developed rule-based clustering method grouped similar patient records. A specific technique, feature selection based adaptive neuro-fuzzy inference system (FS-ANFIS) analyzes the data to predict these diseases. Tests on real-world healthcare data show that the system achieves a high accuracy and outperforms other methods.

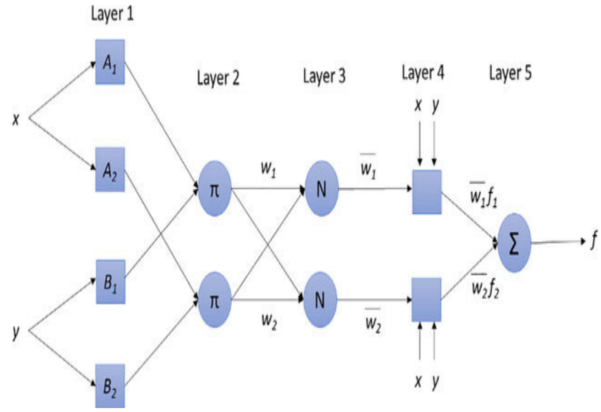

FIGURE 10. A two-input ANFIS with two rules.

In [80] a new scheme based on merging fuzzy temporal decision trees, neuro-fuzzy temporal networks, and fuzzy temporal rules was presented. The proposed scheme was experimentally tested and demonstrated good performance. This scheme combines neural network with fuzzy logic to predict the disease. The use of temporal data increases the accuracy of early disease detection.

In [81], the authors differentiated medical information into disease-free and affected information. An adaptive neuro-fuzzy system has been proposed to enhance security. The results showed a good performance.

The work in [82] uses an Intelligent Mahalanobis distance-aware Fuzzy Weighted K-means Clustering Algorithm (IMFWKCA) for medical data analysis. It also includes a Moth-Flame Optimization tuned Temporal Convolutional Neural Network (MFO-TCNN) for disease prediction, demonstrating improved performance metrics with UCI datasets and live patient records. This e-healthcare system effectively addresses the challenges of high-dimensional data in disease prediction. By leveraging advanced algorithms, it promises enhanced diagnostic accuracy, making it a valuable tool for healthcare professionals in diverse settings.

The study in [83] presents a model that uses machine learning and IoT for the monitoring and prediction of heart failure. It has three stages: data collection, encryption, and classification by adaptive fuzzy-based long short term memory with recurrent neural network. The system outperforms existing techniques in accuracy and sensitivity, alerting doctors when necessary. The combination of IoT with advanced machine learning techniques presents an important advancement in cardiac monitoring. Its robust data handling and predictive capabilities could greatly enhance patient outcomes; though additional field testing is necessary to validate the effectiveness.

The paper in [84] addresses the difficulties in early detection of lung cancer due to new diseases and insufficient diagnostic capabilities. It proposes a fuzzy expert system that uses adaptive neuro-fuzzy inference for better assessment and diagnosing. The results of this method show high accuracy, so that the lung cancer detection process can be greatly improved compared with existing techniques. Overall, the approach shows good potential in early diagnosis and improving treatment options. However, further testing is necessary to ensure the success of the proposed method. The work in [85] presents an IoT-Spiro system that uses machine learning to analyze volatile organic compounds in exhaled breath for diagnosing Chronic Obstructive Pulmonary Disease(COPD). It presents a hybrid Genetic Big Bang-Big Crunch (GBBBC) scheme for feature selection and a fuzzy-based quantum neural network for classification. Results indicate better performance compared to existing diagnostic methods. This innovative approach shows promise for non-invasive and low cost COPD diagnosis, potentially lowering mortality rates. Its dependence on real-time data and advanced algorithms puts it as a valuable tool for healthcare providers, although real-world implementation will need careful testing. Table 4 shows a comparison of the methods and techniques using fuzzy neural network.

D. FUZZY SYSTEM WITH MACHINE LEARNING / OPTIMIZATION ALGORITHM

The paper in [86] presents a hybrid approach combining fuzzy logic and reinforcement learning to address latency

issues in cloud-based healthcare IoT systems. Since IoT generates massive amounts of data, the proposed fuzzy reinforcement learning packet allocation algorithm reduces latency and enhances quality of service by managing data processing and decision making at fog computing nodes, thereby improving real-time response. The paper effectively addresses critical latency challenges in healthcare IoT systems. The proposed hybrid approach enhances decision-making capabilities in fog computing environments. However, the implementation complexity may pose challenges for practical application. The reliance on strong internet connectivity may limit the effectiveness in remote areas. Further testing is needed to validate the performance.

The study in [87] presents a secure IoT computing scheme for healthcare monitoring, using fully homomorphic encryption for data privacy. It includes a clustering method using ant colony optimization algorithm to manage data from IoT devices. Fuzzy C-means clustering identifies typical vital sign patterns, enhancing healthcare monitoring. This scheme addresses privacy concerns in IoT applications while ensuring efficient data management. The encryption and clustering techniques provide a good solution for secure healthcare monitoring.

The paper in [88] discusses the accurate detection of COVID-19, and proposes the use of chest CT as a reliable diagnostic tool. It presents a medical IoT-based platform that uses cloud computing for real-time collaboration between patients and healthcare providers. The proposed method classifies chest CT scan results in COVID-19, pneumonia, and natural cases using the Sugino integrated fuzzy ensemble through three transfer learning models: SqueezeNet, DenseNet-201, and MobileNetV2. The integrated MobileNetV2 model with the fuzzy ensemble achieves a high accuracy of 99.15%, outperforming individual techniques and other ensemble techniques. Finally, this study makes an important contribution to the field of medical imaging and COVID-19 detection. The practical implementation will be helpful to verify its capabilities in various medical conditions.

In [89], an IOMT scheme that uses Wireless Body Area Networks (WBANs) for health monitoring was proposed. It uses fog and cloud computing to analyze big health data from WBANs. It combines WBANs, fog, and cloud to process health data and predict diabetes using fuzzy logic at the fog level and machine learning in the cloud, thereby achieving good prediction accuracy. The fuzzy system provides 64% accuracy in fog while the SVM, RF, and ANN give 89.5%, 88.4%, and 87.2% accuracy respectively for diabetes prediction.

The study in [90] presents a fuzzy system -based secure routing approach utilizing firefly algorithm. The fuzzy system is used to enhance device trust and energy-efficient routing. It improves network lifetime by over 10% compared to existing methods. However, the security is less than other related approaches. The developed approach demonstrates promise in extending network life. However, security vulnerabilities and minor performance drops in delivery rates warrant attention in practical implementation.

The work in [91] proposes a secure routing protocol that integrates fuzzy logic and Whale Optimization Algorithm (WOA) to optimize healthcare IoT systems. It relies on fuzzy trust strategy and WOA-based clustering to improve device reliability and cluster head selection, outperforming existing algorithms in network lifetime, energy efficiency, and packet delivery by 47%, 58%, and 17.7%, respectively. The presented routing protocol demonstrates a good integration between fuzzy logic and WOA, effectively addressing the key challenges in healthcare IoT. The results indicate good performance and efficiency considering the observed performance improvements in lifetime, energy consumption, and packet delivery. However, further evaluation in real-world scenarios would enhance its credibility.

The work in [9] introduces an IoT-based system designed for early disease detection using fuzzy logic and machine learning. It is used to enable early disease detection and personalized health monitoring. The random forest learning algorithm showed the best performance metrics: 82.6% accuracy, 81.5% precision, 83.7% recall, and 82.5% F1-Score in predicting cardiovascular diseases based on the dataset provided. This method assists health monitoring and ensures the importance of combining AI with medical skills for better patient care. This method presents a potential path to enhance early detection. The study may need further validation by

TABLE 2. Comparison of methods and techniques using T1 fuzzy logic.

References	Methods/ Techniques	Merits	Comments
[5], [51], [52], [64]	Home health support Fuzzy logic, Sensors.	A home healthcare monitoring system for elderly person. Help the sick or aged people.	Low cost. Low speed. Acceptable performance .
[42]	Hierarchal fuzzy for classifying data.	Considers a test case to predict the disease spread.	To solve the complexity problem.
[6], [53]	Body sensors, Fuzzy Logic. Disease spreading prediction	Real-time monitoring, provide information about heart rate. Measure the degree of strain.	Low cost, low speed. Important to the healthcare organizations
[16], [58]	Classification of diseases. Sensors, fuzzy classifier, cloud, FPGA.	Alert system. Classification of the pathological conditions of diseases.	High accuracy and fast execution speed.
[17]	Fuzzy system, edge computing. Energy efficient transmission.	Fuzzy clustering technique for IoMT applications.	Better results, and low energy consumption.
[55], [56], [65] [7]	Monitoring and treatment. Arduino , sensors , fuzzy-normal distribution	Determine if the information is of a normal heart or not.	For patients with covid-19 and chronic diseases.
[50]	Fuzzy based fog computing with the cloud.	Optimize real-time data processing and transmission.	implementation complexity may pose challenges in practical applications.
[54]	Fuzzy analytical hierarchy process.	Stabilizing electronic-loyalty to healthcare services.	Highlights the significance of IoT in healthcare.
[57]	IoT healthcare system, fuzzy logic.	Data aggregation using fuzzy logic , aiming to improve network life time.	Outperformed other works by 5–20%.
[59]	IR sensors and fuzzy logic.	Monitoring patients' vital signs. The system measures oxygen saturation and temperature.	Facilitating health monitoring. Reduce disease transmission risks. May aid patient care.
[60]	Fuzzy logic-based privacy-aware algorithm to protect sensitive healthcare information	Addresses the risks of privacy opening in patient data.	Experimental results indicate that it significantly reduces information loss.
[61]	Fuzzy ontology to helps manage fuzzy medical data.	Improve healthcare system's response to COVID-19. It emphasizes early detection and resource management.	Shows effectiveness in managing health crises.
[62]	Remote healthcare system utilizing IoT and fuzzy logic. Fuzzy data aggregation system.	Enhance data analysis efficiency. Improve energy efficiency.	Achieves a 12% accuracy improvement, 56% faster analysis, and reduces energy consumption by 54%.
[63]	Fuzzy logic. Simulated in MATLAB and Simulink and implemented on an ESP8266 microcontroller.	CKD monitoring system for early detection of cardiovascular disease and anemia.	Showed 100% accuracy in detecting patient status and 99% accuracy compared to a commercial pulse oximeter.
[11]	The IoT and a fuzzy system to diagnose different diseases.	A disease diagnosis system.	The system may need additional clinical test.
[66]	IoT and fuzzy logic, advanced sensors and cloud computing.	Monitoring and diagnosing cardiac arrhythmias in COVID-19 patients.	Achieved almost 100% accuracy in ECG data analysis
[67]	IoT and fuzzy classifier, wearable sensors.	The fuzzy classifier aids in data fusion, enabling real-time monitoring and decision-making.	Experimental results show this method outperforms traditional algorithms in accuracy.
[68]	IoT and cloud-based framework and intuitionistic Fuzzy Set.	Predict infection risk in COVID-19 pandemic.	Enhance pandemic response through data-driven risk assessment.
[69]	IoT , fuzzy logic and wearable sensors to collect health data from COVID-19 patients .	The fuzzy classifier aids in data fusion, enabling real-time monitoring and decision-making.	Experimental results show this method outperforms traditional algorithms in accuracy.

practical tests. Table 5 shows a comparison of the methods and techniques using fuzzy system with machine learning / optimization algorithm. Table 6 summarizes the contributions of some of the related works.

VII. DISCUSSIONS

Fuzzy logic integration with the IoT has brought significant advances to healthcare, providing healthcare providers, patients, and health systems with the power to do more.

TABLE 3. Comparison of methods and techniques using T2 Fuzzy logic.

References	Methods/ Techniques	Merits	Comments
[70], [71], [74]	Recommendation system, T2 fuzzy logic, cloud, and wearable sensors.	Monitor the patient and recommend appropriate diets and specific foods.	A new system for monitoring patients with diabetes using wearable sensors.
[13]	IoT-based T2 fuzzy ontology, wearable sensors, recommends specific dietary and medication regimens.	A healthcare recommendation system for the management of chronic diabetes.	Experiment shows the effectiveness in finding patient risk factors and diabetes prescriptions.
[72]	Real options analysis combined with T2 fuzzy logic.	Evaluation of medical devices. Effectively handle ambiguity and provides a practical application and sensitivity analysis.	Enhances the clarity of the decision-making process.
[73]	IoT-enabled smart health system using T2 fuzzy logic and sensors.	Monitor patient stretchers in remote areas.	Enhance monitoring accuracy and reliability.
[75]	An adaptive T2 fuzzy systems to enhance robustness and precision in drug delivery.	An AI-driven IoT system that adjusts anesthesia depth during surgery.	Ensuring patient safety and operational efficiency. Permits for remote adjustments and performs effectively across several patient models.

By leveraging the ability of IoT and the big capabilities of fuzzy logic, healthcare organizations can enhance patient results, optimize resource utilization, and convert the healthcare delivery process to a more transparent, personalized, and proactive approach while reducing costs. However, security and privacy concerns must be treated to obtain responsible and ethical implementation and transparency in the context of fuzzy logic integration with the IoT in healthcare. There are many benefits that can be achieved from using IoT in healthcare such as cost reduction, early detection of chronic diseases, and improved medication use. The benefits offered by integrating fuzzy logic with IoT will be discussed in the following part.

A. BENEFITS AND CHALLEGES

Integrating fuzzy logic with IoT in healthcare offers numerous benefits that enhance patient care and the performance of the healthcare body. However, it faces a number of challenges that require to be treated for effective implementation. The benefits and challenges will be presented and discussed along with appropriate treatments.

One of the primary benefits is the ability to handle real-time data from different IoT devices, like remote monitoring systems and wearables devices. Fuzzy logic has the advantage of interpreting uncertain and inaccurate data, allowing for more accurate decisions.

Another important benefit is the ability to create personalized treatment plans. Classical healthcare approaches often use a one fits all approach, which may not meet the specific needs of each patient. By using fuzzy logic, healthcare systems can plan and design treatments based on individual data profiles, ensuring more effective and personalized treatments. This ability to adapt to the condition of a person is particularly important in the treatment of chronic diseases, where adjustments of treatment policies can have a significant impact on patients' results [92].

The integration of fuzzy logic and IoT also enhances operational efficiency in healthcare environments. With the capability to process data in real time, healthcare providers can optimize resource allocation and improve workflow. For instance, fuzzy system can be adopted to predict patient arrival flow, allowing hospitals to efficiently allocate staff and resources. This proactive approach reduces wait times and improves the overall patient experience [14]. Furthermore, the use of fuzzy logic improves decision systems for healthcare professionals. By providing clear insights from complex data sets, it helps clinicians make informed choices quickly, which is especially important in emergency situations. The ability to synthesize massive amounts of data into actionable visions empowers healthcare providers to improve diagnostic accuracy and treatment decisions [93].

The security and privacy of data are very important in healthcare, and using technologies such as block chain can handle these concerns. Blockchain presents a strong security property, assuring that patient data stays secret and protected from uncertified access. By combining fuzzy logic with secure data handling, healthcare organizations can improve trust and transparency, encouraging patients to share in digital health solutions [94].

Integrating fuzzy logic with IoT in healthcare presents numerous challenges that need to be treated for correct implementation. The complexity of implementation is one of the significant challenge. Integrating fuzzy systems with

IoT can be complicated, and requiring specialized expert. This complexity often leads to higher costs and other complicated problems. This can be relieved by using a design procedure that breaks systems into simple components, assisting easier updates and maintenance. Using block chain

TABLE 4. Comparison of methods and techniques using fuzzy neural network.

References	Methods/ Techniques	Merits	Comments
[76]	Monitoring system, fuzzy neural network and neuro Fuzzy self-learning model.	A neuro Fuzzy system for monitoring patient and supporting medical provider.	Enhanced decisions in diagnosis of diseases.
[77]	A cloud , fuzzy rule-based neural classifier	Monitoring and diagnosing serious diseases.	Improved performance in diagnosing the severity of diabetes.
[78]	Data delivery and acquisition in Internet of IoMT, considering the issue of missing data.	Propose D-ANFIS for estimating missing values, using complete and incomplete datasets.	Results show a 5% performance improvement with ANFIS-GA and 3% with ANFIS-PSO
[8]	Fuzzy neural classifier, standard dataset with real-time data from hospitals.	Propose a model that uses mobile IoT and cloud storage to predict disease severity	Enhances prediction accuracy. Ensuring secure data access and efficient processing.
[38]	IoT and Fuzzy Neural Networks.	Develop a system to bridge critical healthcare gaps in remote areas.	Enhancing accessibility. Supporting improved efficiency and lowering costs.
[79]	Fuzzy convolutional neural network and cloud computing.	Disease classification using image processing and fuzzy convolutional neural network.	Good performance.
[15]	Fog computing and block chain< FS-ANFIS.	Propose a system for secure disease prediction, using fog computing and block chain.	The focus is on diabetes and heart disease.
[80]	Fuzzy decision tree, neuro-fuzzy network and fuzzy temporal rules	A neuro-fuzzy scheme for disease prediction,	Good results in disease prediction
[81]	ANFIS , and cloud.	The medical data is classified into disease-free or affected ones.	Data is protected, good performance.
[82]	IMFWKCA, MFO-TCNN, disease prediction.	Present a clustering Algorithm for high-dimensional medical data analysis.	Improved performance metrics.
[83]	Data collection, encryption, and classification.	Monitor heart patients and predict heart failure .	Outperforms existing techniques in accuracy and sensitivity, alerting doctors when necessary
[84]	Addresses the difficulties in early detection of lung cancer due to new diseases and insufficient diagnostic capabilities.	Propose a fuzzy expert system that uses adaptive neuro-fuzzy inference for better assessment and diagnosis.	show high accuracy, so that the lung cancer detection process can be greatly improved compared with existing techniques
[85]	Feature selection and classification.	Diagnosing Chronic Obstructive Pulmonary Disease.	Experimental results indicate better performance compared to existing diagnostic methods.

for secure data handling ensures that patient information remains accurate and reliable [95].

Data quality and reliability are also of important concerns. In IoT structure a big amounts of data are usually generated and inaccuracies or sensor faults may affect the performance of fuzzy logic methods. It is necessary to have a high-quality data in the analysis and decision-making.

Data quality and reliability are very important for successful healthcare applications. In order to remove inaccuracies from IoT devices, regular sensor calibration and data validation processes are required. The high-speed capabilities of 5G networks can significantly improve real-time data processing. Furthermore, the use of edge computing provides the ability to process data close to the source, enhancing reliability [96], [97].

User interpretation represents another challenge. Healthcare professionals may not be able to understand the output of fuzzy system, which can lead to misinterpretations. This requires user-friendly interfaces and healthcare organizations should provide user-friendly interfaces that improve the usability of these systems [98].

Regulatory and ethical considerations can be considered as another challenge. It is necessary to apply the privacy regulations when handling personal patient data. Integrating fuzzy logic and IoT solutions must align with these regulations, and regular audits must be carried out to ensure compliance with these regulations. Block chain can help ensure that patient data is handled in accordance with regulations and maintain patient trust. Moreover, the various resource and computational requirements of fuzzy logic systems can be a barrier, especially for smaller healthcare providers. The complex nature of fuzzy systems can be a barrier, particularly for smaller healthcare providers. This challenge can be addressed by using cloud computing for computational needs, which

TABLE 5. Comparison of methods and techniques using fuzzy system with machine learning/optimization algorithm.

References	Methods/ Techniques	Merits	Comments
[86]	Fuzzy logic and reinforcement learning	Address latency issues in cloud-based healthcare IoT systems.	Improving real-time response.
[87]	A clustering method using ant colony optimization algorithm , Fuzzy C-Means Clustering	Presents a secure IoT computing scheme for healthcare monitoring, using fully homomorphic encryption for data privacy.	Enhancing healthcare monitoring. Efficient data management.
[88]	IoT, cloud computing. Sugino integrated fuzzy ensemble with three transfer learning models.	Classifies chest CT scan into COVID-19, pneumonia, and natural cases.	MobileNetV2 with fuzzy ensemble achieves a high accuracy of 99.15%, outperforming other techniques.
[89]	Fuzzy logic at fog, machine learning in the cloud .	Health monitoring and prediction of diabetes.	The fuzzy system provides 64% accuracy while the ANN, RF and SVM have 87.2%, 88.4%, and 89.5% accuracy respectively
[90]	Fuzzy logic, firefly algorithm.	The fuzzy system is used to enhance device trust and energy-efficient routing.	It improves network life time by over 10%. The security is less than other related approaches.
[91]	Fuzzy logic and WOA	Optimize healthcare IoT systems. It relies on fuzzy trust strategy and WOA-based clustering to improve reliability and cluster head selection.	Outperforming existing algorithms in network lifetime, energy efficiency, and packet delivery by 47%, 58%, and 17.7%, respectively.
[9]	An IoT- fuzzy logic and machine learning techniques.	IoT-based system for early disease detection	The RF algorithm has the best result: 82.6% accuracy, 81.5% precision, 3.7% recall, and 82.5% F1-Score in predicting cardiovascular diseases.

reduces the local burden on smaller healthcare providers [99], [100].

Interoperability of various systems is another challenge. It is necessary to ensure that various IoT devices can communicate with fuzzy system to achieve the desired outcomes. Ensuring interoperability between various systems is very important. Using standardized communication protocols will ensure seamless merging between IoT devices, fuzzy systems, and block chain. Also middleware solutions can further improve communication to ensure that all parts work together effectively [101].

B. FUTURE RESEARCH DIRECTIONS

Integrating fuzzy logic with IoT in medical applications offers significant benefits such as enhanced decision-making, personalized healthcare, and real-time monitoring, as well as challenges concerning complexity, data privacy, reliability, interpretability, and cost, which must be accurately handled for successful implementation and adoption. Despite these challenges, the benefits of leveraging fuzzy logic with IoT in medical applications are significant, offering opportunities to enhance patient care, improve clinical decision making, and transform healthcare delivery. Addressing these challenges requires interdisciplinary collaboration, stakeholder engagement, and ongoing innovation to realize the full prospect of these technologies in improving health outcomes and patient experiences. Combining fuzzy logic with the IoT for healthcare requires further research and development. Some emerging trends and promising areas for future work are as follows:

1. Explainable fuzzy logic systems with IoT can be used. Explainable fuzzy logic systems (XFLS) have been proposed for better understanding and trust in fuzzy logic decisions. Explainable fuzzy logic systems capable of generating decisions that a human can understand and explicitly explain the way of taking such decision, and it is possible for humans to check the XFLS model decisions and verify whether decisions are made based on accepted rules and principles, so that decisions can be trusted [102].

2. The integration of fuzzy logic with other AI techniques, leads to a more accurate medical data analysis. Combining fuzzy logic with AI and machine learning will enhance fuzzy inference systems for more robust medical decision making.

3. A type-3 fuzzy logic was proposed as a better scheme for managing uncertainty, and has been efficiently applied to control systems. Type-3 fuzzy logic were introduced to overcome the limitations in other types of fuzzy logic by extending the concept of fuzzy logic to include uncertainty in the membership functions themselves. Unlike type1, which use fixed membership functions to represent degrees of truth, and type2 which handles uncertainty with fuzzy sets that have fuzzy boundaries. Type-3 fuzzy systems incorporate fuzzy sets with fuzzy membership functions, allowing them

TABLE 6. Summary of the contributions for some of the related works.

References	Methods / Techniques	Contributions
[16]	IoT Fuzzy classifier, Sensors, Cloud, FPGA, Alert system	Design of a classifier to show pathological conditions of diseases. The classifier is implemented by FPGA to increase the execution speed and accuracy.
[17]	Energy efficient transmission, Fuzzy system, Edge-computing. clustering technique,	Clustering method, better results and low energy consumption.
[55]	Arduino, Sensor. Fuzzy-normal distribution, heart beat signal	The design of an Arduino based analyzer that receive heart-beat signal and determine whether it is of a normal heart or not.
[56]	Fuzzy system ,data mining methods with cloud computing and Big Data	Suggest fuzzy -based Ant Lion optimization classifier for the prediction of diseases accurately.
[80]	Fuzzy system, wireless body area network, fog and cloud computing	Health monitoring. It uses fog and cloud computing for the analysis and predict diabetes using fuzzy logic at the fog and machine learning in the cloud .
[57]	IoT healthcare system, fuzzy logic data aggregation method.	Improve network life time, outperformed other works by 5–20%.
[59]	Using IR sensors and fuzzy logic, monitoring patients' vital signs. measures parameters like oxygen saturation and temperature	Reducing disease transmission risks.
[60]	A fuzzy logic-based privacy-aware algorithm to protect sensitive healthcare information.	Addresses the risks of privacy opening in patient data. Experimental results indicate that it significantly reduces information loss.
[62]	A new remote healthcare system using IoT with fuzzy logic.	12% accuracy improvement, 56% faster analysis, and reduces energy consumption by 54%.
[9]	Fuzzy system , machine learning, early detection system.	An early disease detection. The RF algorithm has the best result: 82.6% accuracy, 81.5% precision, 3.7% recall, and 82.5% F1-Score in predicting cardiovascular diseases.
[63]	Fuzzy model is simulated in MATLAB and Simulink and implemented on an ESP8266 microcontroller.	Monitoring system for early detection of cardiovascular disease and anemia with 100% accuracy in detecting patient status.
[76]	Fuzzy neural network /neuro Fuzzy self-learning model.	An intelligent system to monitor the patient and to support the medical provider in diagnosing the diseases.
[38]	Fuzzy convolution neural network, image processing, cloud computing, fuzzy disease classifier.	A disease classifier using image processing in the cloud with fuzzy convolutional neural network.
[15]	Fog computing and block chain, FS-ANFIS , machine learning.	A system for secure prediction of disease using fog computing and block chain. Health data is stored on a block chain. High accuracy prediction.
[73]	IoT- based health system using T2 fuzzy logic, sensors. Monitoring patient stretchers in remote areas.	Enhance monitoring accuracy and reliability.
[77]	Monitoring diseases, and prediction of disease.	Improved performance in diagnosing the severity of diabetes.
[83]	Data collection, encryption, and classification.	Monitor heart patients and predict heart failure. outperforms existing techniques in accuracy and sensitivity.
[87]	A clustering method using ant colony optimization algorithm. Fuzzy C-Means Clustering.	Presents a secure IoT computing scheme for healthcare monitoring. Enhancing healthcare monitoring.
[88]	IoT, cloud computing, Sugino integrated fuzzy ensemble with three transfer learning models.	Classifies chest CT scan into COVID-19, pneumonia, and natural cases. The MobileNetV2 with fuzzy ensemble achieves a high accuracy of 99.15%.
[90]	Fuzzy logic-based secure hierarchical routing approach using the firefly algorithm.	Enhance device trust. Energy-efficient routing improves network lifetime by over 10% .

to handle higher levels of uncertainty and imprecision. The development of an IoT-based type-3 fuzzy logic system for healthcare is an excellent idea for future research [103].

4. Development of an IoT-enabled smart medical devices. The integration of fuzzy logic with IoT can enable the development of smart medical devices that are capable of adapting to user needs and environmental conditions. For example, fuzzy logic-based control systems can regulate drug delivery rates in smart infusion pumps.

5. The computation of the fuzzy system used with IoT is slow, and The FPGA implementation of the fuzzy system can be used to enhance accuracy and reduce execution time. FPGAs are capable of performing parallel processing, allowing multiple fuzzy rules and operations to be executed simultaneously. These units feature low latency responses, making them ideal for real-time applications. Additionally, FPGAs can be designed to specific tasks, providing optimal performance. High-speed computing in clinical settings speeds up important decision-making, allowing for faster diagnoses and treatment recommendations. Also fast computation enables large data sets to be processed in real time to provide immediate analysis of patient data. This improves decision making, reduce wait times, and leads to more effective healthcare delivery.

6. The employ of the Generative AI in the field of healthcare is very important as the system can be trained using specialized medical databases and used as a basic component in the framework of the fuzzy–based IoT for healthcare. The applications of integrating medical knowledge into GAI are numerous. It can be used to assist medical providers in improving diagnosis and treatment. It can also be used to find distinctive personal treatments that suit the specific patient using the current data of patient, the medical history and genetic factors. Thus, diagnosing the disease and determining the type of medication and method of treatment becomes personal and more effective. In addition, it can be used to guide and educate patients on the correct handling of food, medication and environmental conditions in order to enhance the health condition. In this part we suggest to use the enhanced GAI as a basic tool in the fuzzy logic based IoT healthcare systems [43], [44].

VIII. CONCLUSION

The use of IoT systems in various applications is increasing rapidly. This leads to several problems that require significant solutions, particularly in medical applications. However, the properties of fuzzy logic in dealing with ambiguity make it a powerful tool to solve these issues through an integration process. In this article, research concerning medical applications using fuzzy logic with the IoT are explored. Publications were first classified into four groups based on the type of medical application. They are then classified into four categories based on the type of fuzzy system. A new scheme that combine the generative artificial intelligence within the fuzzy based IoT framework is proposed to enhance the system. The latest innovative technologies developed in this study are demonstrated and discussed. The advantages and challenges of merging the IoT with fuzzy logic for medical applications are highlighted, and emerging trends and promising areas for future research are suggested. While this review aims to provide clear insights and fundamental contributions to the field of integrating fuzzy logic with IoT in healthcare, and despite the existence of innovative and new works, the field is still open for other, good quality works that will generate fundamental improvements in healthcare. The employ of the Generative AI in the field of healthcare is very important as the system can be trained using specialized medical databases and used as a basic component in the framework of the fuzzy–based IoT for healthcare. We propose this generative AI based approach as a major future research direction as outlined in Section VII-B.

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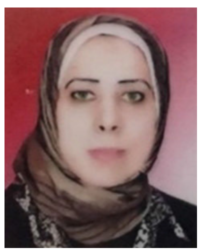

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