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Journal of Emerging Technologies and Computing (JETC)

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is a peer-reviewed, open-access national and international scientific journal. Thematic areas: Computer Science, Infocommunication Technologies, and Mathematics with Applied Aspects

Publisher: SDU University

The journal is registered and licensed as an online publication and printed journal by the Ministry of Information and Social Development of the Republic of Kazakhstan.

Certificate (Online publication): No KZ01VPY00120097

Certificate (Printed journal): No KZ71VPY00120098

ISSN: 3105-6342 (online)

ISSN: 3105-6334 (print)

Frequency: four times a year (March, June, September, December)

Website: https://jetc.sdu.edu.kz

Editorial Board

Ministry of Science and Higher Education of the Republic of Kazakhstan
SDU University

Journal of Emerging Technologies and Computing (JETC)

Volume 5, Issue 2 • June 2026

Kaskelen, Kazakhstan — 2026

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SECTION I

Computer Science

This section focuses on current research directions and applied advancements in Computer Science, particularly in the areas of artificial intelligence, software engineering, and intelligent systems.

Review

Comparative Analysis of Edge-Enabled AI–IoT Healthcare Systems: Toward the Most Effective Predictive Model

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DOI: 10.47344/8kx3yn75

Abstract

The combination of the Artificial Intelligence (AI), the Internet of Things (IoT), and the Internet of Medical Things (IoMT) is driving current developments in the field of intelligent healthcare systems, thus, enabling the continuous, real-time, and remote monitoring of patients. The traditional cloud-based healthcare infrastructure, however, is riddled with latency, bandwidth, scaling, and increased risks to the privacy of data, all of which decrease their efficiency in time-intensive clinical settings. To address these drawbacks, this study performs a comparative analysis of edge-based AI-IoT healthcare systems, in which the most useful predictive model is determined to be deployed on clinical scenarios in real time. Various machine-learning and deep-learning frameworks have been tested on hybrid edge-cloud systems using ECG data gathered by IoT and the performance indices included prediction accuracy, latency, computation efficiency, and edge-feasibility. Table 1 enumerates the results of applying the convolutional neural network (CNN)-based models, showing that they have higher performance, achieving around 99 percent success on arrhythmia detection, with low latency that makes them an option of implementing them in the form of edge devices. Comparatively, a three-layer-based monitoring setup based on the concept of combining IoT devices with a hybrid CNN-UUGRU model achieves 97.7 percent accuracy on public datasets and can be used to partition edge-cloud tasks and mobile-based notifications, but at slightly reduced predictive accuracy. Although benchmark results are strong, the enduring weaknesses are linked to reliance on clean and non-clinical datasets and lack of a thorough test of robustness, privacy, and extended deployment. Comprehensively, it can be indicated that CNN-based models provide the best balance in terms of accuracy,

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Received: December 17, 2025. Reviewed: June 27, 2026. Accepted: June 27, 2026.

real-time performance, and edge feasibility; thus, its significant potential in scalable, patient-centered, and reliable edge-enabled AI-IoT healthcare systems, especially regarding real-time arrhythmia screening.

Keywords: Internet of Medical Things (IoMT), Smart Healthcare Systems, Healthcare Data Privacy, Real-time Monitoring, Wearable Sensors, AI-Driven Analytics

I. INTRODUCTION

Over the last few years, the combination of Artificial Intelligence (AI) and the Internet of Things (IoT) turned the sphere of healthcare into a more intelligent, connected, and patient-oriented one. The rise in chronic illnesses, ageing world, and the general need to be watched constantly on matters related to health has compounded the rate of uptake of smart healthcare systems [1]. The conventional model hospital-based care is usually insufficient in terms of delivering medical care in time particularly to the aged or to the remote patient. Hence, it may be expected that smart-based healthcare, integrating wearable sensors, IoT-based infrastructure, and AI-driven analytics, will become a promising solution in enhancing the early diagnosis of the disease, individual treatment, and patient safety [2]. The topicality of this discipline is supported by the trends in digital medicine across the world today. This publication growth is also visible in Fig. 1, which shows an increasing concentration of AI–IoT healthcare studies in 2024–2025. With the World Health Organization stipulating such a high number of elderly patients growing fast, which makes up 2.1 billion people by the year 2050, there are new challenges of healthcare systems like real-time monitoring of patients and prevention of diseases [3]. Existing healthcare systems cannot cope with all these issues because of the insufficient resources, geographical limitations, and the unavailability of individualized monitoring systems. This results in the increased demand to integrate smart, interrelated networks that gather and process biomedical data in real-time so that physicians could make correct and prompt choices [4].

Although systems have advanced fast, the current systems are faced with a number of challenges that include, latency in data transmission, low interoperability, and inadequate dependability of wearable devices [5]. Furthermore, the issue of privacy and data-security is also a constant barrier in the implementation of AI-IoT healthcare systems on a large scale [6]. So, authors suggest new constructs of edge or fog computing and blockchain systems in order to provide safe and real time data management [7]. To demonstrate it, Baucas et al. (2023) proposed a federated learning and blockchain-based platform of the building of a fog-IoT that permits the execution of computations at the wearable level but keeps users confidential [8]. This model shows how centralized storage of healthcare data in healthcare has transitioned to the distributed, privacy-protecting structures.

What is another important component of the problem is the necessity of reliability and resilience in healthcare systems. Rudimentary monitoring technologies are typically unrelated, which reduces their ability to look at various conditions of health, which are interconnected. To counter this, Healthcare 5.0 technologies can make reliable, resilient, and personalized choices to provide continuity of service and autonomous decision-making [9]. These systems will be able to identify unfavorable conditions, reestablish the functionality automatically, and adjust the treatment plans based on the unique genetic, behavioral or environmental factors of patients. The COVID-19 pandemic has also brought additional weight to value AI-IoT convergence in the medical care. The AI-based IoT applications have played a significant role in identifying the patterns of infections, enabling telemedicine, and automating non-contact health monitoring [10]. These uses made it clear that smart digital health systems can not only decrease the amount of physical contact between patients and healthcare providers but can also guarantee quick responses and mass disease monitoring. This led to the adoption of such solutions in the healthcare system of many countries. According to the recent research, AI and IoT have great pluses in the areas of diagnostic accuracy and treatment efficacy. Mansour et al. (2021) developed an AI-IoT disease-diagnosis model based on deep learning and optimization algorithms, in which the accuracy was over 96 per cent in classifying heart diseases and diabetes. Likewise, Zahid et al. (2022) came up with an adaptive and sustainable IoT-based healthcare model to maintain a real-time data processing and energy efficiency in medical sensors. The innovations presented above show how AI-IoT integration has the potential to transform the sphere of diagnostic and monitoring in smart scenarios of healthcare industry.

Nevertheless, with this technological advancement, there are still many gaps in research. Medical devices are heterogeneous, lack standardization, and are unable to be scaled to be extensively used. Further, moral and legal issues of data sharing and algorithmic transparency are persisting to become impediments to global level implementation. Thus, recent literature is concerned with the formulation of complex schemes that will strike a balance in terms of efficiency and reliability, not to mention ethical accountability.

To sum up, the unification of AI and IoT technologies is a breakthrough into the realm of proactive, preventative, and personalized healthcare. The contemporary work environment attempts to fill deficiencies of the conventional systems through improved connections, accuracy, and decision-making in real time. Thus, the analysis of AI-IoT-based smart healthcare has been relevant to a large extent because it has solutions to the world-wide problems, including population aging, handling chronic diseases, and accessibility of healthcare.

Received: December 17, 2025. Reviewed: June 27, 2026. Accepted: June 27, 2026.

The recent convergence of edge computing, the Internet of Things, and artificial intelligence (AI) has changed the way healthcare systems monitor and assist patients. Thanks to wearable and sensor-based Internet of Things devices that allow continuous data collection, doctors and patients can now stay connected even outside hospital settings. Mansour et al. [11] developed a low-cost Internet of Things prototype that uses Arduino sensors to assess heart rate, grip strength, and sleep to aid stroke patients in their home-based recovery. Wang et al. [12] demonstrated the potential of wearable technology in rehabilitation by creating a smart knee sleeve that gathers motion data in real time and sends it to the cloud.

Making these systems more intelligent and effective was the aim of other researchers. Hassan et al. [13] introduced an edge-based AI system integrating deep and reinforcement learning to accelerate healthcare data processing and minimize network latency. This idea was further developed by Li et al. [14] with UniTS, a deep-learning model for real-time anomaly identification in wearable sensor data intended for low-power devices. An IEEE study [15] described a CNN-based arrhythmia detection system that links IoT devices with edge and cloud layers to balance accuracy and response time, while ElSayed et al. [16] suggested a zero-trust AI model to identify ransomware and DDoS attacks in healthcare IoT networks.

Overall, these studies highlight how combining AI and the Internet of Things will transform healthcare through the possibility of quicker, more intelligent, and more individualized therapy. The majority of these systems, however, are still in the early phases of development and are frequently tested with tiny sample sizes or few trials. To assess how well they continue to work in actual healthcare settings, improve patient confidentiality and data privacy, and guarantee thorough clinical validation, more study is required. By addressing these issues, future developments will be able to fully realize the potential of AI and IoT technology to provide safer, more efficient, and patient-centered healthcare.

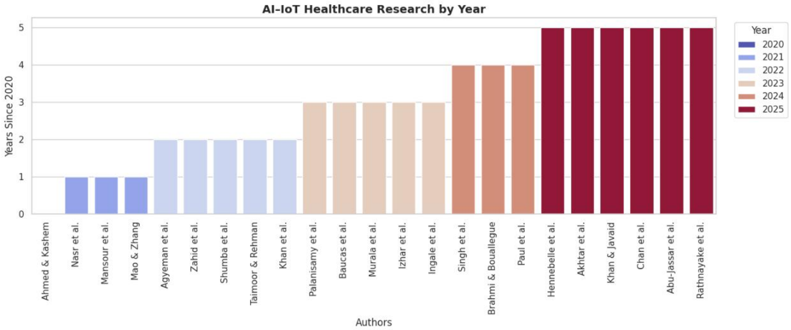

Fig. 1. The chronological distribution of AI-IoT healthcare research from 2020 to 2025 demonstrates the upward trend in publications. An earlier study (2020–2022) focused on the basic principles of IoT–AI integration, while more recent studies (2023–2025) emphasize advanced applications like edge computing, predictive analytics, and wearable health monitoring systems.

TABLE I: Comparative Analysis of Existing AI–IoT Healthcare Research

Research work	Key Findings	Pros	Cons
Zahid et al., 2022	Proposed an AI-based adaptive routing and resource-control algorithm to improve energy efficiency in IoT-enabled healthcare.	Unified routing and rate regulation; clear evaluation setup.	No hardware/clinical validation; real-world data absent.
Mansour et al., 2021	k Built a hybrid AI–IoT diagnosis pipeline with CSO–LSTM for cardiovascular/diabetes detection.	End-to-end sensor-to-cloud design; 96–97% accuracy; practical IoT constraints considered.	Relies on simulated IoT data; limited privacy analysis; no clinician-in-the-loop study.

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Received: December 17, 2025. Reviewed: June 27, 2026. Accepted: June 27, 2026.

Research work	**Key Findings**	**Pros**	**Cons**
Abu-Jassar et al., 2025	ESP32-based Remote Patient Monitoring with AWS IoT Core for real-time streaming and dashboards.	Reproducible hardware–software stack; working cloud prototype.	Only lab-tested; no clinical/security assessment; lacks quantitative latency metrics.
Paul et al., 2024	Lightweight ConvLSTM skeleton-HAR for medical events with real-time IoT alerts.	High accuracy on standard datasets; skeleton data improves privacy.	Limited population diversity; camera-surveillance ethics not fully addressed.
Ahmed & Kashem, 2020	Low-cost IoT+ML (DT, LR, SVM) to predict maternal health risk levels.	Replicable for low-resource settings; inexpensive sensing.	Small dataset; little discussion of consent/security; no long-term deployment.
Baucas et al., 2023	Fog–IoT platform using federated learning and blockchain for privacy-preserving predictions.	Combines FL + blockchain; hardware demo on Raspberry Pi.	Focus on feasibility over accuracy; no clinical or energy benchmarks.
Khan et al., 2022	Systematic review of AI–IoT for COVID-19; highlights deep learning, fog, blockchain for detection/tracing.	Comprehensive taxonomy; interpretable ML; trend analysis.	No empirical validation; limited quantitative evaluation.
Ingale et al., 2023	AI–IoT framework for continuous monitoring with real-time analytics and cloud dashboards.	Improved responsiveness and automation; clear system layering.	Minimal comparative evaluation; scalability not measured.
Taimoor & Rehman, 2022	Survey of Healthcare 5.0 focusing on reliability, resilience, personalization via AI/IoT and blockchain.	Clear three-layer HIoT taxonomy; security threats/countermeasures mapped.	No implementation; lacks empirical metrics.
Shumba et al., 2022	Review of IoT/AI critical-care architectures with edge intelligence and piezoelectric sensing.	Modular low-latency design; privacy-aware on-device processing.	No hardware validation; performance mostly qualitative.
Palanisamy et al., 2023	Three-tier monitoring (IoT + CNN–UUGRU) achieving 97.7% on public data; mobile API for alerts.	High accuracy; efficient edge–cloud split; end-user layer included.	Non-clinical dataset; lacks field deployment; no long-term analysis.
Nasr et al., 2021	Review of AI–IoT–Edge–Blockchain for smart healthcare and AAL systems.	Broad technology coverage; identifies real-time security needs.	Conceptual synthesis; no standardized benchmarks or pilots.
Singh et al., 2024	AAL review mapping CNN/LSTM/RF to elderly-care sensors; calls for multimodal fusion and edge inference.	Comprehensive taxonomy; emphasizes edge-assisted AAL.	Limited real-world data; privacy/interoperability underexplored.
Zahid et al., 2022	Chipless RFID for passive health tracking; compares tag designs and read-range sensitivity.	Battery-free low-cost sensing; detailed hardware review.	No AI/analytics integration; data protection not addressed.
Murala et al., 2023	“MedMetaverse” combining AI, blockchain, wearables for chronic care and consented data sharing.	Strong data-governance stance; decentralized identity/consent.	Conceptual; no latency/energy evaluation; no pilot deployment.
Izhar et al., 2023	IoT–Edge hybrid: $>70\%$ latency and $\sim 68\%$ bandwidth reduction with $>95\%$ accuracy; lightweight security/validation.	Measured edge gains; real devices; privacy-by-locality.	No power-aging model; limited device/network heterogeneity.

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Research work	Key Findings	Pros	Cons
Brahmi & Bouallegue, 2024	Digital Twins over 6G (URLLC/slicing) for proactive monitoring and predictive interventions.	Actionable 6G-twin architecture for telemedicine.	No deployment data; cost/security trade-offs open.
Agyeman et al., 2022	CNN arrhythmia detection for IoT ECG with ∼99% accuracy; discusses edge feasibility.	Strong benchmark results; real-time screening potential.	Clean-data bias; robustness/privacy not fully studied.
Akhtar et al., 2025	An AI-IoT conceptual framework of predictive assistance and real-time monitoring.	Remote care can make use of AI-IoT workflow, which is understandable and suitable.	No metrics, no research, and no respect to privacy.
Khan & Javaid, 2025	Simulated AI–IoT telehealth system using wearables and cloud analytics.	Improves diagnostic speed; considers security.	Simulation only; unclear device compatibility; privacy gaps.
Chan et al., 2025	The accuracy of IoT + AI cardiac prediction in obese youth is ∼90%.	improves model accuracy through the use of clinical sensing.	Minimal testing, simple models, and a small sample size.
Mao & Zhang, 2021	Neural networks and confidence filtering are used in this IoT-AI consultation platform.	Faster consultations; new confidence scoring.	limited attention to privacy, no clinical trials, and simulated data.
Hennebelle et al., 2025	To predict diabetes, the SmartEdge edge-cloud system uses ensemble machine learning.	Strong modeling; favorable latency-accuracy results	Disregard for privacy, simulated data, and benchmark-only testing.
Rathnayake et al., 2025	An examination of wearable AI with an emphasis on sensors and edge inference	Discusses FL + low-power ideas and current trends.	Little practical application and little discussion of regulations.
Mansour et al., 2021	Developed a low-cost IoT prototype using Arduino Nano 33 BLE with sensors for heart rate, grip strength, steps, and sleep to support home-based stroke rehabilitation.	Low-cost, easy to replicate; demonstrates practical IoT use for remote monitoring; transparent testing procedure.	Only three participants; lacks statistical validation and privacy framework; short-term testing only.
Hassan et al., 2021	Proposed an edge-intelligence framework combining deep and reinforcement learning for distributed healthcare analytics, reducing latency and bandwidth load.	Comprehensive review of 15 studies; well-defined edge-AI architecture; addresses delay reduction and scalability.	Conceptual only—no prototype; omits network loss and real deployment; limited data security discussion.
Li et al., 2025	Introduced UniTS, a unified deep-learning model for anomaly detection in wearable sensor data, enabling real-time inference on edge or wearable devices.	Strong empirical evaluation; high F1 and low-latency detection; optimized for limited hardware.	Relies on synthetic anomalies; no clinical or real-patient validation; interpretability not explored.
Wang et al., 2018	Designed an IoT-enabled smart knee sleeve for real-time motion capture and cloud-based rehabilitation feedback.	Demonstrates feasible wearable prototype; enhances patient engagement; achieves accurate motion sensing.	Small sample; restricted to knee movement; no AI analytics or strong privacy analysis.

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Research work	Key Findings	Pros	Cons
ElSayed et al., 2024	Proposed a zero-trust ML-based architecture using the CICIoT2023 dataset to detect DDoS and ransomware attacks in healthcare IoT networks.	High detection accuracy (93.6%); energy-efficient and scalable; validated on real datasets.	No real hospital deployment; limited ethical assessment; lacks blockchain/federated learning integration.
[Anonymous, IEEE], 2023	Presented CNN-based arrhythmia classification integrated with IoT devices through a layered edge–cloud system to balance accuracy and latency.	Comprehensive hardware–AI integration; practical performance evaluation using benchmark datasets; system-level analysis.	Restricted access limits reproducibility; unclear implementation details; lacks diverse environment validation.

Table I summarizes the most representative AI–IoT healthcare studies published between 2018 and 2025. The comparison highlights a clear shift from cloud-centric architectures toward hybrid edge–cloud and fog-based solutions [2], [6], [43]. Studies such as Mansour et al. [2] and Palanisamy et al. [38] demonstrate that integrating edge intelligence significantly reduces latency while maintaining high diagnostic accuracy.

II. EXPERIMENTAL APPROACHES IN AI–IOT HEALTHCARE MONITORING

The experimental designs in most of the reviewed studies involved wearable devices and smart sensors that had the ability to detect human motion and physiological indicators.An experiment, e.g., involved a portable neural-based system to identify leg movement. The subjects were also fitted with a knee sleeve that had a stretch sensor and a smaller accelerometer attached to it to measure the minute change in motion and muscle motion.

Another survey utilized a vision-based device, which consisted of cameras and pose estimation algorithms to project the body joint concerning movements in two and three dimensions. The subjects were asked to do some simple tasks like walking, sitting or some therapy exercises with the system monitoring and computing the joint trajectories, to decrease the effect of minor motion and the fluctuations of camera errors.To enhance reliability, the researchers used correction measures, minimizing the effects of minor motion, and the camera error values. This framework allowed physical activity to be monitored during physiotherapy and rehabilitation and it was also inevitable to do this with accuracy and in real-time.

Multiple other works used medical sensors in the form of ECG, temperature, and oxygen saturation sensor and transmitted the local data feed to bog or edge devices to do preliminary analysis and then transfer the processed information to cloud servers to do an in-depth analysis. This mixed arrangement greatly lowered the communication latency and enabled quicker identification of uncommon body physiological patterns.

In another architecture, the IoT gateways were used to ensure the transfer of physiological data e.g. heart rate, blood pressure and temperature to cloud platforms.Here, artificial intelligence models used the data to evaluate possible health risk and issue alerts when abnormal conditions were found. Such architecture allowed tracking their health without the strain of local devices as well as offered a scalable solution to remote medical supervision.

There were studies that investigated hybrid IoT-edge architectures in which the data processing operations were shared among the local and the cloud elements to find the balance between accuracy and latency. The signals recorded by wearable sensors (ECG and photoplethysmography (PPG)) were partially processed on local devices to identify the relevant features and the summarized data were then migrated to the cloud servers to make the final evaluation and assessments.

To collect the data, the studies utilized either publicly available data or the measurements taken in the case of real experiments with wearable devices. The measurable parameters were usually, motion, acceleration, temperature, heart rate and other physiological measurements. All the signals were marked by the type of activity of the participant, i.e. walking, resting or exercising. The data were preprocessed (noise filter, signal normalization, and missing or corrupted value correction) prior to analysis.

Most researchers used machine learning in order to analyze data and determine the trends and predict the outcomes. The overall workflow was feature extraction such as frequency or intensity, labeling using models such as decision trees, support vectors, or deep neural networks, followed by their aggregation on cloud servers to provide deep analysis.Aggregation of the results of multiple sensors was referred to as edge fusion since it enhanced the accuracy and the reliability.

The methodology also involved statistical validation so that to assess the performance of the models the studies commonly used k-fold cross-validation to separate data into training and testing. Quality of prediction was measured by accuracy, precision, recall,

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F1-score, and ROC curves. Response time and energy used during specific experiments were also noted to determine the system efficiency when comparing models paired tests like t-test were conducted to determine whether there was any significant difference between observed results or not.

The researches were founded on a number of assumptions. The assumption made was that all sensors were calibrated properly, the wireless communication would be stable and the same environment conditions such as lighting where the camera-based systems were used would be consistent across the experiments.It was also assumed that the datasets would be representative of real-life human behaviour and that sufficient amount of training data would allow the various algorithms to generalize to similar real life conditions.

On the whole, the integrated findings of the research indicate that IoT, wearable technology, and intelligent computing can be complementary and complement each other to improve the healthcare system monitoring. These frameworks are known to lead to lower latency, better accuracy, and enhanced responsive health measurements; however, most of the experiments were realized in controlled conditions with a small number of subjects, which means that large clinical studies are required. Nevertheless, these solutions provide a good basis of the creation of the next-generation smart healthcare and activity recognition systems.

III. RESULTS AND DISCUSSION

This part unites and synthesizes the key lessons discovered in the chosen articles on AI-, IoT-, and edge-enabled healthcare systems. Rather than reiterating the initial numerical findings, the point here is to see how larger trends can be traced, how various methodological decisions arrived at the findings and what these findings (taken together) can tell us regarding the future of intelligent medical technologies. To make the discussion easier, it is divided into several thematic sections: overall findings, comparison to the previous research, the remaining limitations, causal and forward-looking interpretations, and a series of deductive conclusions based on the literature.

Findings and Interpretation This subsections provide the research content of the study and its interpretations. One of the similar motifs present in the analyzed literature is that the integration of artificial intelligence and IoT and edge computing leads to significantly more responsive and reliable health monitoring systems. Papers that used some sort of on-device or near-device computation either lightweight neural models or local feature extraction or event-based data transmission were seen to have unmistakable advantages in speed and immediacy of medical feedback. These systems could detect the physiological changes faster by offloading part of the computational load onto the device and therefore, they did not rely on remote servers and bad network connectivity. Such responsiveness is of particular significance in conditions, like cardiac surveillance or mobility evaluation, where responsiveness directly affects clinical significance. The existence of several other contributions, especially those defining Digital Twin concepts or healthcare structures consistent with future 6G technologies, explains how a synchronized representation of the patient can be exploited to predict health problems and make active supervision. Although most of these designs are on paper, they provide an outline of a possible very bright future where virtual models could be the key point in the decision-making cycles. Equally, blockchain-based works, such as the MedMetaverse proposal, are more focused on the management of identity and traceability of data. These initiatives are a reaction to the long history of mistrust of medical systems, lack of transparency, and data sovereignty. Studies that explored the low power sensing technologies including chipless RFID have demonstrated that massive health monitoring does not have to have enormous overhead in hardware. Simultaneously, these methods highlight some of the trade-offs: being very cheap and energy-efficient, these types of sensors do not provide the necessary level of intelligence to make a local decision or may provide limited native protection to sensitive information. Conversely, research on deep learning to perform tasks such as arrhythmia showed that the state of the art level of accuracy could be achieved. Nevertheless, these developments have their limitations, the most obvious one being the fact that they still depend on good connectivity and computing power. Altogether, the discussed publications reflect the current trend of switching to less centralized, cloud-based pipelines to more distributed healthcare systems. Hybrid methods of AI-IoT-Edge seem to be the most sensible trade-offs in terms of the latency, energy usage, and privacy protection. However, they also clarify that designing such systems should be met with keen consideration of size of the model, ability of the devices used, communication protocols and end-to-end data security.

Comparison with Prior Studies When examining the literature on a broader scale it is noticeable on how the field has progressed through time. Early systems themselves, particularly those founded on RFID sensing, were aimed at hardware simplicity, low cost and broad deployability. These early measures formed the basis of the more advanced solutions that ensued afterwards where sensors, communication modules and analytical algorithms were closely combined. The most current studies of Digital Twins and multimodal fusion prove that the integration of various types of sensors (e.g., ECG, PPG, motion) can contribute to a great improvement of the monitoring strength. Despite the fact that a wide consensus on decentralized processing is that the latency

Received: December 17, 2025. Reviewed: June 27, 2026. Accepted: June 27, 2026.

is minimized and responsiveness is enhanced, there is a great difference in the extent to which the studies were able to provide validity to their projections. Theoretical solutions like the MedMetaverse or 6G-enabled Digital Twins have interesting concepts but fail to test their hypotheses experimentally. Conversely, more concrete implementations of IoT-Edge data fusion or CNN-based arrhythmia recognition are available, but usually under constrained test conditions. These place the works together can indicate that the meaningful progress lies in balancing three essential items: the model that is lightweight enough to be operational on the edge devices, communication protocols adjusting to the varying conditions of the network, and system designs that take into account energy consumption and long-term operation.

Limitations of Existing Research Although the mentioned literature presents some impressive progress, there are still a number of limitations that are widespread in research. The experimentation often is based on the relativity small datasets or groups of participants that cannot be considered the complete representation of the existing clinical groups. Consequently, it is hard to determine how effective such systems could be in the less homogenous or predictable conditions. The other common problem is the testing conditions themselves: laboratory or semi-controlled environments can be used to make accurate measurements but cannot be used to model the noise, interruptions, and variability found in real world use. The challenge of hardware diversity is another. The behaviour of different sensor types, microcontrollers, and communication modules in practice can sometimes be incredibly different, and it is not always possible to compare results across studies or repeat them reliably. Secondly, despite several frameworks raising issues about security and privacy systems, many of them are at a conceptual level, i.e. they do not look into how these systems will survive real-life threats. The long-term factors, including battery degradation, persistent power consumption, and effects of the environment on the sensor quality, are mostly not part of the current analysis. Furthermore, one can observe certain causal and speculative insights that are absent in the extensive literature concerning the topic of the study.

Causal and Speculative Insights In addition to that, some causal and speculative insights can be identified that do not exist in the comprehensive literature on the subject matter of the study. Although there is a variety of methodologies, there are a number of plausible causal relationships that can be inferred based on the literature. Making inferences on the device or close to it of course shortens the path of data which consequently lowers communication delays. Local feature extraction prior to transmission reduces data to be transmitted thereby reducing network load as well as the total system energy. The preservation of raw biosignals on the device has its own privacy benefits as well, as it prevents the exposure of sensitive data to other networks. These results indicate that the advantages of distributed AI are not only associated with architectural decisions, but also with core characteristics of data flow, computation, and risk exposure. In the future, there seem to be a few directions that are particularly promising. Federated learning may enable edge devices to customize their models dynamically without transmitting raw data to centralized servers, which will mitigate the issues of personalization and privacy.

IV. Conclusion and Future Work

This paper gives a comparison of edge based AI-iot medical system of arrhythmia detection in ECG graph with specific focus on predictive accuracy and edge viability. As the findings presented in the Table 1 reveals, models based on convolutional neural network (CNN) are always the best in terms of performance with up to 99 per cent accuracy and the low latency allows them to be deployed in real time to detect edges. All these features make the CNN the best predictor model of the considered methods in the IoT-based cardiac monitoring and early arrhythmia detection. However, despite the meticulously designed three-layer architecture integrating IoT devices with the hybrid CNNUUGRU framework with high accuracy (97.7 percent), which proves to be highly functional, it has practical merits in terms of dividing the edge-cloud tasks and executing user alerts with the mobile API. However, its predictive precision is a bit less accurate as compared to that of standalone CNN models. In addition, the two methods are fundamentally founded on clean and publicly accessible data, which creates the risk of bias and limits the ability to generalize it to real-world clinical settings. The absence of field deployment over time, intensive testing of reliability in the harsh environment, and a detailed assessment of privacy and security represent a big gap in research. All in all, the results show that CNN-based models offer the best trade-off of predictive accuracy, computational efficiency, and real-time edge practicability. Further studies must focus on testing these models with clinical data, making them resistant to data noise and variability, and deploying privacy-sensitive functions to enable secure, scalable, and reliable to deploy edge-enabled AI-IoT healthcare platforms.

In conclusion, the present paper has examined the current AI-inspired IoT and IoMT architectures with a specific emphasis placed on the hybrid edge-cloud computing architectures that are intended to solve the shortcomings of the conventional centralized healthcare systems. The discussion proved that federated learning, lightweight AI models,and edge intelligence could be used to promote the system responsiveness, data privacy, and personalized decision-making in smart healthcare settings significantly. Nonetheless, a number of critical issues, such as the inability to ensure the interoperability between gadgets, safe and efficient information processing, energy limitations in wearables, and the compromise between the processing power and the accuracy of the

Received: December 17, 2025. Reviewed: June 27, 2026. Accepted: June 27, 2026.

models, have not been resolved yet. Thus, the future paradigm of research must be to create decentralized, flexible, and patient-centered IoMT systems, which guarantee trustfulness and scalability and also investigate privacy-conserving AI solutions, sustainable wearable technologies, and universally applicable standards of real-time medical systems worldwide. In general, the paper indicates that there is an increased need to have decentralized, privacy-conscious, and highly efficient IoMT architectures that can enable credible and real-time healthcare delivery.

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Received: December 17, 2025. Reviewed: June 27, 2026. Accepted: June 27, 2026.

SECTION II

Infocommunication Technologies

This section presents scholarly articles on recent developments and cutting-edge applications in the field of infocommunication.

Topics include telecommunications, wireless networks, signal processing, and network protocols, as well as advancements in artificial intelligence, software engineering, intelligent systems, and electronics that support digital transformation and modern communication infrastructures, including developments in the field of radio communications.

Article

The societal and technological impact of Quantum Computers

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DOI: 10.47344/mps66a79

Abstract

This research focuses on quantum computing. These are rapidly developing technologies that can significantly advance areas such as cybersecurity, artificial intelligence, and data processing. The study examines both the advantages and limitations of quantum systems. The main goal of this research was to understand whether the world is ready for a quantum computer era and its future consequences. The investigation showed that quantum computing has certain limitations, including potential harms to cybersecurity. However, many studies suggest the development of new encryption methods to prevent quantum cyberattacks. The results of the work show that NISQ is highly noise-proneprone and error-prone. And many researchers expect a gradual transition to hybrid systems that combine classical and quantum computing. The study concludes that, while quantum computing has great potential, it still faces significant challenges, including stability, error correction, and ethical issues. The technology is still too immature for full-scale implementation. Still, a future can be envisioned in which quantum and classical systems coexist in a hybrid model, gradually shaping a new era of computing.

Keywords: Quantum computing, cybersecurity, adaptation, ethics, impact, cryptography.

I. INTRODUCTION

Quantum computing is a technology of the future that will give a massive boost to the development of computers and data processing. Many people are familiar with regular computers and know they use binary code (0 and 1), whereas quantum computers use qubits. They can be in different states at the same time [1]. This allows quantum computers to solve problems much faster.

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Received: December 8, 2025. Reviewed: June 29, 2026. Accepted: June 29, 2026.

Quantum computers could be the beginning of a rapid development in technologies such as quantum mechanisms, networks, cryptography, and gaming [2]. But there are also significant risks that people may not be prepared for. For example, the problems that quantum computers can create in the field of cybersecurity, as they can make all encrypted data accessible to attackers [3]. It means that quantum computers are unstable and require detailed research. This is why this work focuses on studying whether humans can adapt to the power of quantum computers. [4]. This work will aim on identifying opportunities and challenges that bring quantum computers. Quantum computers and their power can be a threat. They give opportunities for solving complex problems, creating new models and advancing other fields in technology area. But they also make risks. Quantum computers can be used to solve complex scientific problems, for example creating more accurate computational models and improving data security. But in other side their advantages can also pose a threats like cracking existing encryption systems. In addition, quantum devices are still imperfect: they are prone to errors, require a lot of energy, and expensive equipment. There are also no clear laws and regulations governing their use. Therefore, the main challenge of this research is to determine whether it is possible to prepare for the emergence of quantum technologies in order to take advantage of their benefits while avoiding potential risks. Despite numerous studies devoted to the technical development, security implications, and potential applications of quantum computing, they still fail to answer the central question of this research: ”Are people ready for a quantum computer?”. Many gaps were addressed, including energy efficiency [5], cybersecurity [6], encryption methods [7], and quantum-powered artificial intelligence [8]. However, none of the articles demonstrated people’s readiness for quantum computing, touching on ethics, the shift in the generally accepted concept of ”computer,” and the potential for a complete transformation of human life, just as it did with the creation of the first telephone and the internet. It would be useful to conduct a survey among ordinary people to gather their opinions on quantum computing, outlining all the pros and cons, as well as the potential risks of the transition from standard computing to quantum computing. Therefore, a clear scientific gap exists on this topic. Further research is needed, to understand how people will accept and adapt to a world with quantum computers. It is important to fill this gap to eliminate potential risks and assess humanity’s readiness for quantum computing. In order to solve the problems that are associated with quantum computers, it is important to find a balance between their potential and the risks associated with them. In this work there are a couple suggestions that are brought in order for society to better prepare itself with the integration of quantum systems. On one hand it is important to support research and development related to quantum and quantum adjacent technologies, otherwise limiting progress in that field. On the other hand the international standards and regulations associated with them must be developed before it’s wide adoption to the public mass, otherwise risking the situation similar to generative artificial intelligence models, which at the time of writing, include abuse and misuse of the technologies. Although already present, educational organizations should develop existing programs and consider opening new ones related to quantum technologies. However, basic programs added to the general curriculum should also be added to raise awareness. Despite all that, it’s practically impossible for quantum technologies to gain immediate acceptance, however it’s a necessary period, before it’s wide adoption can be expected, which is crucial for future progress of the field.

Quantum technologies are not a thing of fiction today. And quantum computing will be introduced into people’s lives in the near future. When the application of quantum computing will be used in practical tasks, and the more questions may arise, how much are humanity ready for this change? The purpose of this study is to find out what impact quantum technologies can have and how it will affect society, macroeconomics, science and the political arena. Despite the fact that quantum computing opens up a vast horizon of possibilities, it can not be forgotten that there are huge risks in areas ranging from cybersecurity to increasing tension in the global arms race. Each participant in this study studied this issue from different angles: Some studied the impact on cybersecurity; The second studied the technical barriers; Still others studied the economic and political consequences of the introduction of quantum technologies; And combining all these studies has provided complete picture on the topic of readiness for the quantum era. The purpose of the research. The goal is to understand and find out whether the world is ready for a quantum computer era and its future progress consequences. The Objectives of the research. In the studies of this dissertation, three main objectives are set: To analyze the current state of quantum computing technologies and assess their potential benefits and risks for science, industry, and society. Identify strategies for a safe and effective way to integrate quantum technologies, including the development of any international standards, educational programs, and collaboration between research institutions and governments. To understand and assess society’s readiness for the quantum era by defining how humanity can take advantage of quantum computing, minimizing possible problems, and ensuring sustainable technological progress.

In this research work, multiple approaches were taken regarding investigating the topic of Quantum computing, including, but not limited to. quantum algorithms, quantum hardware, quantum software, and practical uses. and limitations. Particular emphasis was given to the study of the technology’s current and future state, illustrating the current limitations imposed by the system’s complexity, and its practical applications once those issues are overcome, particularly in quantum chemistry, optimization, cryptography, machine learning [9] and AI models [10]. The research also revealed the possibility and practicality of the hybrid systems, derived using two

Received: December 8, 2025. Reviewed: June 29, 2026. Accepted: June 29, 2026.

separate architectures - semiconductor and quantum - in a single system, utilizing the advantages of both in workloads that they are each optimized towards [11].

TABLE I
CASE STUDIES ON CYBERSECURITY AND FUNDAMENTALS

Case Study	**Key Contributions**	**Rationale**
[6]	*Supercomputers and quantum com- puting on the axis of cyber security. (2024)* RSA/AES algorithms are ineffective against quantum systems; need for quantum-resistant encryption algorithms	Illustrates the need of new encryption algorithms for cybersecurity to stay relevant
[12]	*Quantum Computing and Ethical Hacking: Redefining Vulnerability Assessment in Cyber Security. (2023)* New encryption and legal frameworks are needed.	Covers not only techinical, but also ethical and legal implications of quantum hacking
[7]	*Quantum cryptography with coherent states. (1995)* Physical phenomenas unique to quantum systems are capable to be used for hack detections	Provides potentially very strong security measures to prevent hacking
[13]	*Certified random number generation using quantum computers. (2025)* Random number generator is truly random, unlike classical one with pseudo-randomness.	Shows the impossibility to predict quantum randomness
[14].	*A Survey of Important Issues in Quantum Computing and Communications. (2023)* Difficulties of manufacturing stable quantum computers, possibility of quantum network	Covers the quantum computing broadly

The table above presents articles related more to technological issues of quantum computers, such as cybersecurity, encryption methods, and key exchange for secure communication.

Compared to the table above, which focused more on security, the table below is more focused on the future and the artificial intelligence that will be created using quantum computers. Many studies suggest that it would be far better to transition to a hybrid use of quantum computers, that is, to use quantum computers alongside the conventional computers that are used in everyday life. Several articles in the table below also discuss the benefits and risks of quantum computers in the future. This helps us understand the ethical norms for using quantum computers and further analyze how society will adapt to this new method of using computers.

Received: December 8, 2025. Reviewed: June 29, 2026. Accepted: June 29, 2026.

TABLE II
CASE STUDIES ON FUTURE QUANTUM POWER AND MACHINE LEARNING

Case Study	**Key Contributions**	**Rationale**
[1]	*The future of quantum computing with superconducting qubits. (2022)* Quantum systems are not purely theoretical, but practical. Possibility of hybrid quantum/classical systems.	Shows the possibility of emerging hybrid systems, having advantages of both.
[15]	*On the impact of quantum computing technology on future developments in high-performance scientific computing. (2017)* Quantum systems are not universally good against all problem fields.	Show the both the negative and positive aspects of quantum computing
[16]	*Our future with quantum computers. (2023)* There are 3 developments paths, with high probability of multiple approaches combined	Discusses not only technological, but also ethical and practical side of quantum computers
[17]	*Quantum machine learning for image classification. (2024)* Quantum integration to classical systems decreases parameters needed	Demonstrates quantum system capability in hybrid context
[8]	*Challenges and opportunities in quantum machine learning. (2022)* Quantum system and machine learning connection. Quantum computing already used in present	It uses real-world studies to come to the conclusions

Compared to the first table, which focused more on security, the table above is more focused on the future and the artificial intelligence that will be created using quantum computers. Many studies suggest that it would be far better to transition to a hybrid use of quantum computers, that is, to use quantum computers alongside the conventional computers that are used in everyday life. Several articles in the table below also discuss the benefits and risks of quantum computers in the future. This helps us understand the ethical norms for using quantum computers, and further analyze how society will adapt to this new method of using computers.

Received: December 8, 2025. Reviewed: June 29, 2026. Accepted: June 29, 2026.

TABLE III
CASE STUDIES ON HARDWARE, INDUSTRY DEVELOPMENT, AND SOCIETAL RISKS

Case Study	**Key Contributions**	**Rationale**
[11]	*Quantum Computer Architecture Toward Full-Stack Quantum Accelerators. (2020)* Qubit behavior, hardware complexity, hybrid systems.	Shows where quantum advantage appears.
[18]	*Advances in Quantum Computation and Quantum Technologies: A Design Automation Perspective. (2022)* Physical limits of classical transistor chips; quantum systems having quantum advantage	Motivates necessity of quantum computing.
[9]	*IBM quantum computers: evolution, performance, and future directions. (2025)* Large qubit processors already developed, existence of Qiskit software tools, possibility for cloud access to quantum technologies	Shows actual industry progress from one of the notable technological companies
[19]	*A Battle for the Future: Quantum Computing Chips Markets analysis in the light of Game Theory. (2018)* There is a possiblity of further inequality driven by the access of quantum technology	Covers quantum computing from economical standpoint
[20]	*The Impact of Quantum Computing on Present Cryptography. (2018)* Current encryption potential to become ineffective with quantum systems	Approaches cybersecurity problems from critical standpoint
[3]	*Early Fault-Tolerant Quantum Computing. (2024)* Neccesity of Error correction algorithms and scalability issues introduced after 1000+ qubits.	Explains why quantum systems can't grow too big currently

The table above lists articles that address aspects of quantum computer installation, including where and how they will be located, cooling methods, and so on. It also discusses the economics of the transition to quantum computers, how affordable they will be for people with an average standard of living, which regions will use quantum computers more often, and methods which will help society adapt to this new computing method.

Received: December 8, 2025. Reviewed: June 29, 2026. Accepted: June 29, 2026.

TABLE IV
CASE STUDIES ON ADDITIONAL ARTICLES (PART 1)

Case Study	Key Contributions	Rationale
[2]	*A Review on Quantum Computing Trends & Future Perspectives. (2022)* Identifies history, current approaches, and unresolved challenges; outlines potential applications	Provides wide background context and defines open problems in quantum research.
[4]	*Review of Distributed Quantum Computing: From single QPU to High Performance Quantum Computing. (2025)* Describes DQC models, inter-QPU communication, and scaling issues that appear with high performance quantum systems	Relevant to understanding to models and of scalability quantum systems.
[5].	*Energy-Consumption Advantage of Quantum Computation. (2025)* Shows where quantum reduces energy usage and where overheads eliminate benefits.	It asseses the environmental and practical aspects of quantum computing and its adoption
[10]	*Quantum Computing and AI: Impacts & Possibilities. (2022)* Improvements in machine learning tasks involving large, complex datasets from quantum integration	Show the role of quantum systems in AI models and software related to it
[21]	*Next Steps in Quantum Computing: Computer Science's Role. (2019)* Identifies software, compiler, and algorithmic needs for practical quantum systems.	Explains the necessity of hybrid and cross-disciplinary approaches.

The additional studies cited in the table above highlight the challenges inherent in the transition to quantum computers. Furthermore, these studies reveal several new opportunities as humanity transitions to quantum computers. Specifically, new communication methods without network latency, powerful new machine learning models, and new software and their capabilities. Each scientific paper presents a problem, possible solutions, and a series of steps to adapt to new types of computing machines with minimal or no consequences.

At the same time, it's not hard to see that the transition from conventional computer systems, which use binary arithmetic for calculations, to quantum computers, which use qubits for mathematical operations, is a labor-intensive and time-consuming process. Researchers emphasize that this process is still in its early stages and requires not only technological breakthroughs in this area but also human adaptation to these changes. People must still rely on academic and industrial norms to navigate this labor-intensive transformation.

Received: December 8, 2025. Reviewed: June 29, 2026. Accepted: June 29, 2026.

TABLE V
CASE STUDIES ON ADDITIONAL ARTICLES (PART 2)

Case Study	**Key Contributions**	**Application**
[22]	*Machine learning methods in quantum computing theory. (2019)* Describes that ML helps analyze quantum systems and develop algorithms.	Improve connection between ML and quantum computing.
[23]	*Prediction by Linear Regression on a Quantum Computer. (2016)* Quantum computers help make quick predictions	Provides an example of quantum speedup in ML tasks.
[24]	*Machine Learning Applications of Quantum Computing: A Review. (2024)* Discusses real applications, limitations and opportunities of QML.	Supplements theoretical reviews with practical context.
[25]	*Strengths and Weaknesses of Quantum Computing. (1997)* Defines problem classes with quantum speedup and problem classes without advantage.	Provides a theoretical basis and refutes highly optimistic claims about quantum computers.

The second section of case studies on additional articles explores the application of all the above-mentioned methods for using quantum computers, not only in theory but also in practice. Researchers conducted experiments and tests to determine how each technique can improve the performance of quantum computers. Attention is also focused on the connection between quantum computers and machine learning. Researchers see enormous potential in machine learning and AI with quantum computers, and this is practically their only area of application. O studies in this table, however, present less optimistic arguments regarding quantum computers.

II. THE SOCIETAL AND TECHNOLOGICAL IMPACT OF QUANTUM COMPUTERS

In this case, various articles served as input, providing a more detailed understanding of quantum computers and a deeper understanding of topics related to security, AI, machine learning, the future of quantum computing, and other similar subjects. In addition to the articles, a survey was conducted that provided a clear picture of how people view quantum computers and their potential implications. However, a limited amount of testing was done through the statistical analysis, with only the basic pool being performed, which was done on the Telegram social platform, with samples being represented via the groups functionality. The poll contained only descriptive analysis, using broad questions to identify the overall public opinion on quantum computing; it was not a focus of the research and instead focused mostly on qualitative analysis of articles covered in the paper.

Considering the lack of experts relating to the field of quantum engineering and its related fields, it's assumed and to a point proven that all the data, graphs, diagrams, visuals, etc. that were present in the articles do not contain any major inconsistencies or inaccuracies of any relevant information from which conclusions were drawn. Similarly, it is assumed that the information present is self-sufficient for competency in the topics that the articles provide for the writing of the paper.

The study conducted was centered around the basics of quantum computing, namely its hardware and software at a conceptual level, the disadvantages and advantages of the technology related to it, and practical applications that come with the adaptation in the future. The scope of the article excludes topics without relevance to quantum and semiconductor computing, engineering, and architecture, with the writing being limited to the subjects within the scope of the paper, with outside topics only briefly mentioned. A survey was conducted among 51 people who are studying or have studied at SDU University. The results of the survey are presented below.

Received: December 8, 2025. Reviewed: June 29, 2026. Accepted: June 29, 2026.

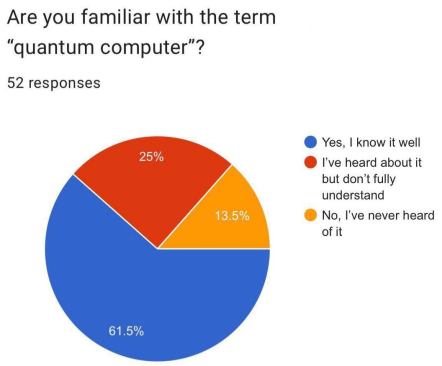

Fig. 1.

During the survey, most respondents understood what quantum computers are (61.5% were familiar with the term, 25% had heard of it but not fully understood it, and 13.5% had never heard of it). While it shows most of the population knows about quantum computers, that being 86.5%, there is only small supermajority of people who actually have acceptable understanding of it, implying limited awareness of the term. It appears there is higher proportion of people understanding the term well in younger groups compared to older groups.

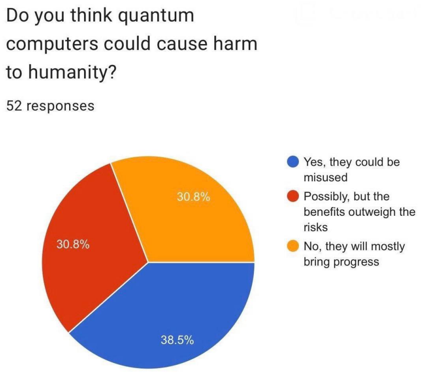

Fig. 2.

However, opinions were divided on the potential harm to humanity. 38.5% believed they could be used for harm, 30.8% believed the benefits outweigh the risks, and 30.8% believed they would primarily bring progress. This demonstrates that people are still cautious and uncertain about the impact quantum computers will have, which in turn points to the need for research in this area. However, there is still a significant number of respondents who responded that the potential of misuse is significant, mostly from younger groups.

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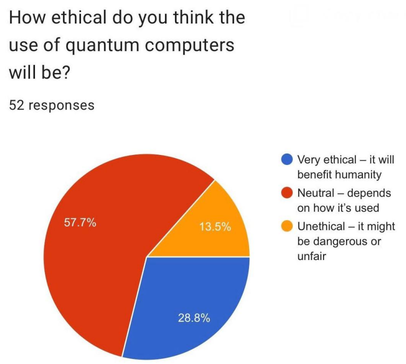

Fig. 3.
In terms of ethics, people recognize the benefits quantum computers could bring but are also wary of the risks. A supermajority appears to hold the neutral opinion regarding the ethicality of quantum computer use at 57.7%, followed by respondents' positive responses about the ethics at 28.8%, followed by a minority that holds the opposite opinion at 13.5%. It appears that the population at large is not against quantum computers in terms of ethics.

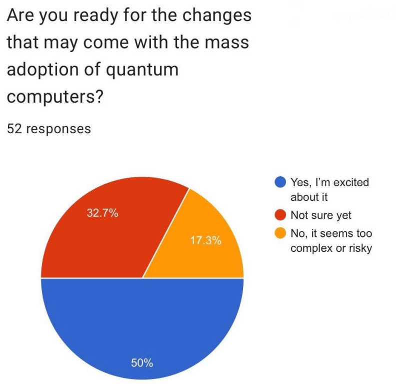

Fig. 4.
From the responses, It is pretty clear that most people are not against about the changes that may be required in order to adapt to the quantum era, with 50% being confident, 32.7% being unsure, and 17.3% in disagreement. It shows that the vast majority of respondents, it being at 82.7%, are not opposed to the potential changes in multiple fields brought with quantum computers. There is still, minority at 17.3% expressing negative opinion, however with majority of them having insufficient knowledge of quantum computers, suggesting some uncertainty among the public

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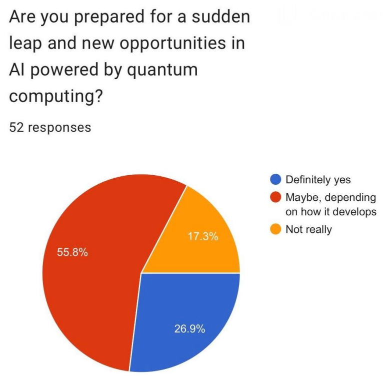

Fig. 5.

From the graph, it can be seen that most people hold neutral stance regarding quantum computing prospect in fields related to AI(Artificial Inteliigence) at 55.8%. However there is also non-negligible support and opposition to quantum computing use in AI, being 26.9% and 17.3% respectively It is also worth noting that there are outside factors relating to either AI or quantum computing which may affect the responses related to the question. However the data is still valuable for recognizing the general trend.

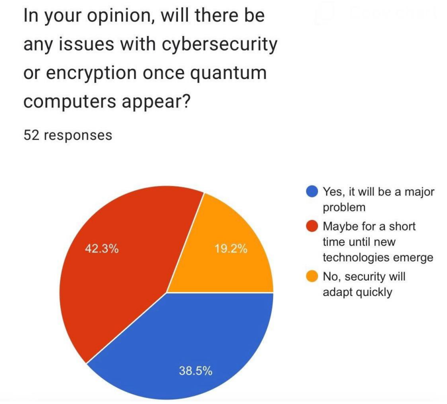

Fig. 6.

According to the graph, it can be seen that vast majority of respondents acknowledge the possible risks and issues related to the introduction of quantum computers on cybersecurity and encryption fields, with 42.3% responding with it being present until new technologies are present, and 38.5% holding stronger opinion with it being a major problem. There is, however, still about 19.2% respondents answering with period of vulnerability being brief.

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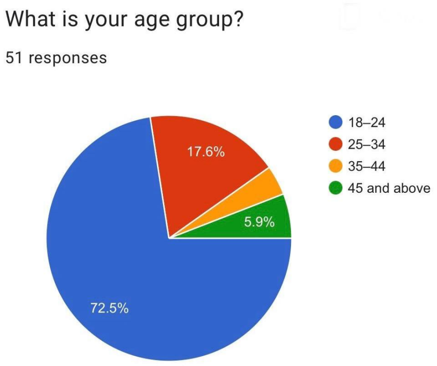

Fig. 7.

The survey was conducted among the groups which revealed that most respondents are young adults (72.5% of those aged 18–24), who are either pursuing higher education or working in the professional sector (85.5% students, 25.5% employed). The younger group has shown general trend to be well aware of quantum computers and the sentiments being more favorable to the changes these technologies could bring. However, similarly to older groups, younger groups are concerned about the issues with possibility to live in a secure digital world that could be disrupted.

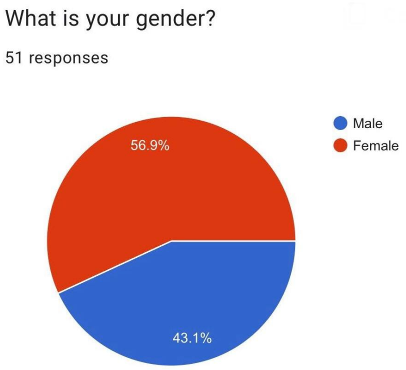

Fig. 8.

The overwhelming majority of respondents were women (56.9%), with the remainder being men. No meaningful differences were observed between the responses of men and women, leading us to conclude that gender is irrelevant in this regard. However there appears to be noticeably higher proportion of males in specialized fields in comparison to females among the respondents, however due to insufficient sample specifically of specialists, it can’t be regarded as representative of specialist proportion.

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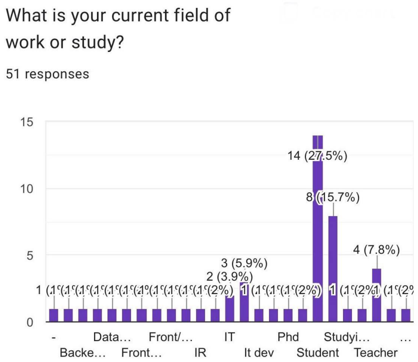

Fig. 9.

Since the survey was conducted within the framework of the SDU University, it was not difficult to assume that the majority of survey participants would be students of IT and other IT-related fields of activity, since the Engineering Faculty makes up the largest number of students in comparison to other departments. However it also shows that there were multiple respondents in specialized fields, with their responses being of higher importance.

III. RESULTS AND DISCUSSION

The analysis of the research results indicates that quantum computers can revolutionize the world of big computing. It is also important to note that this study revealed the risks and problems associated with them, which go hand in hand with their capabilities and specifications, their computing potential can lead to breaking all existing ciphers, as well as lead to additional costs for protecting sensitive data from attacks using quantum computer. As well as the current disadvantages of quantum computers, such as their high sensitivity. Due to the noise, increased consumption and high cost, they are inaccessible to open laboratories, which increases the risk of monopolization and further use as a kind of weapon in the global arena. Comparing the results of analysis with the results of other studies, it is worth noting that most of them note only the advantages of quantum technologies and their speed, power and new features. However, this research has also revealed their weaknesses at the moment. Just as other authors wrote about the era of “quantum supremacy” in their research, this study also addressed the challenges of scalability and high cost. Unlike other studies, the conclusion indicates that quantum computing is not yet ready for mass use. In other words, the study had several shortcomings. First of all, the work depends on the results of other investigations and their analysis. The conclusions are solely dependent on previous research because there are no novel experiments and no access to quantum computers. Second, knowledge that is current may become out of date in two to three years, particularly in the quickly evolving field of quantum computing. However, the study offers positive findings, highlights important issues, and suggests areas for future investigation. Quantum computers have the ability to process information in ways not available to classical computers. Thanks to this, they can solve complex tasks much rapidly, which will lead to major changes in science, medicine and technology. As a result, as quantum technologies become more accessible, industries such as medicine, finance, and artificial intelligence will develop rapidly. At the same time, this rapid progress may also create new risks. Since quantum computers can crack traditional encryption systems, their development can cause serious security problems. In addition, quantum devices are expensive and complex, only a few countries or companies can produce them, which can increase global inequalities in access to technology and research. In the future, quantum computers can make significant progress and significantly change people’s lives. They can accelerate the development of artificial intelligence by allowing systems to learn and make decisions on a new level. This will pave the way for the creation of more accurate and faster models for forecasting, medical diagnostics and production optimization. And those countries that are the first to master quantum technologies will be able to gain a significant advantage in the field of science, technology and economics

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IV. CONCLUSION

The main goal of this research was to understand and find out whether the world is ready for a quantum computer era and its future progress consequences. The studies which were selected always mentioned that quantum computers will have a profound impact on many areas, such as cybersecurity. However, there were studies that proposed working systems for combating quantum cyberattacks and new quantum encryption methods. As a result, people are quite prepared to prevent the threat of quantum cyberattacks by implementing new data protection methods. [6] All reviewed studies examined the prospects of quantum technologies and their possible future implementation. Currently, NISQ systems are noisy and error-prone. [1] Over time, a transition to hybrid systems is expected, in which conventional computers will work together with quantum ones. [5] Which is further supported by some studies that note that quantum computers are unlikely to completely replace conventional ones, as there are many challenges, such as maintaining their stability and error correction. Furthermore, the advent of such powerful technologies raises many new questions about security, ethics, and trust. Therefore, the most likely future for quantum computers is a hybrid operating system.

Based on the research that was done, it became clear that quantum computing still has some challenges to overcome, but at the moment, this technology is still too raw for full use, and there are risks in the future that could change the way the world is seen in the era of quantum technologies.

Over the course of this research, it was often mentioned that quantum systems possess quantum supremacy, or, in other words, problems that classical computers cannot solve in a reasonable amount of time due to exponential growth in complexity. However, the exponential growth of computing power with increasing qubits and true parallelism in quantum computers makes it possible to solve problems related to machine learning, chemistry, and other fields with very low time and energy consumption compared to classical architectures. [10] Experimental research and the development of digital twins will be crucial in the future, since the effective implementation of quantum systems cannot be guaranteed without first models that illustrate their working principles.

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Received: December 8, 2025. Reviewed: June 29, 2026. Accepted: June 29, 2026.

SECTION III
Mathematics with Applied Aspects

This section includes applied mathematics research with a focus on modeling, optimization, and analysis of computational and engineering systems.

Article

Varieties of right-commutative algebras defined by the identity $a(aa) = 0$

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DOI: 10.47344/07yat580

Abstract

An algebra R is called a *right-commutative* algebra if it satisfies the right-commutative identity

$$(x_1x_2)x_3 - (x_1x_3)x_2 = 0,$$

for all elements $x_1, x_2, x_3 \in R$.

This algebra is also well known by another name, for example, *NAP* algebra or a *non-associative permutative* algebra. Varieties of right-commutative algebras contain important subvarieties such as Novikov and bicommutative algebras.

In this paper, we consider two subvarieties $\mathfrak{M}$ and $\mathfrak{N}$ of the variety of right-commutative algebras. The subvariety $\mathfrak{M}$ is defined by the identities $x_1(x_1x_1) = 0$, $x_1[x_1, x_2] = 0$ and $x_1(x_2x_1) - x_2(x_1x_1) = 0$. The subvariety $\mathfrak{N}$ is defined by the identities $x_1(x_1x_1) = 0$, $x_1(x_1x_2) - 2x_1(x_2x_1) + x_2(x_1x_1) = 0$ and $[x_1, x_2]x_1 = 0$.

We study the free algebras in the varieties $\mathfrak{M}$ and $\mathfrak{N}$ of right-commutative algebras. We investigate the S_n-module structures of the free algebras $F_n(\mathfrak{M})$ and $F_n(\mathfrak{N})$ in the varieties $\mathfrak{M}$ and $\mathfrak{N}$, respectively. As a consequence, we prove that the subvarieties $\mathfrak{M}$ and $\mathfrak{N}$ of the variety of right-commutative algebras satisfy the distributivity conditions. Moreover, we describe all subvarieties of the varieties $\mathfrak{M}$ and $\mathfrak{N}$.

Keywords: variety of algebras, lattice of subvarieties, free algebra, right-commutative algebra, S_n-module structure

I. INTRODUCTION

An algebra R is called a *right-commutative* algebra if for all elements $x_1, x_2, x_3 \in R$

$$(x_1x_2)x_3 - (x_1x_3)x_2 = 0. \tag{1}$$

This algebra is also well known by another name, for example, NAP algebra or *non-associative permutative* algebra, see [1], [2]. The variety of NAP algebras contains several important subvarieites. In particular, the varieties of left-Novikov algebras and bicommutative algebras (or LR-algebras) are examples of right-commutative algebras. These varieties have been extensively studied

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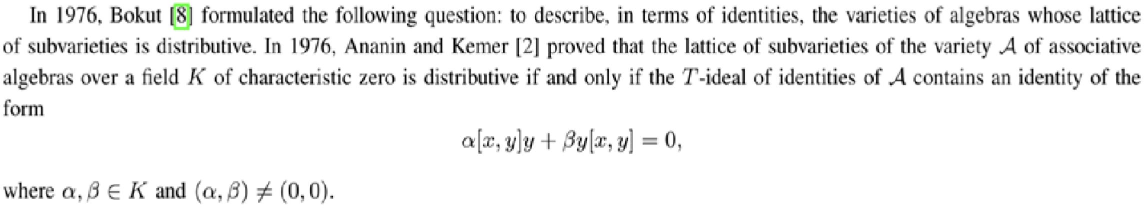
Received: April 17, 2026. Reviewed: May 13, 2026. Accepted: May 18, 2026.

from the point of view of free algebras, codimension growth, operads, and polynomial identities. For example, in [3], a free basis was constructed and the codimensions of Novikov algebras were found. Moreover, it was shown that the Novikov operad is not Koszul operad. In [4], the S_n-module structures of free Novikov algebras were investigated.

LR-algebras first appeared in the work of Dzhumadil'daev and Tulenbaev [5]. In [6], a free basis was constructed, the codimensions were calculated, and the S_n-module structures of free LR-algebras were fully studied. In 2018, Drensky and Zhakhayev [7] gave an affirmative answer to the Specht problem for LR-algebras.

Let $\mathfrak{V}$ be a variety of algebras. The set of all subvarieties of the variety $\mathfrak{V}$ of algebras form a lattice $L(\mathfrak{V})$ with respect to the inclusion order. The lattice $L(\mathfrak{V})$ is distributive if for all subvarieties $\mathfrak{V}_1$, $\mathfrak{V}_2$, and $\mathfrak{V}_3 \subseteq \mathfrak{V}$ the following identity holds

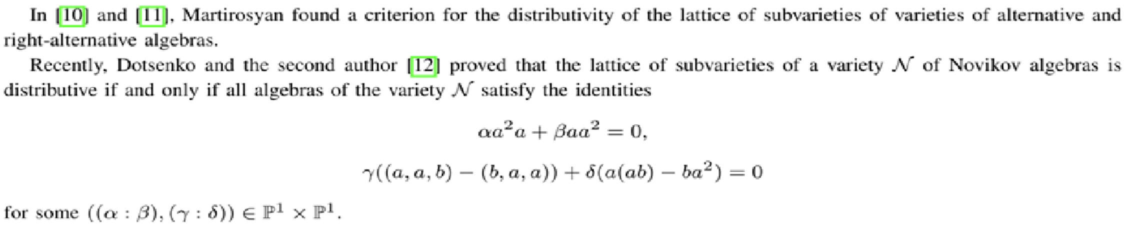
$$(\mathfrak{V}_1 \vee \mathfrak{V}_2) \wedge \mathfrak{V}_3 = (\mathfrak{V}_1 \wedge \mathfrak{V}_3) \vee (\mathfrak{V}_2 \wedge \mathfrak{V}_3).$$



In 1976, Bokut [8] formulated the following question: to describe, in terms of identities, the varieties of algebras whose lattice of subvarieties is distributive. In 1976, Ananin and Kemer [2] proved that the lattice of subvarieties of the variety $\mathcal{A}$ of associative algebras over a field K of characteristic zero is distributive if and only if the T-ideal of identities of $\mathcal{A}$ contains an identity of the form

$$\alpha[x,y]y + \beta y[x,y] = 0,$$

where $\alpha, \beta \in K$ and $(\alpha, \beta) \neq (0,0)$.



In [10] and [11], Martirosyan found a criterion for the distributivity of the lattice of subvarieties of varieties of alternative and right-alternative algebras.

Recently, Dotsenko and the second author [12] proved that the lattice of subvarieties of a variety $\mathcal{N}$ of Novikov algebras is distributive if and only if all algebras of the variety $\mathcal{N}$ satisfy the identities

$$\alpha a^2 a + \beta a a^2 = 0,$$

$$\gamma((a,a,b) - (b,a,a)) + \delta(a(ab) - ba^2) = 0$$

for some $((\alpha : \beta), (\gamma : \delta)) \in \mathbb{P}^1 \times \mathbb{P}^1$.

Let $\mathfrak{M}$ be a subvariety of the variety of right-commutative algebras defined by the identities

$$a(aa) = 0, \tag{2}$$

$$a[a,b] = 0, \tag{3}$$

$$a(ba) - b(aa) = 0. \tag{4}$$

Let $\mathfrak{N}$ be a subvariety of the variety of right-commutative algebras defined by the identities (2), and

$$a(ab) - 2a(ba) + b(aa) = 0, \tag{5}$$

$$[a,b]a = 0. \tag{6}$$

In this work, we consider the free algebras $F_n(\mathfrak{M})$ and $F_n(\mathfrak{N})$ of rank n in the varieties $\mathfrak{M}$ and $\mathfrak{N}$, respectively. We study the S_n-module structures of the free algebras $F_n(\mathfrak{M})$ and $F_n(\mathfrak{N})$, and show that the varieties $\mathfrak{M}$ and $\mathfrak{N}$ satisfy the distributive conditions. Moreover, we describe all subvarieties of the varieties $\mathfrak{M}$ and $\mathfrak{N}$.

Received: April 17, 2026. Reviewed: May 13, 2026. Accepted: May 18, 2026.

In 1950, Malcev [13] and Specht [14] were the first to independently apply the representation theory of the symmetric group to the study of polynomial identity algebras (PI-algebras). In the 1970s, Regev [15] further developed the Malcev–Specht method. In the 1980s, Drensky [16] and Berele [17] began applying the representation theory of the general linear group to the study of PI-algebras.

In 1986, Vladimirova and Drensky [18], using methods from the representation theory of the symmetric and general linear groups, completely described all subvarieties of the variety of associative algebras satisfying an identity of degree three over a field of characteristic zero. In the present paper, we apply the methods developed in [18].

Proposition III.1. *As S_n-modules*

$$P_1(\mathfrak{M}) \cong V(1), \quad P_2(\mathfrak{M}) \cong V(2) \oplus V(1,1),$$

$$P_3(\mathfrak{M}) \cong V(3) \oplus V(2,1) \oplus V(1,1,1),$$

$$P_n(\mathfrak{M}) \cong V(n) \oplus V(n-1,1), \ n \geq 4.$$

The submodules $V(n)$ and $V(n-1,1)$ are generated by the linearizations of $(\cdots \underbrace{(aa)\cdots)a}_{n}$ and $(\cdots([a,b]\underbrace{a)\cdots)a}_{n-2}$, respectively.

The submodule $V(1,1,1)$ is generated by $a(bc)-a(cb)+c(ab)-b(ac)+b(ca)-c(ba)$.

II. METHODS

III. RESULTS AND DISCUSSION

Throughout this paper, the field K is of zero characteristic. Let $P_n(\mathfrak{M})$ be a multilinear component of the free algebra $F_n(\mathfrak{M})$. Let $V(\lambda)$ be an irreducible S_n-module for partition $\lambda \vdash n$.

Proof. Multiplying (2), (3) and (4) by a on the left, we obtain

$$a(a(aa)) = 0, \tag{7}$$

$$a(a[a,b] = 0, \tag{8}$$

$$a(a(ba)) - a(b(aa)) = 0. \tag{9}$$

Multiplying (2) by b on the left, we get

$$b(a(aa)) = 0. \tag{10}$$

Applying identities (8), (9) and (10) to the expression $\Delta_{a\mapsto b}a(a(aa)) = 0$, we obtain

$$a(b(aa)) = a(a(ba)) = a(a(ab)) = 0. \tag{11}$$

Multiplying identities (3) and (4) by b on the left, we get

$$b(a(ab)) - b(a(ba)) = 0, \tag{12}$$

$$b(a(ba)) - b(b(aa)) = 0. \tag{13}$$

Interchanging a and b in (12) and (13), we get

$$a(b(ba)) - a(b(ab)) = 0, \tag{14}$$

$$a(b(ab)) - a(bb)) = 0. \tag{15}$$

Applying identities (12) and (13) to the expression $\Delta_{a\mapsto b}b(a(aa)) = 0$, we obtain

$$b(b(aa)) = 0. \tag{16}$$

Received: April 17, 2026. Reviewed: May 13, 2026. Accepted: May 18, 2026.

Applying (16) to identities (12)-(15), we get

$$a(a(bb)) = a(b(ab)) = b(a(ab)) = a(b(ba)) = b(a(ba)) = 0. \tag{17}$$

Multiplying identities (3) and (4) by c on the left, we obtain

$$c(a(ab)) - c(a(ba)) = 0, \tag{18}$$

$$c(a(ba)) - c(b(aa)) = 0. \tag{19}$$

It follows from (18) and (19) that

$$c(a(ab)) - c(b(aa)) = 0. \tag{20}$$

After swapping b and c in (18)-(20), we get

$$b(a(ac)) - b(a(ca)) = 0, \tag{21}$$

$$b(a(ca)) - b(c(aa)) = 0, \tag{22}$$

$$b(a(ac)) - b(c(aa)) = 0. \tag{23}$$

Applying identities (22) and (23) to the expression $\Delta_{a\mapsto c} b(a(aa)) = 0$, we obtain

$$b(c(aa)) = 0. \tag{24}$$

Applying (24) to identities (18)-(23), we get

$$b(a(ca)) = b(a(ac)) = c(b(aa)) = c(a(ba)) = c(a(ab)) = 0. \tag{25}$$

Applying (25) to the expression $\Delta_{a\mapsto c} a(a(ab)) = 0$, we get

$$a(c(ab)) + a(a(cb)) = 0. \tag{26}$$

Applying (26) to the expression $\Delta_{b\mapsto c} a(a(bb)) = 0$, we get

$$a(c(ab)) - a(a(bc)) = 0. \tag{27}$$

Applying (25) and (26) to the expression $\Delta_{a\mapsto c} a(a[a, b]) = 0$, we get

$$a(c(ba)) + a(a(bc)) = 0. \tag{28}$$

After swapping b and c in (26), we obtain,

$$a(b(ac)) + a(a(bc)) = 0. \tag{29}$$

The difference of (28) and (29) is

$$a(c(ba)) - a(b(ac)) = 0. \tag{30}$$

Interchanging b and c in (27) and (30), we get

$$a(b(ac)) - a(a(cb)) = 0, \tag{31}$$

$$a(b(ca)) - a(c(ab)) = 0. \tag{32}$$

Applying identities (25), (27) and (30)-(32) to the expression $\Delta_{a\mapsto c}(\Delta_{a\mapsto b} a(a(aa))) = 0$, we obtain

$$a(a(bc)) + a(c(ab)) = 0. \tag{33}$$

Adding of (27) and (33), we obtain

$$a(c(ab)) = 0. \tag{34}$$

Applying (34) to (27) and (30)-(32), we get

$$a(c(ba)) = a(b(ca)) = a(b(ac)) = a(a(cb)) = a(a(bc)) = 0. \tag{35}$$

Received: April 17, 2026. Reviewed: May 13, 2026. Accepted: May 18, 2026.

Applying (35) to the expression $\Delta_{b\mapsto cd}a(ab) - a(ba) = 0$, we obtain

$$a((cd)a) = 0. \tag{36}$$

From (36) follow

$$a((ba)a) = a((ab)a) = 0. \tag{37}$$

Applying (37) to the expression $\Delta_{a\mapsto b}a((aa)a) = 0$, we obtain

$$b((aa)a) = 0. \tag{38}$$

Applying (36) to the expression $\Delta_{a\mapsto b}a((ba)a) = 0$, we obtain

$$b((ba)a) = 0. \tag{39}$$

Interchanging a and b into (39), we get

$$a((ab)b) = 0. \tag{40}$$

Applying (39) to the expression $\Delta_{a\mapsto b}b((aa)a) = 0$, we get

$$b((ab)a) = 0. \tag{41}$$

Applying (36) to the expression $\Delta_{a\mapsto c}a((ba)a) = 0$, we obtain

$$c((ba)a) = 0. \tag{42}$$

Applying (42) to the expression $\Delta_{a\mapsto c}b((aa)a) = 0$, we obtain

$$b((ac)a) = 0. \tag{43}$$

Applying (43) to the expression $\Delta_{a\mapsto c}a((ab)a) = 0$, we get

$$a((ab)c) = 0. \tag{44}$$

Hence,

$$a((bc)d) = 0. \tag{45}$$

Applying (35) and (45) to the expression $\Delta_{a\mapsto cd}a(aa) = 0$, we obtain $(cd)(aa) = 0$. Applying the derivation $\Delta_{a\mapsto b}$ to the identity $(cd)(aa) = 0$, we get

$$(cd)(ab) + (cd)(ba) = 0. \tag{46}$$

Applying (45) and (46) to the expression $\Delta_{a\mapsto cd}a(ab) - a(ba) = 0$, we obtain

$$2(cd)(ab) - a(b(cd)) = 0. \tag{47}$$

Applying the derivation $\Delta_{a\mapsto b}$ to the identity $a(a(cd)) = 0$, we get

$$a(b(cd)) + b(a(cd)) = 0. \tag{48}$$

Applying identities (45) and (48) to the expression $\Delta_{a\mapsto cd}a(ba) - b(aa) = 0$, we get

$$(cd)(ba) + 2a(b(cd)) = 0. \tag{49}$$

Applying (46) to the summing of twice (47) and (49), we obtain

$$(cd)(ab) = 0. \tag{50}$$

Applying (50) to (47), we obtain

$$a(b(cd)) = 0. \tag{51}$$

□

Received: April 17, 2026. Reviewed: May 13, 2026. Accepted: May 18, 2026.

Proposition III.2. *As S_n-modules*

$$P_1(\mathfrak{N}) \cong V(1), \quad P_2(\mathfrak{N}) \cong V(2) \oplus V(1,1),$$

$$P_3(\mathfrak{N}) \cong V(3) \oplus V(2,1) \oplus V(1,1,1),$$

$$P_n(\mathfrak{N}) \cong V(0), \; n \geq 4.$$

The submodules $V(1)$, $V(2)$ and $V(1,1,1)$ are generated by the linearizations of a, aa and $ab-ba$, respectively.

The submodules $V(3)$, $V(2,1)$ and $V(1,1,1)$ are generated by the linearizations of $(aa)a$, $a[a,b]$ and $a(bc)-a(cb)+c(ab)-b(ac)+b(ca)-c(ba)$, respectively.

Let $P_n(\mathfrak{N})$ be a multilinear component of the free algebra $F_n(\mathfrak{N})$.

Proof. Multiplying (2) by a on the left, we obtain

$$a(a(aa)) = 0. \tag{52}$$

Multiplying (2) by a on the right and applying (1), we obtain

$$(aa)(aa) = 0. \tag{53}$$

Applying (52) and (53) to $\Delta_{a\mapsto aa}(2)$, we get

$$a((aa)a) = 0. \tag{54}$$

Applying (1) and (53) to $\Delta_{b\mapsto aa}(6)$, we obtain

$$((aa)a)a = 0. \tag{55}$$

From (6) and (55) follows

$$((ab)c)d = 0. \tag{56}$$

Applying (1) and (56) to $\Delta_{a\mapsto aa}(6)$, we obtain

$$(ab)(aa) - 2(ba)(aa) = 0. \tag{57}$$

Multiplying (2) by b on the right and applying (1), we get

$$(ab)(aa) = 0. \tag{58}$$

Applying (58) to (57), we obtain

$$(ba)(aa) = 0. \tag{59}$$

Multiplying (5) by a on the right, and applying (1) and (59), we obtain

$$2(aa)(ba) - (aa)(ab) = 0. \tag{60}$$

Applying (58) and (59) to $\Delta_{a\mapsto b}(53)$, we obtain

$$(aa)(ba) + (aa)(ab) = 0. \tag{61}$$

Summing of (60) and (61), we get

$$(aa)(ba) = 0. \tag{62}$$

Applying (62) to (61), we obtain

$$(aa)(ab) = 0. \tag{63}$$

Applying (58) to $\Delta_{b\mapsto ab}(5)$, we get

$$2a((ab)a) - a(a(ab)) = 0. \tag{64}$$

Applying (58) to $\Delta_{a\mapsto ab}(2)$, we get

$$a((ab)a) + a(a(ab)) = 0. \tag{65}$$

Received: April 17, 2026. Reviewed: May 13, 2026. Accepted: May 18, 2026.

Summing of (64) and (65), we obtain

$$a((ab)a) = 0. \tag{66}$$

Applying (59) to $\Delta_{b \mapsto ba}(5)$, we get

$$2a((ba)a) - a(a(ba)) = 0. \tag{67}$$

Applying (59) to $\Delta_{b \mapsto ba}(2)$, we obtain

$$a((ba)a) + a(a(ba)) = 0. \tag{68}$$

Summing of (67) and (68), we get

$$a((ba)a) = 0. \tag{69}$$

Applying (1), (66) and (69) to $\Delta_{a \mapsto b}(54)$, we obtain

$$b((aa)a) = 0. \tag{70}$$

Applying (66) to (65), we obtain

$$a(a(ab)) = 0. \tag{71}$$

Applying (69) to (68), we obtain

$$a(a(ba)) = 0. \tag{72}$$

Applying (62), (63), (66) and (70), we get

$$2a(b(aa)) - b(a(aa)) = 0. \tag{73}$$

Multiplying (2) by a on the left, we get

$$b(a(aa)) = 0. \tag{74}$$

Applying (74) to (73), we obtain

$$a(b(aa)) = 0. \tag{75}$$

Multiplying (5) by a on the right and applying (1), we obtain

$$(ab)(ab) - 2(ab)(ba) + (bb)(aa) = 0. \tag{76}$$

Applying the derivation $\Delta_{a \mapsto b}$ to (58), we get

$$(ab)(ab) + (ab)(ba) + (bb)(aa) = 0. \tag{77}$$

Subtracting (76) from (77), we get

$$(ab)(ba) = 0. \tag{78}$$

Interchanging a and b into (78), we obtain

$$(ba)(ab) = 0. \tag{79}$$

Applying (1), (56) and (79) to the expression $\Delta_{a \mapsto ab}(6)$, we get

$$(ab)(ab) = 0. \tag{80}$$

Interchanging a and b into (80), we get

$$(ba)(ba) = 0. \tag{81}$$

Multiplying (6) by b on the left, we get

$$b((ab)a) - b((ba)a) = 0. \tag{82}$$

Applying the derivation $\Delta_{a \mapsto b}$ to (70), we get

$$b((ba)a) + 2b((ab)a) = 0. \tag{83}$$

Received: April 17, 2026. Reviewed: May 13, 2026. Accepted: May 18, 2026.

Summing of (82) and (83), we obtain

$$b((ab)a) = 0. \tag{84}$$

Interchanging a and b into (84), we get

$$a((ba)b) = 0. \tag{85}$$

Applying (84) to (82), we get

$$b((ba)a) = 0. \tag{86}$$

Interchanging a and b into (86), we get

$$a((ab)b) = 0. \tag{87}$$

Multiplying (5) by b on the left, we get

$$b(a(ab)) - 2b(a(ba)) + b(b(aa)) = 0. \tag{88}$$

Applying the derivation $\Delta_{a\mapsto b}$ to (74), we obtain

$$b(a(ab)) + b(a(ba)) + b(b(aa)) = 0. \tag{89}$$

Subtracting (88) from (89), we obtain

$$b(a(ba)) = 0. \tag{90}$$

Interchanging a and b into (90), we get

$$a(b(ab)) = 0. \tag{91}$$

Applying (78) and (80) to (77), we get

$$(bb)(aa) = 0. \tag{92}$$

Interchanging a and b in (92), we get

$$(aa)(bb) = 0. \tag{93}$$

Applying (85) and (92) to $\Delta_{a\mapsto bb}a(aa) = 0$, we obtain

$$a(a(bb)) = 0. \tag{94}$$

Interchanging a and b into (94), we get

$$b(b(aa)) = 0. \tag{95}$$

Multiplying (5) by c on the right and applying (1), we get

$$(ac)(ab) - 2(ac)(ba) + (bc)(aa) = 0. \tag{96}$$

Applying the derivation $\Delta_{b\mapsto c}$ to (78), (80) and (92), respectively, we get

$$(ab)(ca) + (ac)(ba) = 0, \tag{97}$$

$$(ab)(ac) + (ac)(ab) = 0, \tag{98}$$

$$(bc)(aa) + (cb)(aa) = 0. \tag{99}$$

Applying (97), (98) and (99) to $\Delta_{a\mapsto c}(ab)(aa) = 0$, we get

$$-(ac)(ab) - (ac)(ba) - (bc)(aa) = 0. \tag{100}$$

Summing of (96) and (100), we get

$$(ac)(ba) = 0. \tag{101}$$

Applying (1), (56) and (101) to $\Delta_{a\mapsto ca}(6)$, we get

$$(ba)(ca) = 0. \tag{102}$$

Received: April 17, 2026. Reviewed: May 13, 2026. Accepted: May 18, 2026.

Applying (1) and (56) to $\Delta_{a\mapsto ca}(6)$, we get

$$(aa)(bc) = 0. \tag{103}$$

Applying (1) and (56) to $\Delta_{a\mapsto ac}(6)$, we get

$$(ab)(ac) - 2(ba)(ac) = 0. \tag{104}$$

Applying (103) to $\Delta_{a\mapsto b}(aa)(ac) = 0$, we obtain

$$(ba)(ac) + (ab)(ac) = 0. \tag{105}$$

Subtracting (104) from (105), we get

$$(ba)(ac) = 0. \tag{106}$$

Applying (106) to (105), we obtain

$$(ab)(ac) = 0. \tag{107}$$

Applying (101) and (107) to (100), we obtain

$$(bc)(aa) = 0. \tag{108}$$

Multiplying (6) by c on the left, we obtain

$$c((ab)a) - c((ba)a) = 0. \tag{109}$$

Applying the derivation $\Delta_{a\mapsto b}$ to $c((aa)a) = 0$, we get

$$c((ba)a) + 2c((ab)a) = 0. \tag{110}$$

Summing of (109) and (110), we obtain

$$c((ab)a) = 0. \tag{111}$$

Applying (111) to (110), we obtain

$$c((ba)a) = 0. \tag{112}$$

Applying (1) to $\Delta_{b\mapsto c}(87)$, we get

$$a((ab)c) = 0. \tag{113}$$

Applying (108) to $\Delta_{a\mapsto bc}(2)$, we obtain

$$a((bc)a) + a(a(bc)) = 0. \tag{114}$$

Applying (108) to $\Delta_{a\mapsto bc}(5)$, we obtain

$$2a((bc)a) - a(a(bc)) = 0. \tag{115}$$

Summing of (114) and (115), we get

$$a((bc)a) = 0. \tag{116}$$

Applying (116) to (114), we obtain

$$a(a(bc)) = 0. \tag{117}$$

Applying (101), (103), (107) and (111) to $\Delta_{a\mapsto ac}(5)$, we obtain

$$2a(b(ac)) - b(a(ac)) = 0. \tag{118}$$

Applying (117) to $\Delta_{a\mapsto b}a(a(ac)) = 0$, we get

$$b(a(ac)) + a(b(ac)) = 0. \tag{119}$$

Summing of (118) and (119), we obtain

$$a(b(ac)) = 0. \tag{120}$$

Applying (120) to (119), we obtain

$$b(a(ac)) = 0. \tag{121}$$

Received: April 17, 2026. Reviewed: May 13, 2026. Accepted: May 18, 2026.

Applying (102), (106), (112) and (116) to $\Delta_{a\mapsto ca}(5)$, we get

$$2a(b(ca)) - b(a(ca)) = 0. \tag{122}$$

Applying (117) to $\Delta_{a\mapsto b}a(a(ca)) = 0$, we obtain

$$a(b(ca)) + b(a(ca)) = 0. \tag{123}$$

Summing of (122) and (123), we obtain

$$a(b(ca)) = 0. \tag{124}$$

Applying (124) to (123), we obtain

$$b(a(ca)) = 0. \tag{125}$$

Applying (121) and (125) to $\Delta_{a\mapsto b}c(a(aa)) = 0$, we obtain

$$c(b(aa)) = 0. \tag{126}$$

Applying (1) and (56) to $\Delta_{a\mapsto cd}(6)$, we obtain

$$2(ba)(cd) - (ab)(cd) = 0. \tag{127}$$

Applying the derivation $\Delta_{a\mapsto b}$ to $(aa)(cd) = 0$, we get

$$(ba)(cd) + (ab)(cd) = 0. \tag{128}$$

Summing of (127) and (128), we obtain

$$(ba)(cd) = 0. \tag{129}$$

From (54), (66), (69), (70), (84)-(87), (111)-(113), (116) follows

$$a((bc)d) = 0. \tag{130}$$

Applying (129) and (130) to $\Delta_{a\mapsto cd}(5)$, we get

$$2a(b(cd)) - b(a(cd)) = 0. \tag{131}$$

Applying the derivation $\Delta_{a\mapsto b}$ to $a(a(cd)) = 0$, we get

$$a(b(cd)) + b(a(cd)) = 0. \tag{132}$$

Summing of (131) and (132), we obtain

$$a(b(cd)) = 0. \tag{133}$$

$\square$

Theorem III.1. *Let $f \in F_n(\mathfrak{M})$. Then the consequences of higher degree of f are equivalent to the following identities*

$$a)a(bc) - a(cb) + c(ab) - b(ac) + b(ca) - c(ba), \quad \textit{if} \quad f = aa;$$

$$b)a(bc) - a(cb) + c(ab) - b(ac) + b(ca) - c(ba), \quad \textit{if} \quad f = ab - ba;$$

$$c)(\cdots(\underbrace{(aa)a)\cdots)a}_{n+1} \;\; \textit{and} \;\; (\cdots([a,b]\underbrace{a)\cdots)a}_{n-1}, \quad \textit{if} \;\; f = (\cdots(\underbrace{(aa)a)\cdots)a}_{n}, \;\; n \geq 1;$$

$$d)(\cdots(\underbrace{(aa)a)\cdots)a}_{n+1} \;\; \textit{and} \;\; (\cdots([a,b]\underbrace{a)\cdots)a}_{n-1}, \quad \textit{if} \;\; f = (\cdots([a,b]\underbrace{a)\cdots)a}_{n-2}, \;\; n \geq 2.$$

Proof. $a)$ Applying $aa = 0$ to (4), we get

$$(ba)a = 0.$$

Received: April 17, 2026. Reviewed: May 13, 2026. Accepted: May 18, 2026.

Applying the derivation $\Delta_{a\mapsto c}$ to the identity $(ba)a=0$, we obtain

$$(bc)a+(ba)c=0.$$

Applying (1) to the identity $(bc)a+(ba)c=0$, we get

$$(bc)a=0.$$

Since $a(bc)=-(bc)a$. Hence,

$$a(bc)-a(cb)+c(ab)-b(ac)+b(ca)-c(ba)=0.$$

$b)$ This follows from identity $ab-ba=0$.

$c)$ $(\cdots(\underbrace{(aa)a)\cdots)a}_{n+1}=((\cdots(\underbrace{(aa)a)\cdots)a}_{n})a=0.$

Let $n=1$. It is clear.

Let $n>1$. Then

$$((\cdots(\underbrace{(aa)a)\cdots)a}_{n})b=0.$$

Applying the last identity and (1) to the expression $\Delta_{a\mapsto b}(\cdots(\underbrace{(aa)a)\cdots)a}_{n+1}=0$, we obtain

$$(\cdots(\underbrace{(ba)a)\cdots)a}_{n+1}=0.$$

Hence, $(\cdots([a,b]\underbrace{a)\cdots)a}_{n-1}=0$.

$d)$ $(\cdots([a,b]\underbrace{a)\cdots)a}_{n-1}=((\cdots([a,b]\underbrace{a)\cdots)a}_{n-2})a=0.$

Applying (2) to the expression $\Delta_{b\mapsto aa}(\cdots([a,b]\underbrace{a)\cdots)a}_{n-2}=0$, we obtain

$$(\cdots(\underbrace{(aa)a)\cdots)a}_{n+1}=0.$$

□

Theorem III.2. *Let $f\in F_n(\mathfrak{N})$. Then the consequences of higher degree of f are equivalent to the following identities*

$$a)\ aa,\ ab-ba,\ \textit{if}\ \ f=a;$$

$$b)\ (aa)a,\ a[a,b],\ a(bc)-a(cb)+c(ab)-b(ac)+b(ca)-c(ba),\ \textit{if}\ \ f=aa;$$

$$c)\ a[a,b],\ a(bc)-a(cb)+c(ab)-b(ac)+b(ca)-c(ba),\ \textit{if}\ \ f=ab-ba.$$

Proof. $a)$ It is clear.

$b)$ From $(aa)a=0$ and (6) follows $(ab)c=0$. Applying the last identity to the expression $\Delta_{a\mapsto bc}aa=0$, we obtain $a(bc)=0$.

$c)$ This follows from identity $ab-ba=0$. □

Received: April 17, 2026. Reviewed: May 13, 2026. Accepted: May 18, 2026.

IV. CONCLUSION AND FUTURE WORK

In this paper, we studied the free algebras in the varieties $\mathfrak{M}$ and $\mathfrak{N}$. We investigated the S_n-module structures of the free algebras $F_n(\mathfrak{M})$ and $F_n(\mathfrak{N})$. As a consequence, we proved that the varieties $\mathfrak{M}$ and $\mathfrak{N}$ satisfy the distributivity conditions. Moreover, we described all subvarieties of the varieties $\mathfrak{M}$ and $\mathfrak{N}$.

It would be of interest to investigate whether there exist further subvarieties of the variety of right-commutative algebras satisfying the distributivity conditions.

V. ACKNOWLEDGMENT

The authors would like to express their gratitude to SDU University for providing the necessary resources and facilities to conduct this study.

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Received: April 17, 2026. Reviewed: May 13, 2026. Accepted: May 18, 2026.

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Journal of Emerging Technologies and Computing (JETC)

Published by SDU University •