

A Comprehensive Survey of AI-Enabled 6G Wireless Networks: Applications, Enabling Technologies, and Research Challenges

Murad Bashabsheh ^{a,1,*}, Maen Alzubi ^{b,2}

^a Department of Robotics and Artificial Intelligence, Faculty of Information Technology, Jadara University, Irbid, Jordan

^b Department of Software Engineering, Faculty of Information Technology, Jadara University, Irbid, Jordan

¹ m.bashabsheh@jadara.edu.jo; ² m.alzubi@jadara.edu.jo

* Corresponding Author

ARTICLE INFO

Article history

Received August 14, 2025

Revised September 27, 2025

Accepted December 18, 2025

Keywords

AI-Enabled 6G Networks;
Terahertz Communications;
Reconfigurable Intelligent
Surfaces;
Edge Intelligence;
Internet of Everything;
Survey Methodology;
Systematic Literature Review

ABSTRACT

The rapid evolution of wireless communication has increased the shift towards sixth generation (6G) networks, which are projected to deliver very high data rates, less than one millisecond latency, connectivity at mass scale, and pervasive intelligence. Although there are a few surveys on 6G, most of them are either technology-specific or overall, and they do not necessarily make a systematic connection to applications, enabling technologies, and research issues. This survey fills in that gap by providing the unified outlook on Artificial Intelligence (AI)-enabled 6G wireless networks. We consider weak areas like the emerging use of immersive extended reality, autonomous vehicles, holographic communication, smart healthcare, and Industry 5.0 and how they affect society and industry. Enabling technologies, such as terahertz communications, reconfigurable intelligent surfaces, integrated sensing and communication, AI-native networks, and quantum communication, are discussed in a systematic way and combined with edge computing, the Internet of Everything, and digital twins. Finally, we determine the important open research issues in energy efficiency, security, scalability, interoperability, and ethics. This survey provides a systematic roadmap for researchers and practitioners to use in innovating AI-driven 6G wireless systems in the future.

© 2025 The Authors.

Published by Association for Scientific Computing Electrical and Engineering.

This is an open-access article under the [CC-BY-NC](https://creativecommons.org/licenses/by-nc/4.0/) license.



1. Introduction

Over the past decades, the Mobile wireless communication networks have undergone an astonishing transformation. The mobile wireless Generation (G) usually defines a shift in the character of the system, velocity, technology, frequency, data capacity, reaction time, etc. Every generation possesses certain standards, various abilities, new methods, and new possibilities that make it different in comparison with the past one [1]. Mobile communication is an increasingly popular trend in recent years because mobile technology is rapidly being reformed. This reformation is attributable to the necessity of service-compatible transmission technology and exceedingly high growth in telecom users. Generation implies change in the nature of service compatible transmission

technology, and novel frequency bands. The mobile cellular age had begun in 1980, and since then communications have changed significantly and have experienced tremendous growth [2]-[4].

The development of mobile wireless communications has been changing significantly throughout the last several decades, being associated with the increased requirements of faster speeds and an enhanced quality of service. The accelerated growth has been made possible by the sustained growth in access technologies, which constitute the foundation of mobile networks [5]-[13]. The evolution of wireless communication has passed through the generations, starting with 1G, 2G, 3G, 4G and more recently 5G. The generations came with radical changes in the throughput, latency, reliability, and connectivity. With 5G and 5G-Advanced starting to come of age, these issues of bandwidth scarcity, latency exceeding the requirements of ultra-reliable low-latency communication (URLLC), and energy efficiency become evident, especially in regard to the new applications of real-time robotics [14], holography telepresence, and massive Internet of Things (IoT) deployments [15]-[19].

Although some recent surveys and reports have covered elements of 6G, most have weaknesses regarding the role of AI with regard to developing 6G architectures and applications. To illustrate, Park et al. [20] and Feng et al. [21] dwell more on ultra-reliable low-latency communication, whereas Salameh and El Tarhuni [22] give a general overview of 6G technologies and challenges without having a systematic discussion of the AI-native integration. It is important but does not offer a comprehensive synthesis that directly links AI methods with enabling technologies, application scenarios, and unresolved challenges. This discontinuity is the motivation behind a survey that does not just enumerate technological advances but is also critical about the way AI can be used as a foundational facilitator of 6G wireless systems.

To eliminate this gap, the current paper reviews AI-enabled 6G wireless networks in a single manner. The goals are tri-fold: (i) synthesizing the recent literature on the new applications, extended reality, autonomous vehicles, holographic communications, smart healthcare, and Industry 5.0; (ii) to collectively study enabling technologies, involving terahertz communication, RIS, integrated sensing and communication, AI-native architectures, and quantum communication, in the context of AI integration; and (iii) to define the unanswered research questions, including energy efficiency, security, scalability, interoperability, and ethics. The combination of these dimensions in the survey can offer a systematic roadmap to academic as well as industrial researchers.

The 6G vision is far-reaching: terabit-per-second data rates, sub-milliseconds or even microsecond latency, universal connectivity with both terrestrial and non-terrestrial networks, network intelligence everywhere, and massive numbers of energy-efficient devices [23]. Most of these features are at the concept stage or early prototyping, but they comprise the core of what researchers claim is needed in future applications like extended reality (XR/VR/AR), autonomous systems, digital twins and tactile internet [24].

Parallel to this, there is the emergence of the enabling technologies. Active development is being done on edge computing, AI-native architectures, reconfigurable intelligent surfaces (RIS), terahertz (THz) communication, and quantum-safe security. As an example, intelligent metasurface surveys emphasize design and standardization issues of connecting them to wireless systems [25]. On the same note, it is also being highlighted in research that URLLC is becoming increasingly significant in 6G-based applications that are critically important to the mission [26]. RIS are also capable of improving physical layer security by dynamically shaping the radio environment, hence augmenting secrecy in addition to communication and sensing performance [27]-[31].

Meanwhile, there are major trends that are influencing the 6G research and deployment environment. Worldwide large investments are being undertaken in R&D, testbeds, spectrum planning (in particular to THz and sub-THz bands), regulation, and standardization [32]. Such areas as the Middle East are actively implementing roadmaps on 6G infrastructure and regulatory frameworks. According to market reports, the 6G networking solutions are also in high demand in the field of enterprise, healthcare, industrial automation, augmented/virtual reality, and smart city

applications [33]. Even with this push there are challenges that are still open. These are among others; energy efficiency and sustainability (self-powered or zero-energy equipment), security and privacy in the highly connected, AI-native future, spectrum allocation and propagation in THz bands, hardware design (antennas, new materials, RIS), interoperability between terrestrial and non-terrestrial networks, and ethical and regulatory aspects. It has also been mentioned by some studies that several of the goals originally set by 6G are actually re-prioritised, and this indicates that a realistic roadmap should be taken that does not overambit but remains implementable [34].

Fig. 1 gives a synopsis of the 6G vision, which relates the major performance requirements to the enabling applications and technologies. The figure showcases the key metrics of data rate, latency, reliability, connectivity, energy efficiency, and AI-native intelligence, and details how these goals are relevant to the new applications of XR/AR/VR, autonomous systems, digital twins, smart healthcare, non-terrestrial networks, and sustainable IoE. It graphically highlights the interaction of opportunities and the real world use, and the potential of the transformative power of 6G.

The contributions of this paper can be summed up as follows. First, it makes AI not a supporting tool but a fundamental enabler of 6G, connecting applications and underlying technologies and trends. Second, it offers a recent synthesis of the state of the art, which will be based on research and market reports published in 2023-2025 and therefore be timely. Third, it determines the gaps in the research and defines the future directions to ensure that researchers and practitioners focus on the areas of innovation that have high impacts. Comprising these dimensions, the given survey contributes to the discussion on AI-enabled 6G further than the existing reviews do and presents a unique way of leading future research.

The rest of the paper is arranged in that manner. Section 2 includes the key performance requirements and use-cases of 6G. Section 3 discusses facilitating technologies and architectures. Section 4 is a market, regulation and deployment survey. Section 5 examines open research issues, such as energy, security, hardware, and ethical issues. Lastly, Section 6 provides inferences and recommendations on future studies.

2. Survey Methodology

To provide a comprehensive and reproducible overview of AI-enabled 6G wireless networks, this paper follows a systematic approach to the survey, which is based on the principles of systematic review with the elements following the PRISMA guidelines. It is a method that is able to bring transparency, clarity, and rigor to the review process, which allows other researchers to reproduce and expand the findings.

The survey is limited to literature published since 2015, covering both the first conceptual coverage of 6G and the latest technological developments. Peer-reviewed journal articles, conference proceedings, industry white papers, and standardization documents were searched to provide a comprehensive and trustworthy evidence base. A literature search was conducted in leading scientific databases, such as IEEE Xplore, Scopus, Web of Science, and ACM Digital Library, with white papers of standardization organizations like International Telecommunication Union (ITU), 3GPP, and industry consortia leaders being added as supplements.

Peer-reviewed journal papers and conference papers, official white papers, and technical reports that were widely cited were considered. Non-English articles, unpublished drafts, and sources not of technical interest were excluded. The studies that have coined new frameworks, performed performance analysis, or created technology roadmaps were prioritized and offered a good base upon which analysis and synthesis could be carried out.

All the chosen works were critically examined to determine their contributions, technological opinions, and limitations. The literature was then categorized into groups based on the applications, technologies, trends, and challenges. This organization helped to identify thematic recurrences, new technologies, and trans-cutting issues in the landscape of AI and 6G. The synthesis stage

summarized the results into a technology roadmap, which is a perspective of AI-powered 6G network development. The roadmap indicates the developed and the missed areas of research, which can be used in future academic and industrial activities.

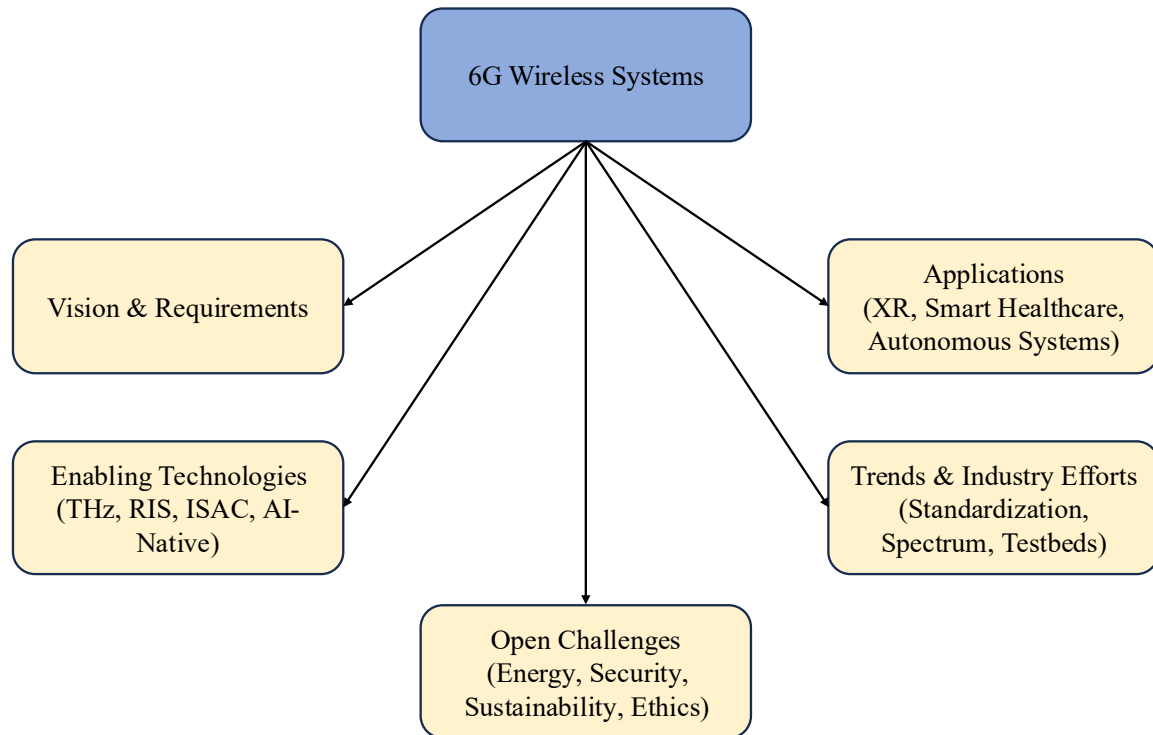


Fig. 1. Overview of 6G visions, applications, enabling technologies, industry trends, and open challenges

This step-by-step methodology is shown in Fig. 2. It starts by a literature search where a wide range of research materials are collected using related databases and keywords. This is then succeeded by a screening process, and inclusion and exclusion criteria are undergone to exclude irrelevant or poor-quality sources. The chosen literature is then sorted out in the classification phase, whereby the studies are classified according to the applications, technologies, trends, and challenges. During the analysis stage, the major AI-related observations are brought to the fore, and research gaps and opportunities are established. Lastly, the synthesis phase will entail bringing together all the findings into a roadmap towards the future of the AI-enabled 6G networks. This is a systematic and comprehensive review of the available body of knowledge that is evidence-based.

3. Performance Requirements and Use-Cases for 6G

The sixth generation (6G) wireless systems are anticipated to satisfy performance levels never experienced before and far exceeding the capability of 5G. Although 5G has brought about mobile broadband (eMBB), URLLC, and massive machine-type communication (mMTC), 6G will have to take these new dimensions of speed, intelligence, and scalability to the next level [35]-[38].

3.1. Performance Requirements

The 6G vision has performance specifications that are orders of magnitude beyond the available 5G networks. Some of the most important targets would be the highest data rates in the terabit-per-second (or higher) range and the rates perceived by the user that are higher than one gigabit per second. These are necessary to enable high-demand applications like holographic telepresence and massive digital twin environments. Latency is also another characteristic requirement, and the expectations are to decrease the end-to-end delay down to milliseconds in 5G to sub-milliseconds and even microseconds. Such low latency will allow real-time communication in areas like the tactile internet, autonomous robotics, and remote surgery [39], [40].

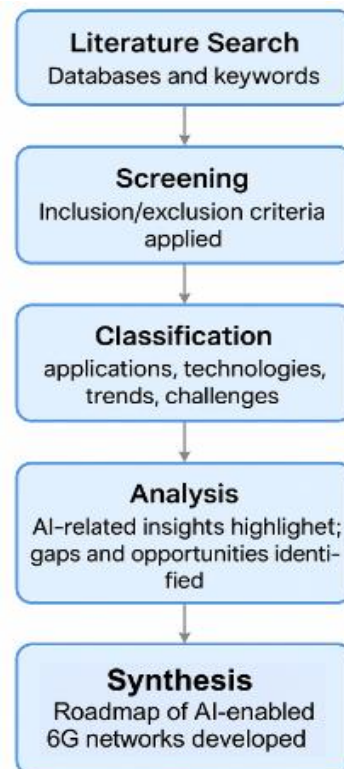


Fig. 2. The survey methodology flowchart

The 6G vision also places reliability at its core, with the known acronym of extreme ultra-reliable low-latency communication (xURLLC) being aimed at achieving the level of reliability of 99.9999999% so that mission-specific tasks such as vehicular networks and industrial automation could operate safely. Additionally, the density of connectivity will increase exponentially and serve up to 10 million devices per square kilometer to enable the IoE. Together with these objectives, energy and spectrum efficiency gains of tenfold improvement or more over 5G are projected to continue to support the increasing size of connected devices, as well as meet sustainability demands. Lastly, 6G will likely be AI-native, with machine learning applications implemented at every layer of the network to allocate resources intelligently, provide adaptive security, and deliver services in a self-optimizing manner [41], [42]. Fig. 3 shows important performance requirements of 6G and the related use cases in the real world. The diagram on the left notes important metrics, such as peak data rate, latency, reliability, connectivity density, energy efficiency, and AI-native intelligence.

These are the pillars on which higher communication capabilities further than 5G are to be supported. The nexus node will be the 6G core, which will connect these performance targets to a variety of applications. The right side presents the examples of representative use cases, which include immersive extended reality (XR/AR/VR), autonomous systems, digital twins, smart healthcare, non-terrestrial networks (NTNs), and sustainable IoE ecosystems. The links graphically present the concept that the attainment of certain performance objectives directly leads to the fulfillment of next-generation applications with the focus on the transformative nature of 6G technologies.

3.2. Use-Cases

The high performance standards of 6G are driven by a line of varying expected use cases that are bound to transform industries and everyday life. Extensive communication scenarios, including extended reality (XR), augmented reality (AR), virtual reality (VR), and holographic conferencing, will require new bandwidth and ultra-low latency capability to support smooth and realistic user experiences. Another eminent use case is autonomous systems, whether vehicle-to-everything

networks and aerial drones or maritime robotics and smart factories as a part of Industry 5.0. To work in dynamic and mission-critical systems, these applications need very high-speed and highly reliable links [43]-[46].

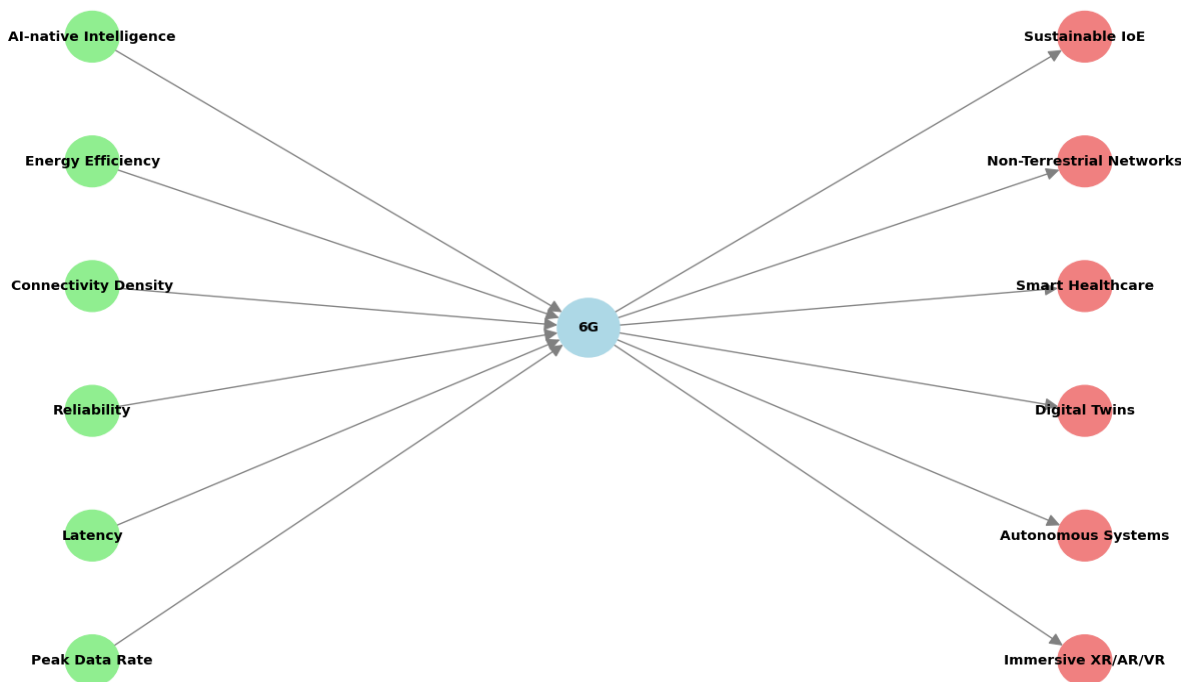


Fig. 3. 6G Performance requirements and use cases

The emergence of the digital twins and the metaverse also emphasizes the necessity of 6G since they are based on real-time matching of physical and virtual worlds on the basis of massive information exchange, facilitated by edge intelligence. In the world of healthcare, 6G is projected to facilitate remote surgery, AI-based diagnostics, and ubiquitous patient monitoring that require high reliability and energy efficiency. Also, the introduction of non-terrestrial networks (NTNs), such as satellite constellations, high-altitude platforms, and unmanned aerial vehicles, will likely offer coverage all over the world and resilient connectivity in disaster-prone or remote areas. Lastly, 6G will support sustainable IoE ecosystems, in which billions of sensors, wearables, and autonomous devices will work without using much energy, frequently with self-powered or zero-energy communication techniques. These many uses highlight how revolutionary 6G is and serve as a basis for both technology advancement and regulatory planning [47].

4. Enabling Technologies and Architectures for 6G

4.1. Advanced Radio Access Technologies

The development of 5G to 6G requires a paradigm shift of radio access technologies to address the high requirements of ultra-high data rates, low latency, and massive connectivity. The major developments are ultra-massive MIMO (Multiple Input Multiple Output), THz communication and RIS. Ultra-massive MIMO takes the size of the antennas array to the next level in order to provide more spectral efficiency through spatial multiplexing and beamforming. THz communication is the study of the use of the frequencies of over 100 GHz and provides enormous bandwidths to transmit data at high speeds. The RIS technology entails the implementation of programmable surfaces, capable of reflecting and refracting the electromagnetic waves, to enhance signal propagation to improve coverage and minimize energy consumption. All these technologies will help to ensure the expected data traffic of 1000x and the connection of up to 10 million devices per square kilometer in 6G networks [48], [49].

4.2. Artificial Intelligence and Machine Learning Integration

The development of 6G needs the intelligence of the network that could be provided by traditional optimization methods only to a small degree. The growing heterogeneity, dynamism of spectrum environment and the necessity to have ultra-low latency and reliability require the management to be dynamic. Machine Learning (ML) and Artificial Intelligence (AI) thus have become an unavoidable part of designing self-optimizing, adaptive and secure 6G networks [50]. Simultaneously, 6G will be able to serve a multitude of applications from autonomous vehicles to immersive extended reality, for which applications demand real-time responses to changing network conditions. This scale and dynamism cannot be handled manually or by rule.

AI technologies, including machine learning, deep learning, and reinforcement learning, are poised to be crucial in optimizing network operations in 6G networks. This section provides an overview of these key AI technologies and their relevance in enhancing the performance, adaptability, and security of 6G communications. Machine learning forms the backbone of AI-driven network optimization, providing algorithms capable of identifying patterns in vast datasets and making predictive decisions. In 6G networks, ML algorithms are anticipated to support a range of functions, such as predictive maintenance, traffic forecasting, and user behavior analysis. By learning from historical data and real-time network conditions, ML algorithms can optimize resource allocation, and adapt network configurations to current demands. Supervised and unsupervised ML techniques will be particularly valuable for anomaly detection and intrusion prevention, enhancing network security in response to emerging threats [51].

Embedded AI/ML throughout every layer of the network enables 6G to make predictions related to maintenance, fault prevention, smart use of spectrum, and better security. As an example, handover mechanisms based on reinforcement learning can be used to guarantee the seamless connectivity of ultra-dense deployments, whereas the edge AI can be used to provide autonomous driving with real-time analytics [52]. While AI/ML integration holds promise, it also introduces additional obstacles, such as algorithm robustness to adversarial situations, computing efficiency, energy consumption for training big models, and interpretability of decision-making. Future research will also focus on co-designing hardware and software, with AI accelerators and energy-efficient models possibly bringing scaled intelligence to 6G without compromising sustainability [53]. Fig. 4 demonstrates the facilitating nature of AI/ML and other fundamental technologies and shows how intelligence is the cornerstone of the communication systems of the next generation.



Fig. 4. Overview of key enabling technologies for 6G networks

The diagram also brings to the fore the advanced technological pillars that 6G requires such as Quantum Communication, Beam forming, Ultra Massive MIMO, Re-configurable Intelligent

Surfaces, AI/ML, Millimeter Waves, UAV/Satellite Communication and THZ Waves. All these technologies serve to increase the data rate, reliability and general efficiency of future wireless communication systems.

4.3. Network Architecture Evolution

The 6G network architecture is expected to be adapted to a more scalable, flexible and smart design. Some of the important elements are network slicing, cloud-native infrastructure, and open radio access networks (Open RAN). Network slicing, enables the development of virtualized and isolated networks according to application needs, and it increases service differentiation. Cloud-native infrastructure is used to roll out microservices and containerized application and support agile and efficient network management. The Open RAN fosters vendor diversity and interoperability by standardising interfaces, and disaggregating hardware and software. These architectural developments are to meet the heterogeneous and flexible requirements of 6G applications [54].

4.4. Digital Twins and Autonomous Networks

Virtual replicas of the physical objects called digital twins will be crucial to the design, functioning and optimization of the 6G networks. Digital twins enable proactive decisions and predictive analytics through the simulation of both network elements and user behavior in real time. The ability is important in handling the complexity and size of 6G systems. Combined with autonomous network management (that uses AI/ML to self-configure and self-heal), digital twins can create a more resilient and adaptive network. Digital twins and autonomous networks are likely to make 6G services more efficient and reliable [55].

An example of a conceptual architecture of 6G networks is shown in Fig. 5. The architecture shows the development of the 6G network, with a focus on the combination of highly developed radio access technologies, network control with the use of AI/ML, digital twins, and open RAN. It is graphical in nature and shows the relationship between these different components to create a smart and integrated 6G ecosystem.

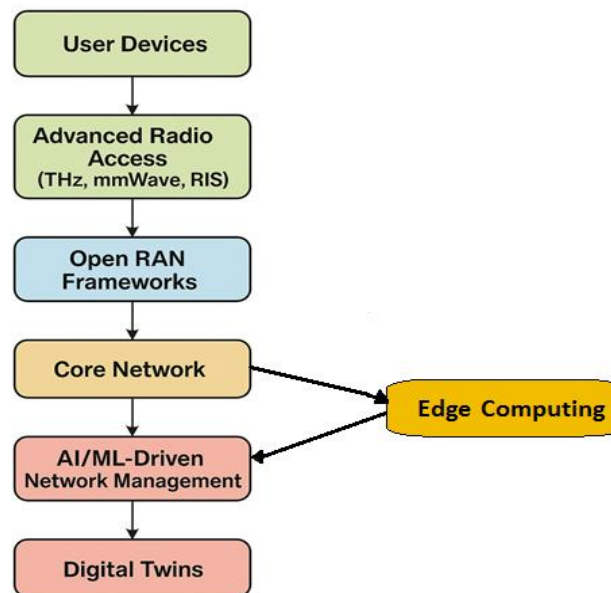


Fig. 5. Conceptual architecture of 6G networks

5. Survey of Trends in Market, Regulation, and Deployment

5.1. Market Trends and Growth Projections

The market of 6G is rapidly growing around the globe due to the technological breakthrough and the growing demand on the high-speed connectivity. The market size is estimated to be about

USD 7.77 billion in 2025 with a compound annual growth rate (CAGR) of 25.9 with a possible increase of over USD 128 billion by 2037 [56].

This is driven by forging together of AI, IoT, and cloud computing, which is generating a strong backbone of 6G possibilities [57]. The principal areas that are contributing to this growth are:

- Automotive and Transportation: It is expected to have 27% market share by 2024, and is used in autonomous automobile and smart transportation systems.
- Healthcare: It is projected to increase at a CAGR of 72.45 and will be fueled by the need to have higher connectivity in telemedicine and remote patient monitoring [58].
- Consumer Electronics: The leading category of the market is expected to be mobile devices which will take up 46 percent of the market in 2024, with well-developed IoT and edge devices [59].

Fig. 6 presents the 6G market projections in the world between 2025 and 2037. The line graph shows the projected market size of USD billion and shows the contributions of major sectors, such as automotive, healthcare and consumer electronics. The figure reflects a considerable growth in the overall market value during the period with the highest growth percentage of healthcare [60]-[62], consumer electronics, and automotive applications respectively.

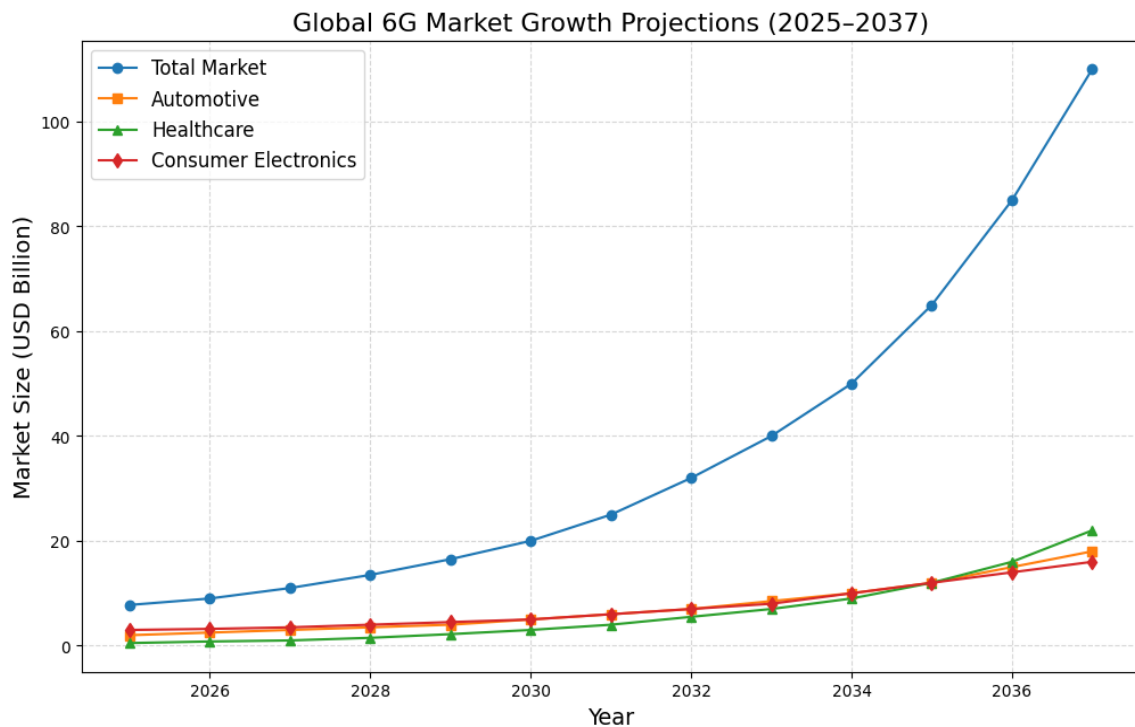


Fig. 6. Global 6G market growth projections (2025–2037)

5.2. Regulatory Landscape and Policy Development

Regulatory environment is an important factor in the adoption and deployment of 6G networks. Spectrum allocation, especially in high frequencies, above 100 GHz that are needed to communicate at THz frequency is one of the main problems facing regulators. Telecom operators in Europe have pointed to the need to get these bands allocated before they fall behind the U.S. and China, where some of the spectrum have already been re-used to provide sophisticated wireless services. Besides spectrum management, regulators have started to work on AI and machine learning regulation in networks, and it guarantees that autonomous and self-optimizing systems adhere to ethical, security, and privacy requirements. The issues of cybersecurity and data privacy are important as well since 6G technologies will process huge amounts of sensitive information. Moreover, the standards are

being harmonized across the globe with the help of international organizations like ITU with the aim of achieving interoperability and keeping the market fragmentation down.

Fig. 7 presents the policy frameworks and 6G spectrum allocations on a global scale. The world map identifies the various regions and their statuses in terms of spectrum allocation such as assigned, deliberated and unused bands. This visual map represents the differences in regional regulatory developments and supports the need to create joint policy actions to deploy global 6G.

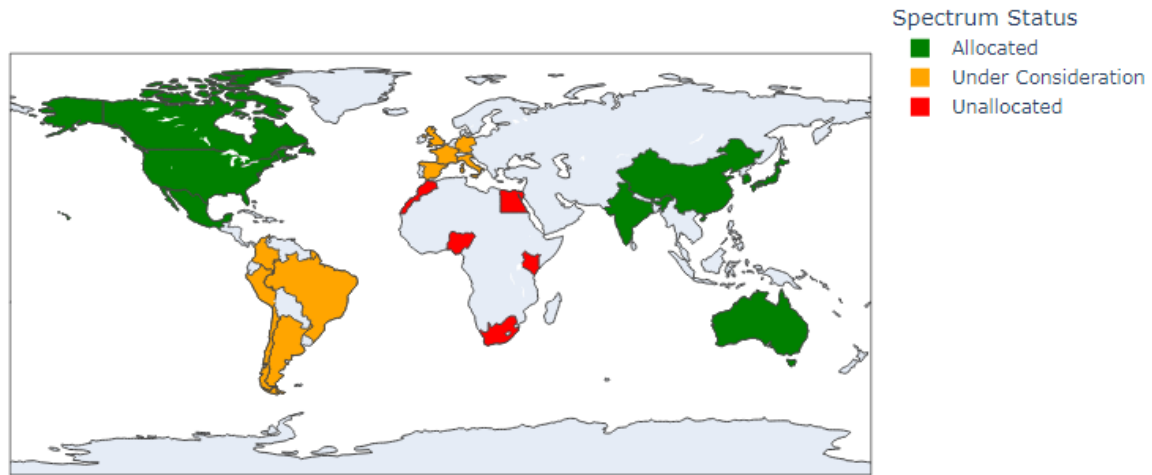


Fig. 7. Global 6G market growth projections (2025–2037)

Table 1 provides an overview of major 6G regulation and policy endeavors on a regional basis. It emphasizes the priorities attributed to the various areas in terms of spectrum allocation, AI control, and security-related issues, giving a brief perspective of the international regulation trends and strategic planning of deploying 6G networks.

Table 1. Key 6G regulatory and policy initiatives by region

Region	Key Policies / Initiatives	Focus Area	Timeline
North America	FCC 6G spectrum plans, AI network governance	Spectrum allocation, AI/ML standards	2025–2030
Europe	EU 6G Action Plan, ITU coordination	Standardization, security, interoperability	2025–2030
Asia-Pacific	Government 6G R&D funding, national testbeds	Spectrum, innovation, pilot deployments	2025–2035

5.3. Deployment Strategies and Infrastructure Development

The implementation of 6G networks necessitates new approaches and hardware design to respond to the challenges of high data rates, low latency, and connections to masses of devices. Network slicing is a highly important enabler, which enables operators to design various virtualized and isolated networks focused on particular applications, including autonomous vehicles, industrial IoT, and immersive extended reality. Cloud-native also enables microservices and container deployments which help in agile network operation, service provisioning, and scaling. Open Radio Access Networks (Open RAN) provide more flexible use of deployed hardware and software, ensuring vendor compatibility and lowering the cost of operations. Moreover, with non-terrestrial network integration (satellites and unmanned aerial vehicles (UAVs)), coverage is extended to isolated and underserved locations. Edge computing and distributed AI offer complimentary solutions that optimize resource allocation, project shorter latencies, and bring intelligence much closer to end users. The platform for implementing 6G is made durable, scalable, and adaptable by all of these actions.

Fig. 8 demonstrates a conceptual 6G network deployment architecture. The figure shows the combination of the essential network elements, edge computing nodes, radio access networks such

as Open RAN, network slicing, and non-terrestrial communication links. This visualization can be used to learn how various deployment strategies intersect to form a powerful and adaptable 6G architecture that can be used to run various applications.

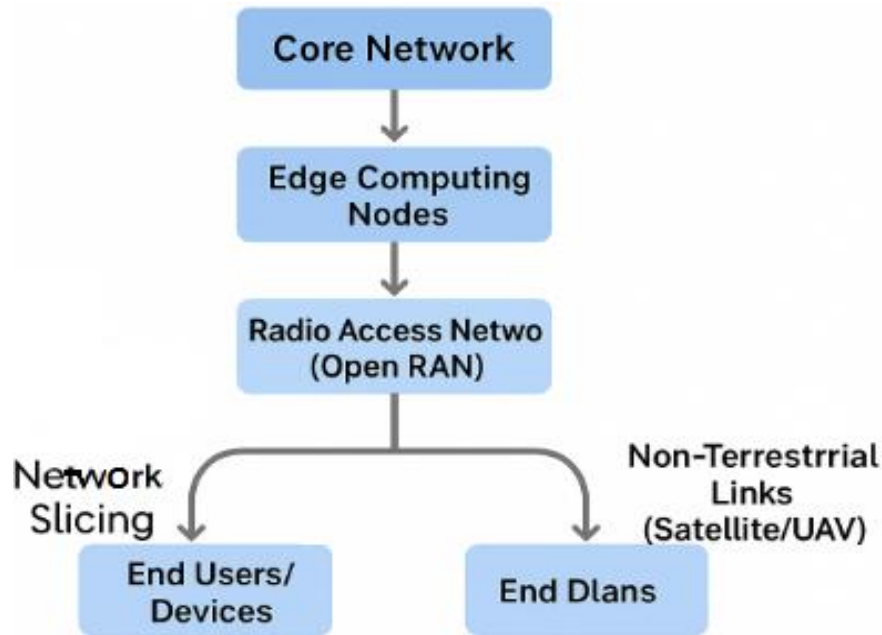


Fig. 8. Conceptual 6G network deployment architecture

Some of the important deployment strategies and their benefits are summarized in Table 2. It points out the role that each strategy plays in network performance, flexibility, and scalability, and offers a brief summary of the types of infrastructures required to carry out the successful implementation of the 6G network.

Table 2. Key 6G regulatory and policy initiatives by region

Deployment Strategy	Description	Key Benefits
Network Slicing	Virtualized isolated networks tailored for applications	Service differentiation, efficiency
Cloud-native Infrastructur	Microservices and containerized deployments	Agile management, rapid scaling
Open RAN	Disaggregated hardware/software, multi-vendor support	Interoperability, reduced costs
Non-Terrestrial Networks	UAV and satellite communication integration	Global coverage, connectivity

5.4. Regional Insights and Strategic Initiatives

The evolution and implementation of 6G networks differ considerably by the region, as investment priorities, regulation, and technological focus are different. Governments and the private sector in the Asia-Pacific region are also on the forefront in 6G research and development and are heavily investing in smart city projects, industrial IoT, and AI-based communication infrastructure. Pilot projects and national testbeds are currently being put in place to test 6G emerging technologies and fasten commercialization. North America is aimed at developing the cooperation between the industry players and research organizations with the focus on open standards, interoperability, and early implementation of sophisticated communication technology. In the meantime, Europe is grappling with issues of spectrum allocation, which has forced the telecom operators to push the regulators to make timely rulings so as to keep up with the global competition. To achieve the optimal network architecture, test new technologies, and be able to deploy on large scale, regional strategies tend to incorporate cross-sector partnerships, pilot deployments, and innovation hubs. Knowledge of regional advantages, drawbacks, and investment priorities is paramount in order to

adjust 6G deployment plans and gain fair access to the high-quality wireless services across the continents.

Fig. 9 indicates regional 6G plans and investment summary. A heat map or a bar chart identifies the level of investment, pilot deployments, and R&D in the major areas, which describes the global 6G innovation picture. This number gives good visual comparison of what areas are ahead in terms of adoption and readiness of technology. Table 3 includes a summary of regional 6G strategic focus areas. It lays focus on the initiatives, technologies and key stakeholders across the various regions and gives a holistic picture of the work around the world to deploy and adopt 6G.

Table 3. Regional 6G strategic focus areas

Region	Strategic Initiatives	Focus Technologies	Key Stakeholders
Asia-Pacific	Smart city pilot projects, national R&D programs	IoT, AI, THZ communication	Government, Telecoms
North America	Industry collaboration, open standard adoption	Open RAN, edge AI	Operators, Research Labs
Europe	ITU coordination, cross-border testbeds	Standardization, network slicing	Regulators, Operators

6. Research Challenges in 6G

The development of sixth-generation (6G) networks has several open research opportunities including energy efficiency, security, hardware, and ethics. These challenges need to be addressed in order to make 6G meet its high-performance goals and objectives and be sustainable, secure, and socially responsible.

6.1. Energy Efficiency and Sustainability

Although 6G is projected to be significantly more energy efficient than its predecessors, the real sustainability of the technology is an important issue to consider. Network management based on AI, Open RAN architecture, and smart distribution of the resources will focus on maximizing the use of energy and minimizing electronic waste. Nevertheless, higher data rates, ubiquitous connectivity and the need to reduce latency to levels never before achieved, can offset such energy savings, requiring new hardware and software designs to keep network performance and environmental effect in an optimal balance [63].

6.2. Security and Privacy

The 6G networks are heterogeneous, which means that they have terrestrial, aerial, and satellite elements that present complex security vulnerabilities. New threats are the attack of ultra-massive MIMO systems in THZ, and network services that are vulnerable to adversarial manipulation, which is based on AI. More advanced security solutions, such as blockchain-based data integrity and trustworthiness assurance methods, AI-based intrusion detection, and quantum-resistant communications protocols, are being investigated to lessen these concerns [64].

6.3. Hardware and Infrastructure

The implementation of 6G requires major progress in hardware, which can accommodate THZ communications and ultra-low latency activities. The most important problems are the creation of energy-efficient antennas, energy-efficient signal processing units, and scalable edge computing infrastructures. Furthermore, enabling dependable and durable 6G networks requires seamless interoperability across heterogeneous elements in addition to supporting the increased computing and storage capacities [65].

6.4. Ethical and Social Considerations

The massive introduction of 6G technologies brings with it some critical ethical and social issues, such as privacy of data, algorithm discrimination, and fair access to advanced communication

services. The adoption of AI in the decisions making procedure must have visible, responsible and explainable procedures to prevent discrimination and encourage equity. Furthermore, the regulatory frameworks should be flexible and keep abreast with technological innovations in order to protect the user's rights and to guarantee societal advantages [66]-[71].

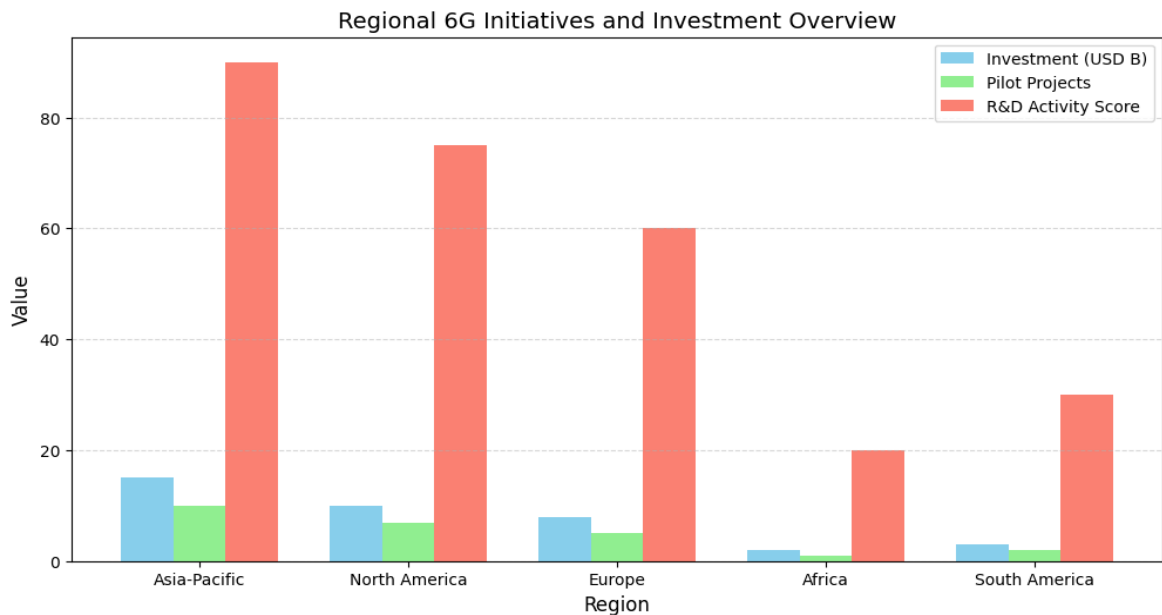


Fig. 9. Regional 6G initiatives and investment overview

These research issues are very interrelated with developments in one area affecting results in others. As an example, hardware design can be energy efficient, and security systems are affected by such a design, and the deployment of hardware is influenced by ethical issues, and AI-based network regulation. These interrelationships are depicted in Fig. 10 in which 6G research is shown to be multidisciplinary and interdependent. Resolving these issues will need to be a collaborative effort between academia, industry, and policymakers to come up with coordinated actions to guarantee secure, sustainable, and ethically sound 6G networks.

All nodes are critical domains: energy efficiency, security and privacy, hardware development and ethical considerations, and they are colored in unique colors. The bidirectional effects of these issues are represented by curved arrows as the progress of one field or a limitation of the other has a tendency to influence the others. To illustrate, energy efficiency designs may affect the hardware development, which subsequently may affect the security mechanism, whereas the ethical issues also affect the security and energy-related choices. This value shows the interdisciplinary and multifaceted character of the 6G research that demonstrates the necessity of comprehensive solutions to cover technical, environmental, and social factors. The primary 6G research challenges, their principal problems, and their relationships and influences are compiled in Table 4. The diverse and interdependent nature of these difficulties is clearly summarized by this tabular representation.

7. Results and Discussion of Survey

The discussion of AI-powered 6G wireless networks shows that it is a very interdependent world in which technological advances, market demands, and research issues are tied together to shape the future of mobile communications. Various similar themes can be identified across the literature reviewed; both opportunities and constraints of the 6G evolution can be outlined. Among the most noticeable lessons is the fact that AI is a critical foundational enabler. AI and machine learning are also being used to optimize a network, but are also being integrated throughout the architecture to handle ultra-dense connectivity, traffic prediction, spectrum resource optimization, and adaptive security. However, this integration poses a fundamental trade-off between energy

efficiency and computing demands, underscoring the need for hardware-software co-design techniques and energy-conscious AI models.

Table 4. The main 6G challenges, their key issues, and how they influence or relate to one another.

Challenge Domain	Key Issues/Considerations	Interconnections with Other Domains
Energy Efficiency	High data rates, sustainable hardware, AI-driven optimization	Impacts hardware design, affects security (energy-hungry security protocols), influenced by ethical constraints (green policies)
Security & Privacy	Quantum-safe communication, AI-driven attacks, blockchain data integrity	Dependent on hardware capabilities, influenced by energy-efficient designs, constrained by ethical/privacy requirements
Hardware Development	THz antennas, low-latency components, edge computing	Enables energy-efficient operation, supports secure systems, influenced by ethical deployment considerations
Ethical Considerations	Data privacy, fairness, equitable access, algorithmic transparency	Shapes hardware and software design, constrains energy use, influences security policies

Regarding performance, 6G is estimated to be orders of magnitude higher than its performance predecessors, in terms of data rate, latency, reliability, and connectivity density. Examples of applications that can be based on the implementation of such extreme metrics of performance include extended reality, autonomous systems, digital twins, and remote healthcare. The tensions between the need to reach ultra-low latency and the need to have sustainable energy consumption are always noted in surveyed studies. This contradiction emphasizes how important it is to design the system holistically in order to reconcile energy constraints with high-speed real-time communication. Furthermore, the research shows that while theoretical performance targets are ambitious, many real-world deployments are still in the prototype stage, suggesting that real-world implementations will be restricted to the creation of hardware and AI-powered management.

The analysis of enabling technologies is revealing a great variety of approaches. Advanced radio access solutions such as ultra-massive MIMO, terahertz communication and reconfigurable intelligent surfaces are at the heart of boosting the data throughput and reliability. Equally, digital twin models and autonomous network management can offer predictive analytics and self-optimization toolkit to allow networks to predict and dynamically respond to demand. In the literature, we can see a distinct trend: to achieve the multi-dimensional goals of 6G, there is a need to integrate multiple technologies, instead of depending on any particular innovation. Significant barriers are also noted in the literature, such as the incompatibility of land-based and non-land networks, security challenges with AI-based systems, and the moral dilemmas associated with ubiquitous data collection and decision-making.

Market and deployment trends also provide a deeper understanding of the global trends that are shaping the development of 6G. The surveyed studies have shown that key sectors of the economy like health, vehicles, and consumer electronics are expanding at a tremendous pace with a compound annual growth rate that is a measure of high demand and serious investment in research and infrastructure. Strategic contrasts are indicated by local overviews: Europe is focused on regulatory harmonization and spectrum availability, North America is focused on industry collaboration and open standards, while Asia-Pacific is focused on smart city programs and national testbeds. These results indicate that the distribution of lessons and best practice is not uniform and that cross-regional knowledge transfer might speed up the introduction of 6G all over the world. Most importantly, market forecasts in the literature tend to take ideal conditions; the uncertainty in regulation, spectrum, and technological preparedness of technology may have a dramatic impact on the adoption schedules.

Interdependencies which are usually ignored in descriptive surveys are brought to the fore in the synthesis of open research challenges. Ethical consideration, security, hardware, and energy efficiency are highly interrelated. As an example, the implementation of the highest energy

efficiency will require AI algorithms as well as hardware design and strategies of sustainable deployment. Similarly, security policies are affected by ethical limits, and energy usage and system latency are dependent on security mechanisms. The literature suggests that the effective implementation of 6G will involve multi-disciplinary coordination between academia, industry and regulators and adaptive frameworks able to adapt to changing technological, social and regulatory environment.

All in all, the critical review of the AI-enhanced 6G literature indicates that even though the conceptualization of technologies and identification of their usage have been made, there is still the necessity of the integrated studies to calculate trade-offs, test the feasibility, and present findings in different regions, fields, and technological methodologies. These findings combined provide the significance of a holistic approach that would bind AI, network design, performance requirements, and practical deployment considerations, and this survey provides researchers and practitioners with the roadmap to the selected innovation and evidence-based decision-making in 6G networks.

The implications are summarized and the key findings of this survey are highlighted in [Table 5](#) that presents the main dimensions of AI-enabled 6G networks and the directions in which this field should be prioritized in future research. It combines knowledge on the basis of performance requirements, enabling technologies, AI/ML integration, trend on deployment, security, sustainability, and on ethical aspects. Connecting the identified trends with the research priorities that can be pursued as the result of the study, the table gives a clear roadmap to the researchers and practitioners who strive to resolve the existing problems and set the path of the next-generation wireless networks.

Table 5. Key findings and research priorities in AI-enabled 6G networks

Dimension	Key Findings	Implications / Insights	Future Research Priorities
AI & ML Integration	AI-native networks essential for adaptive, secure, and self-optimizing 6G	High computational demand may conflict with energy efficiency; edge AI is critical for real-time applications	Reinforcement learning for RIS security, federated learning for edge intelligence, explainable AI frameworks
Performance Requirements	Terabit-per-second data rates, sub-millisecond latency, ultra-high reliability, massive device density	Achieving all metrics simultaneously is challenging; trade-offs must be considered in design	Optimized multi-layer resource allocation, predictive maintenance, context-aware network intelligence
Enabling Technologies	THz communication, ultra-massive MIMO, RIS, digital twins, Open RAN	Technologies interdependent; integration complexity is high	Energy-efficient hardware for THz, AI-assisted coordination among technologies, interoperability frameworks
Deployment & Market Trends	Regional variation in investment, policy, and infrastructure strategies	Global alignment is needed for interoperability; context-specific strategies are effective	Comparative studies across regions, pilot deployments, standardization initiatives
Security & Privacy	Distributed, heterogeneous networks increase vulnerability	AI-enhanced intrusion detection, blockchain-based trust, and quantum-safe protocols required	Resilient AI security mechanisms, privacy-preserving edge intelligence, secure cross-network communication
Sustainability & Ethics	Energy efficiency and social responsibility are critical but challenging	Trade-offs between performance and energy use; ethical AI and equitable access must be addressed	Green network design, energy-aware AI models, ethical and regulatory frameworks

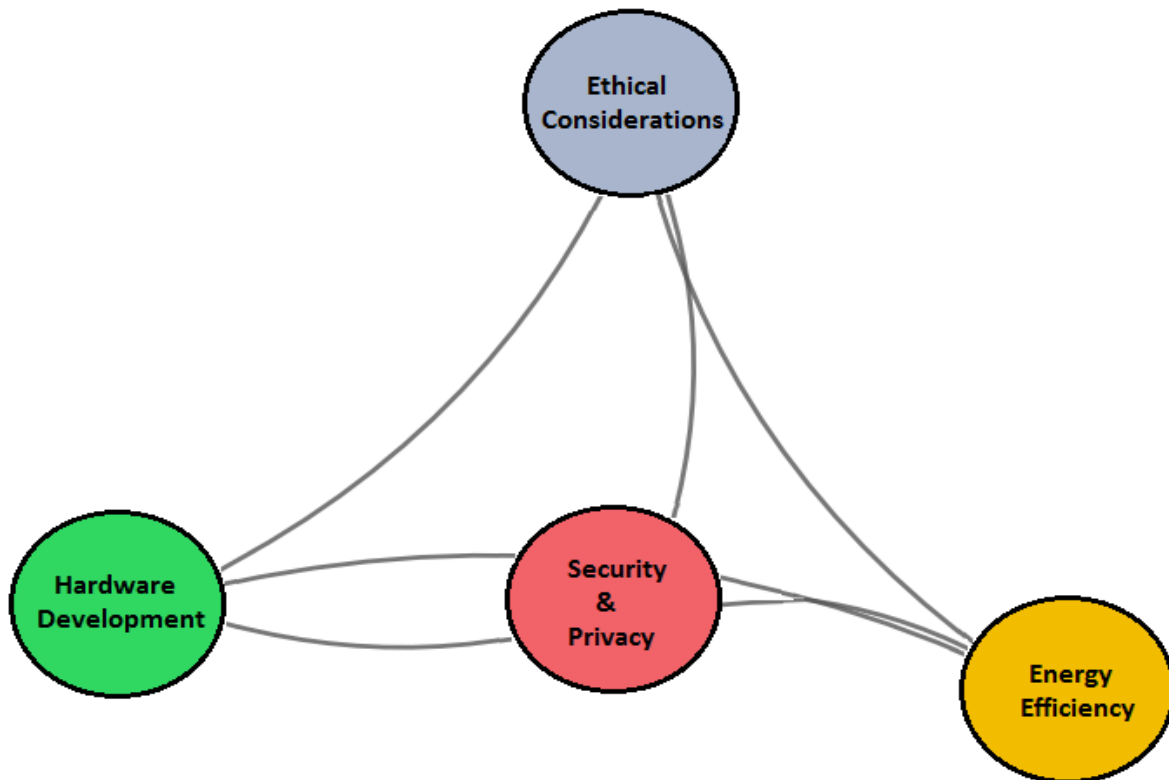


Fig. 10. Interconnections of 6G research challenges

8. Conclusion

This survey has looked critically at AI-enabled 6G wireless networks, including performance needs, enabling technologies, deployment trends, and open research issues. The analysis shows that 6G is not a simple upgrade in terms of speed, latency and connectivity, but a revolutionary paradigm that incorporates network intelligence, energy conservation, and social responsibility. This paper synthesizes the recent literature by establishing interdependencies between technological, operational, and societal dimensions, which present a systematic framework that should be used to guide research and industrial practice.

The major findings can be summed up in the following way. To start with, self-optimizing, adaptive and secure networks can only happen with AI and ML integration, which also comes with trade-offs between the computational demand of those networks and their energy consumption, especially in high-density deployments and edge computing scenarios. Second, the target technologies such as THz communication, ultra-massive MIMO, RIS, digital twins, or open RAN have been demonstrated to have unrivaled potential, but they need to be coordinated to ensure performance, security, and sustainability. Third, regional approaches and strategies of deployment differ dramatically, and the emphasis of on context-specific policy, regulatory alignment and cross-sector collaboration. Finally, the research issues are paramount, including energy-efficient hardware, robust security systems, ethical integration of AI, and fair access, where it should be stressed that the development of technology should be in accordance with social and regulatory rates.

When considering the methodology, this survey takes in form of a systematic, transparent literature review; nonetheless, the research is confined with the available literature depictions, and variability provided through reports of performance measures, deployment performance, and market-based forecasts. To strengthen evidence-based conclusions, the work could be expanded in subsequent surveys that include cross-regional surveys, quantitative benchmarking, and empirical performance data. Based on this survey, some research priorities are visible in the future. The most promising directions in AI integration are related to reinforcing learning applied to RIS security,

federated learning as applied to edge intelligence, and explicable AI systems that will provide transparency in autonomous network management. In hardware and infrastructure, it is important to develop energy efficient and scalable equipment that is capable of supporting THz communication and ultra-low latency. In addition, the ethical, societal, and regulatory ramifications of 6G deployments will also necessitate interdisciplinary methodologies that incorporate engineering, social sciences, and policy studies.

This work enters the field by synthesizing the range of research on AI-enabled 6G in a holistic manner, drawing the trade-offs, interdependencies, and future directions, and presents a conceptual roadmap to researchers and practitioners. It aligns itself with a base of new research on the design, optimization, and implementation of intelligent, sustainable, and socially responsible 6G networks by integrating the understanding of technological, market, and regulatory views. Finally, 6G implementation will likely trigger wireless communications, AI, hardware systems, and socio-technical infrastructures innovations and set the stage of a connected, intelligent and sustainable digital future.

Author Contribution: All authors contributed equally to the main contributor to this paper. All authors read and approved the final paper.

Funding: This research received no external funding.

Acknowledgment: The authors sincerely thank Jadara University, for its valuable support of this research. The university's financial assistance played a crucial role in the successful completion of this work.

Conflicts of Interest: The authors declare no conflict of interest.

References

- [1] H. Shukur, S. Zeebaree, R. Zebari, D. Zeebaree, O. Ahmed, and A. Salih, "Cloud Computing Virtualization of Resources Allocation for Distributed Systems," *Journal of Applied Science and Technology Trends*, vol. 1, no. 2, pp. 98-105, 2020, <https://doi.org/10.38094/jastt1331>.
- [2] F. Arabian and M. Shoushtari, "A Comparative Study of Waveforms Across Mobile Cellular Generations: From 0G to 6G and Beyond," *Telecom*, vol. 6, no. 3, p. 67, 2025, <https://doi.org/10.3390/telecom6030067>.
- [3] K. Muppavaram, S. Govathoti, D. Kamidi, and T. Bhaskar, "Exploring the Generations: A Comparative Study of Mobile Technology from 1G to 5G," *International Journal of Electronics and Communication Engineering*, vol. 10, no. 7, pp. 54-62, 2023, <https://doi.org/10.14445/23488549/IJECE-V10I7P106>.
- [4] H. Hodara and E. Skaljic, "From 1G to 5G," *Fiber and Integrated Optics*, vol. 40, no. 2-3, pp. 85-183, 2021, <https://doi.org/10.1080/01468030.2021.1919358>.
- [5] F. Zhou and M. Cheriet, "Intelligent Network Slicing Management and Control for 6G Mobile Networks," *6G Wireless Communications and Mobile Networking*, pp. 189-207, 2021, <https://doi.org/10.2174/9781681087962121010007>.
- [6] M. H. Alsharif, A. H. Kelechi, M. A. Albreem, S. A. Chaudhry, M. S. Zia, and S. Kim, "Sixth Generation (6G) Wireless Networks: Vision, Research Activities, Challenges and Potential Solutions," *Symmetry*, vol. 12, no. 4, p. 676, 2020, <https://doi.org/10.3390/sym12040676>.
- [7] M. Z. Chowdhury, M. Shahjalal, S. Ahmed and Y. M. Jang, "6G Wireless Communication Systems: Applications, Requirements, Technologies, Challenges, and Research Directions," *IEEE Open Journal of the Communications Society*, vol. 1, pp. 957-975, 2020, <https://doi.org/10.1109/OJCOMS.2020.3010270>.
- [8] H. Tataria, M. Shafi, A. F. Molisch, M. Dohler, H. Sjöland and F. Tufvesson, "6G Wireless Systems: Vision, Requirements, Challenges, Insights, and Opportunities," *Proceedings of the IEEE*, vol. 109, no. 7, pp. 1166-1199, 2021, <https://doi.org/10.1109/JPROC.2021.3061701>.

-
- [9] I. F. Akyildiz, A. Kak and S. Nie, "6G and Beyond: The Future of Wireless Communications Systems," *IEEE Access*, vol. 8, pp. 133995-134030, 2020, <https://doi.org/10.1109/ACCESS.2020.3010896>.
- [10] H. H. H. Mahmoud, A. A. Amer, and T. Ismail, "6G: A comprehensive survey on technologies, applications, challenges, and research problems," *Transactions on Emerging Telecommunications Technologies*, vol. 32, no. 4, p. e4233, 2021, <https://doi.org/10.1002/ett.4233>.
- [11] M. Z. Asghar, S. A. Memon, and J. Hämäläinen, "Evolution of Wireless Communication to 6G: Potential Applications and Research Directions," *Sustainability*, vol. 14, no. 10, p. 6356, 2022, <https://doi.org/10.3390/su14106356>.
- [12] D. Uzunidis *et al.*, "A Vision of 6th Generation of Fixed Networks (F6G): Challenges and Proposed Directions," *Telecom*, vol. 4, no. 4, pp. 758-815, 2023, <https://doi.org/10.3390/telecom4040035>.
- [13] Z. Chen, K.-C. Chen, C. Dong, and Z. Nie, "6G Mobile Communications for Multi-Robot Smart Factory," *Journal of ICT Standardization*, vol. 9, no. 03, pp. 371-404, 2021, <https://doi.org/10.13052/jicts2245-800X.934>.
- [14] M. Bashabsheh, "Simulation of An Automatic System of Robotics for Artificial Animated Being Manufacturing Using AnyLogic Simulation Software," *International Journal of Electrical and Electronics Engineering*, vol. 11, no. 5, pp. 129-137, 2024, <https://doi.org/10.14445/23488379/IJEEE-V11I5P112>.
- [15] O. Liberg *et al.*, "Introducing 5G Advanced," *IEEE Communications Standards Magazine*, vol. 8, no. 1, pp. 52-57, 2024, <https://doi.org/10.1109/MCOMSTD.0003.2200059>.
- [16] C. Cox, "An Introduction to 5G: The New Radio, 5G Network, 5G Advanced and Beyond," *John Wiley & Sons*, 2025, <https://doi.org/10.1002/97811394284757>.
- [17] A. Toskala and H. Holma, "5G-Advanced Overview," *John Wiley & Sons*, pp. 485-503, 2024, <https://doi.org/10.1002/9781119816058.ch16>.
- [18] W. Chen *et al.*, "5G-Advanced Toward 6G: Past, Present, and Future," *IEEE Journal on Selected Areas in Communications*, vol. 41, no. 6, pp. 1592-1619, 2023, <https://doi.org/10.1109/JSAC.2023.3274037>.
- [19] D. H. Morais, "5G/5G-Advanced Overview," *5G/5G-Advanced, Wi-Fi 6/7, and Bluetooth 5/6*, pp. 103-148, 2025, https://doi.org/10.1007/978-3-031-82830-0_8.
- [20] J. Park *et al.*, "Extreme ultra-reliable and low-latency communication," *Nature Electronics*, vol. 5, no. 3, pp. 133-141, 2022, <https://doi.org/10.1038/s41928-022-00728-8>.
- [21] D. Feng, L. Lai, J. Luo, Y. Zhong, C. Zheng, and K. Ying, "Ultra-reliable and low-latency communications: applications, opportunities and challenges," *Science China Information Sciences*, vol. 64, no. 2, 2021, <https://doi.org/10.1007/s11432-020-2852-1>.
- [22] A. I. Salameh and M. El Tarhuni, "From 5G to 6G—Challenges, Technologies, and Applications," *Future Internet*, vol. 14, no. 4, p. 117, 2022, <https://doi.org/10.3390/fi14040117>.
- [23] H. Pannanen, T. Hänninen, O. Tervo, A. Tölli and M. Latva-Aho, "6G: The Intelligent Network of Everything," *IEEE Access*, vol. 13, pp. 1319-1421, 2025, <https://doi.org/10.1109/ACCESS.2024.3521579>.
- [24] L. U. Khan, W. Saad, D. Niyato, Z. Han and C. S. Hong, "Digital-Twin-Enabled 6G: Vision, Architectural Trends, and Future Directions," *IEEE Communications Magazine*, vol. 60, no. 1, pp. 74-80, 2022, <https://doi.org/10.1109/MCOM.001.21143>.
- [25] M. V. Katwe *et al.*, "An Overview of Intelligent Meta-Surfaces for 6G and Beyond: Opportunities, Trends, and Challenges," *IEEE Communications Standards Magazine*, vol. 8, no. 4, pp. 62-69, 2024, <https://doi.org/10.1109/MCOMSTD.0001.2400032>.
- [26] S. Kamath, S. Anand, S. Buchke, and K. Agnihotri, "A Review of Recent Developments in 6G Communications Systems," *Engineering Proceedings*, vol. 59, no. 1, p. 167, 2024, <https://doi.org/10.3390/engproc2023059167>.
- [27] W. M. Othman *et al.*, "Key Enabling Technologies for 6G: The Role of UAVs, Terahertz Communication, and Intelligent Reconfigurable Surfaces in Shaping the Future of Wireless Networks,"
-

- Journal of Sensor and Actuator Networks*, vol. 14, no. 2, p. 30, 2025, <https://doi.org/10.3390/jsan14020030>.
- [28] F. Naeem, M. Ali, G. Kaddoum, C. Huang and C. Yuen, "Security and Privacy for Reconfigurable Intelligent Surface in 6G: A Review of Prospective Applications and Challenges," *IEEE Open Journal of the Communications Society*, vol. 4, pp. 1196-1217, 2023, <https://doi.org/10.1109/OJCOMS.2023.3273507>.
- [29] K. Neelima, C. Kavya, and D. Pandey, "6G communications – security issues and possible solutions," *6G Communication Network*, pp.137-154, 2024, <https://doi.org/10.1201/9781003522003-11>.
- [30] Y. Li *et al.*, "RIS-Based Physical Layer Security for Integrated Sensing and Communication: A Comprehensive Survey," *IEEE Internet of Things Journal*, vol. 12, no. 16, pp. 32444-32468, 2025, <https://doi.org/10.1109/JIOT.2025.3567553>.
- [31] B. K. Pandey *et al.*, "Beyond Data Breaches: Enhancing Security in 6G Communications," *Security Issues and Solutions in 6G Communications and Beyond*, pp. 212-229, 2024, <https://doi.org/10.4018/979-8-3693-2931-3.ch013>.
- [32] P. S. R. Henrique, R. Prasad, "6G The Road to the Future Wireless Technologies 2030," *River Publishers*, 2022, <https://doi.org/10.1201/9781003336884>.
- [33] H. Sridharan and S. Govindarajan, "The Future of Wireless Technologies: Beyond 5G and the Path to 6G," *International Journal of Science and Research (IJSR)*, vol. 13, no. 7, pp. 1606-1619, 2024, <https://doi.org/10.21275/SR24913031614>.
- [34] M. W. Akhtar, S. A. Hassan, R. Ghaffar, H. Jung, S. Garg, and M. S. Hossain, "The shift to 6G communications: vision and requirements," *Human-centric Computing and Information Sciences*, vol. 10, no. 1, 2020, <https://doi.org/10.1186/s13673-020-00258-2>.
- [35] B. S. Khan, S. Jangsher, A. Ahmed and A. Al-Dweik, "URLLC and eMBB in 5G Industrial IoT: A Survey," *IEEE Open Journal of the Communications Society*, vol. 3, pp. 1134-1163, 2022, <https://doi.org/10.1109/OJCOMS.2022.3189013>.
- [36] N. H. Mahmood, I. Atzeni, E. A. Jorswieck, and O. L. A. López, "Ultra-Reliable Low-Latency Communications: Foundations, Enablers, System Design, and Evolution Towards 6G," *Foundations and Trends® in Communications and Information Theory*, vol. 20, no. 5-6, pp. 512-747, 2023, <https://doi.org/10.1561/0100000129>.
- [37] A. Salh *et al.*, "A Survey on Deep Learning for Ultra-Reliable and Low-Latency Communications Challenges on 6G Wireless Systems," *IEEE Access*, vol. 9, pp. 55098-55131, 2021, <https://doi.org/10.1109/ACCESS.2021.3069707>.
- [38] S. M. Mohammed, A. Al-Barrak, and N. T. Mahmood, "Enabling Technologies for Ultra-Low Latency and High-Reliability Communication in 6G Networks," *Ingénierie des systèmes d'information*, vol. 29, no. 3, pp. 1195-1208, 2024, <https://doi.org/10.18280/isi.290336>.
- [39] M. Bashabsheh, "Autonomous Robotic Systems with Artificial Intelligence Technology Using a Deep Q Network-Based Approach for Goal-Oriented 2D Arm Control," *Journal of Robotics and Control (JRC)*, vol. 5, no. 6, pp. 1872-1887, 2024, <https://doi.org/10.18196/jrc.v5i6.23850>.
- [40] A. A. Puspitasari, T. T. An, M. H. Alsharif, and B. M. Lee, "Emerging Technologies for 6G Communication Networks: Machine Learning Approaches," *Sensors*, vol. 23, no. 18, p. 7709, 2023, <https://doi.org/10.3390/s23187709>.
- [41] R. Gupta, D. Reebadiya, and S. Tanwar, "6G-enabled Edge Intelligence for Ultra -Reliable Low Latency Applications: Vision and Mission," *Computer Standards & Interfaces*, vol. 77, p. 103521, 2021, <https://doi.org/10.1016/j.csi.2021.103521>.
- [42] M. Bashabsheh, "Comprehensive and Simulated Modeling of a Centralized Transport Robot Control System," *International Journal of Advanced Computer Science and Applications*, vol. 15, no. 5, 2024, <https://doi.org/10.14569/IJACSA.2024.0150552>.
- [43] C. -X. Wang *et al.*, "On the Road to 6G: Visions, Requirements, Key Technologies, and Testbeds," *IEEE Communications Surveys & Tutorials*, vol. 25, no. 2, pp. 905-974, 2023, <https://doi.org/10.1109/COMST.2023.3249835>.

- [44] Y. Zuo, J. Guo, N. Gao, Y. Zhu, S. Jin and X. Li, "A Survey of Blockchain and Artificial Intelligence for 6G Wireless Communications," *IEEE Communications Surveys & Tutorials*, vol. 25, no. 4, pp. 2494-2528, 2023, <https://doi.org/10.1109/COMST.2023.3315374>.
- [45] I. Ishteyaq, K. Muzaffar, N. Shafi and M. A. Alathbah, "Unleashing the Power of Tomorrow: Exploration of Next Frontier With 6G Networks and Cutting Edge Technologies," *IEEE Access*, vol. 12, pp. 29445-29463, 2024, <https://doi.org/10.1109/ACCESS.2024.3367976>.
- [46] D. A. Milovanovic, Z. S. Bojkovic, and T. P. Fowdur, "5G-Advanced Mobile Communication," *Driving 5G Mobile Communications with Artificial Intelligence towards 6G*, pp. 3-81, 2023, <https://doi.org/10.1201/9781003205494-2>.
- [47] A. Pradhan, S. Das, M. J. Piran and Z. Han, "A Survey on Physical Layer Security of Ultra/Hyper Reliable Low Latency Communication in 5G and 6G Networks: Recent Advancements, Challenges, and Future Directions," *IEEE Access*, vol. 12, pp. 112320-112353, 2024, <https://doi.org/10.1109/ACCESS.2024.3429285>.
- [48] P. K. Gkonis, A. Giannopoulos, N. Nomikos, P. Trakadas, L. Sarakis, and X. Masip-Bruin, "A Survey on Architectural Approaches for 6G Networks: Implementation Challenges, Current Trends, and Future Directions," *Telecom*, vol. 6, no. 2, p. 27, 2025, <https://doi.org/10.3390/telecom6020027>.
- [49] M. Ahmed *et al.*, "A Survey on RIS Advances in Terahertz Communications: Emerging Paradigms and Research Frontiers," *IEEE Access*, vol. 12, pp. 173867-173901, 2024, <https://doi.org/10.1109/ACCESS.2024.3482564>.
- [50] K. B. Letaief, Y. Shi, J. Lu and J. Lu, "Edge Artificial Intelligence for 6G: Vision, Enabling Technologies, and Applications," *IEEE Journal on Selected Areas in Communications*, vol. 40, no. 1, pp. 5-36, 2022, <https://doi.org/10.1109/JSAC.2021.3126076>.
- [51] Y. Sanjalawe, S. Fraihat, S. Al-E'Mari, M. Abualhaj, S. Makhadmeh and E. Alzubi, "A Review of 6G and AI Convergence: Enhancing Communication Networks With Artificial Intelligence," *IEEE Open Journal of the Communications Society*, vol. 6, pp. 2308-2355, 2025, <https://doi.org/10.1109/OJCOMS.2025.3553302>.
- [52] H. Yang, A. Alphones, Z. Xiong, D. Niyato, J. Zhao and K. Wu, "Artificial-Intelligence-Enabled Intelligent 6G Networks," *IEEE Network*, vol. 34, no. 6, pp. 272-280, 2020, <https://doi.org/10.1109/MNET.011.2000195>.
- [53] A. Alhammadi *et al.*, "Artificial Intelligence in 6G Wireless Networks: Opportunities, Applications, and Challenges," *International Journal of Intelligent Systems*, vol. 2024, no. 1, pp. 1-27, 2024, <https://doi.org/10.1155/2024/8845070>.
- [54] M. Polese *et al.*, "Empowering the 6G Cellular Architecture With Open RAN," *IEEE Journal on Selected Areas in Communications*, vol. 42, no. 2, pp. 245-262, 2024, <https://doi.org/10.1109/JSAC.2023.3334610>.
- [55] M. Shu, W. Sun, J. Zhang, X. Duan, and M. Ai, "Digital-twin-enabled 6G network autonomy and generative intelligence: Architecture, technologies and applications," *Digital Twin*, vol. 2, p. 16, 2025, <https://doi.org/10.12688/digitaltwin.17720.3>.
- [56] F. Sguaizer, L. Vigoroso, M. Micheletti Cremasco, and F. Caffaro, "Perceived Working Conditions and Intention to Adopt Digital Safety Training in High-Risk Productive Sectors: An Exploratory Study in Manufacturing and Agriculture in Northwest Italy," *Safety*, vol. 11, no. 2, p. 51, 2025, <https://doi.org/10.3390/safety11020051>.
- [57] K. Kalaiselvi, R. Sankar, S. Supriya, G. Kaushik, H. Swamy and M. Devika, "Towards Seamless Connectivity: Implementing 6G Communication Technologies In Next-Generation Networks," *2024 3rd International Conference for Advancement in Technology (ICONAT)*, pp. 1-6, 2024, <https://doi.org/10.1109/ICONAT61936.2024.10775248>.
- [58] A. Samad, D. R. Obando Nuñez, G. C. Solis Castillo, B. Laquai, and U. Vogt, "Effect of relative humidity and air temperature on the results obtained from low-cost gas sensors for ambient air quality measurements," *Sensors*, vol. 20, no. 18, p. 5175, 2020, <https://doi.org/10.3390/s20185175>.

-
- [59] L. Wang *et al.*, “Effects of light intensity and photoperiod on ovarian development of *Procambarus clarkii* (Girard, 1852): Comparative proteomics analysis, growth performance and biochemical,” *Aquaculture Reports*, vol. 46, p. 103302, 2026, <https://doi.org/10.1016/j.aqrep.2025.103302>.
- [60] M. Bashabsheh, “A Combined Model for Simulating the Spatial Dynamics of Epidemic Spread: Integrating Stochastic Compartmentalization and Cellular Automata Approach,” *International Journal of Mathematical, Engineering and Management Sciences*, vol. 10, no. 2, pp. 522-536, 2025, <https://doi.org/10.33889/IJMEMS.2025.10.2.026>.
- [61] M. Bashabsheh, “Mathematical model of the spread of COVID-19 using any logic system,” *AIP Conference Proceedings*, vol. 2930, no. 1, p. 020012, 2023, <https://doi.org/10.1063/5.0175416>.
- [62] M. Bashabsheh, M. Alzubi, “Integrated Simulation Model of the Spatial Distribution of Dynamic Systems Using Intelligent Cellular Automaton,” *Panamerican Mathematical Journal*, vol. 34, no. 3, pp. 29-37, 2024, <https://doi.org/10.52783/pmj.v34.i3.1771>.
- [63] H. Ahmadi *et al.*, “Toward Sustainability in 6G and Beyond: Challenges and Opportunities of Open RAN,” *IEEE Communications Standards Magazine*, vol. 9, no. 3, pp. 126-135, 2025, <https://doi.org/10.1109/MCOMSTD.2025.3575488>.
- [64] V. -L. Nguyen, P. -C. Lin, B. -C. Cheng, R. -H. Hwang and Y. -D. Lin, “Security and Privacy for 6G: A Survey on Prospective Technologies and Challenges,” *IEEE Communications Surveys & Tutorials*, vol. 23, no. 4, pp. 2384-2428, 2021, <https://doi.org/10.1109/COMST.2021.3108618>.
- [65] R. Yuvarani, R. Mahaveerakannan, T. Thanarajan, and L. Kartheesan, “Energy-aware cluster head optimization and secure blockchain integration for heterogeneous 6G-enabled IoMT networks,” *Scientific Reports*, vol. 15, no. 1, 2025, <https://doi.org/10.1038/s41598-025-15462-2>.
- [66] Y. Wu, “Ethically Responsible and Trustworthy Autonomous Systems for 6G,” *IEEE Network*, vol. 36, no. 4, pp. 126-133, 2022, <https://doi.org/10.1109/MNET.005.2100711>.
- [67] M. M. Alzubi, M. Almseidin, M. Alkasassbeh, M. Bashabsheh, J. Al-Sawwa, and A. S. Mashaleh, “AI-Driven Threat Detection in Business Intelligence Systems,” *Strategic AI Integration in Business Intelligence*, pp. 111-134, 2025, <https://doi.org/10.4018/979-8-3373-6801-6.ch005>.
- [68] M. M. Alzubi, M. Almseidin, M. Alkasassbeh, M. Bashabsheh, J. Al-Sawwa, and A. S. Mashaleh, “Zero Trust and Predictive Security in Business Intelligence Architectures,” *Driving Modern Business Intelligence Architecture for Operational Efficiency*, pp. 327-352, 2025, <https://doi.org/10.4018/979-8-3373-2125-7.ch011>.
- [69] M. Almseidin, A. Gawanmeh, M. Alzubi, J. Al-Sawwa, A. S. Mashaleh, and M. Alkasassbeh, “Hybrid Deep Neural Network Optimization with Particle Swarm and Grey Wolf Algorithms for Sunburst Attack Detection,” *Computers*, vol. 14, no. 3, p. 107, 2025, <https://doi.org/10.3390/computers14030107>.
- [70] M. Bashabsheh, “Reinforcement Learning for Multi-Task Manipulation in Robotic Arm Systems Operating in Dynamic Environments,” *Journal of Robotics and Control (JRC)*, vol. 6, no. 5, pp. 2272-2283, 2025, <https://doi.org/10.18196/jrc.v6i5.27780>.
- [71] A. R. Shorman, M. Alzubi, M. Almseidin, and R. Rateb, “Adaptive Intrusion Detection for IoT Networks using Artificial Immune System Techniques: A Comparative Study,” *Journal of Robotics and Control (JRC)*, vol. 6, no. 2, pp. 570-582, 2025, <https://doi.org/10.18196/jrc.v6i2.23645>.