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Review

Review on multi-dimensional applications and technological evolution of metamaterials in the Internet of Things

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Abstract: This paper investigated the application of metamaterials in the Internet of Things (IoT) and provides a comprehensive review of their state-of-the-art developments. A systematic research panorama was established by summarizing representative application scenarios and compiling a comparative table of key performance parameters. The review focused on four major application domains of metamaterials: communication antennas, energy harvesting, electromagnetic regulation, and sensing and detection, while also outlining the underlying physical mechanisms and relevant theoretical foundations. In communication antennas, metamaterial-enabled designs realize antenna miniaturization to the order of millimeters, high radiation performance, and multi-scenario adaptability. By integrating structures such as split-ring resonators (SRRs) and complementary split-ring resonators (CSRRs), together with intelligent optimization algorithms, these antennas support diverse IoT scenarios, including 5G/6G communications, the Internet of Vehicles (IoV), and underwater communications. In energy harvesting, metamaterials exploit local resonance and multi-source fusion mechanisms to enhance the conversion efficiency of electromagnetic, vibrational, and acoustic energy, achieving efficiencies approaching near-unity under controlled conditions. These advances enable the development of self-powered IoT systems. For sensing and detection, metamaterial-based sensors enable trace-level detection and high-selectivity recognition, with reported sensitivities spanning a wide range depending on design and operating conditions, demonstrating broad applicability in areas such as food safety monitoring and biomedical diagnostics. In electromagnetic absorption and related regulation mechanisms, tailored metamaterial absorbers achieve broadband, high-efficiency electromagnetic absorption and effective radiation shielding, typically reaching strong attenuation levels, thereby mitigating electromagnetic interference in emerging 5G/6G IoT devices. Finally, this paper summarizes the core technical routes, major performance breakthroughs, existing challenges—such as high-frequency losses and large-scale manufacturability—and emerging research trends, including 6G high-frequency optimization and artificial intelligence (AI)-driven metamaterial design. The comparative performance table further highlights key metrics and application scenarios across different technical schemes, providing a valuable reference for both academic research and engineering deployment of metamaterials in IoT systems.

Keywords: metamaterials; IoT; communication antennas; energy harvesting; sensing and detection

1. Introduction

As a core pillar of next-generation information technology, the Internet of Things (IoT) is accelerating the global transition toward an intelligent era of the Internet of Everything. The large-scale deployment of IoT systems imposes stringent requirements on terminal devices, particularly in communication performance, energy supply stability, sensing accuracy, and electromagnetic compatibility. However, conventional materials are constrained by intrinsic physical limits. As a result, they struggle to simultaneously meet the IoT requirements for miniaturization, high performance, and multifunctional integration. This limitation constitutes a critical bottleneck for further technological advancement.

Metamaterials are artificially engineered composite materials that exhibit extraordinary physical properties—such as simultaneously negative permittivity and permeability, negative Poisson's ratio, negative effective mass density, and near-zero refractive index—through precisely designed micro- and meso-scale architectures [1–3]. The conceptual origin of metamaterials can be traced to the late 20th century. In 1996, Pendry et al. proposed the theoretical framework of materials possessing concurrent negative permittivity and permeability, establishing the theoretical foundation for metamaterials [4]. In the early 21st century, Smith and co-workers successfully fabricated the first experimental double-negative metamaterials, experimentally demonstrating their electromagnetic wave manipulation capability and marking a pivotal transition from theoretical conception to practical realization [5].

Subsequently, driven by continuous innovations in fundamental unit-cell structures—such as artificial magnetic conductors (AMCs) and complementary split-ring resonators (CSRRs) [6–8]—metamaterials have evolved from single-field electromagnetic regulation to multi-physics control encompassing acoustics, mechanics, and thermology. This evolution has propelled metamaterials from laboratory-scale fundamental research toward broad, application-oriented exploration across multiple domains. Owing to their unparalleled capability for precise and programmable manipulation of electromagnetic waves, acoustic fields, and vibration energy, metamaterials have emerged as a disruptive technological paradigm for addressing the core challenges faced by next-generation IoT systems.

In recent years, metamaterial research in the IoT domain has extensively addressed key application directions, including communication antennas, energy harvesting, sensing and detection, and electromagnetic regulation, forming a multi-dimensional technical framework with substantial research outcomes. In communication applications, structural integration of split-ring resonators (SRRs) and CSRRs, combined with optimization via intelligent algorithms [6,7,9,10], has enabled antenna miniaturization (down to $12 \times 12 \times 1$ mm^3), high radiation efficiency (up to 86.23%), high sensitivity (6.07 GHz/ε), and strong adaptability across diverse scenarios such as 5G/6G, vehicle-to-everything (V2X), and wireless communication systems [11,12]. In the field of energy supply and harvesting, genetic algorithm–based optimization of metamaterial structural parameters enables triboelectric nanogenerators sharing a common negative electrode to operate synergistically with capacitor units. Efficient acoustic-to-electric energy conversion is achieved through local resonance mechanisms, offering self-powered and energy-harvesting solutions for IoT devices. This is particularly advantageous for low-power sensors, ultra-wideband applications, and wearable electronics [13–16]. For instance, Liu et al. [17] proposed an electromagnetic metamaterial based on a parametric equation, functioning as a dual-band Wi-Fi energy harvester operating at 2.45 and 5.8 GHz. Yadav et al. [15] introduced a novel tunable terahertz metamaterial perfect absorber, achieving an absorption level exceeding 90% across a broad frequency range, with near-unity absorption (100%) between 4.0 and 6.8 THz. Meanwhile, Chen et al. [13] developed a triboelectric metamaterial with a charge-pumping mechanism designed to harvest energy from linear mechanical motions and generate a direct-current (DC) output. In sensing applications, metamaterial-enabled sensors demonstrate trace-level detection capability and high specificity, with sensitivities reaching up to 8635.43 MHz/RIU, supporting applications in food safety, new energy security, and structural health monitoring [18–20]. For electromagnetic regulation, customized metamaterial absorbers incorporating ring, split-ring, and meander-cross dipole structures loaded with lumped resistors have been proposed [21]. These designs enable broadband and ultra-high-efficiency electromagnetic absorption (exceeding 99%) and radiation shielding, effectively mitigating electromagnetic interference and radiation safety challenges associated with 5G/6G equipment [22,23]. Meanwhile, foundational theoretical investigations and comprehensive review studies continue to advance, establishing a robust bridge between technological innovation and engineering implementation. These efforts cover metamaterial classification systems, fundamental characteristics, key enabling technologies, and pathways toward industrial application [24–27]. Specifically, Tan et al. [28] demonstrated that metamaterials can enhance local energy density, improving energy harvesting. Akbari-Farahani and Ebrahimi-Nejad [25] explored various metamaterial structures, analyzing their advantages and disadvantages for energy harvesting. They found that ambient sound could serve as an energy source, with the material through which the sound travels affecting the amount of harvested energy. Meanwhile, Xu et al. [26] provided an overview of reconfigurable metadevices, discussing everything from the fundamental principles of metamaterial resonant systems to the design mechanisms of functional THz metamaterial devices and their applications.

Building upon representative research achievements across five major IoT-related subfields, this paper systematically synthesizes advances in communication antennas, energy harvesting, sensing and detection, and electromagnetic regulation, as well as foundational theoretical and review studies, thereby constructing a comprehensive reference framework for both academic research and engineering practice. By summarizing key technical routes, major performance breakthroughs, persistent challenges—such as high-frequency losses and large-scale manufacturing constraints—and emerging trends including 6G-oriented high-frequency optimization and AI-driven metamaterial design, this review aims to present a coherent and holistic landscape of metamaterial-enabled IoT technologies. Ultimately, it seeks to promote cross-disciplinary integration, accelerate the transition from laboratory demonstrations to scalable engineering applications, and provide critical technical support for key IoT scenarios, including 5G/6G communications, smart wearable systems, and precision medicine.

The remainder of this paper focuses on four core application directions of metamaterials—communication antennas, energy harvesting, sensing and detection, and electromagnetic regulation—as illustrated in Figure 1.

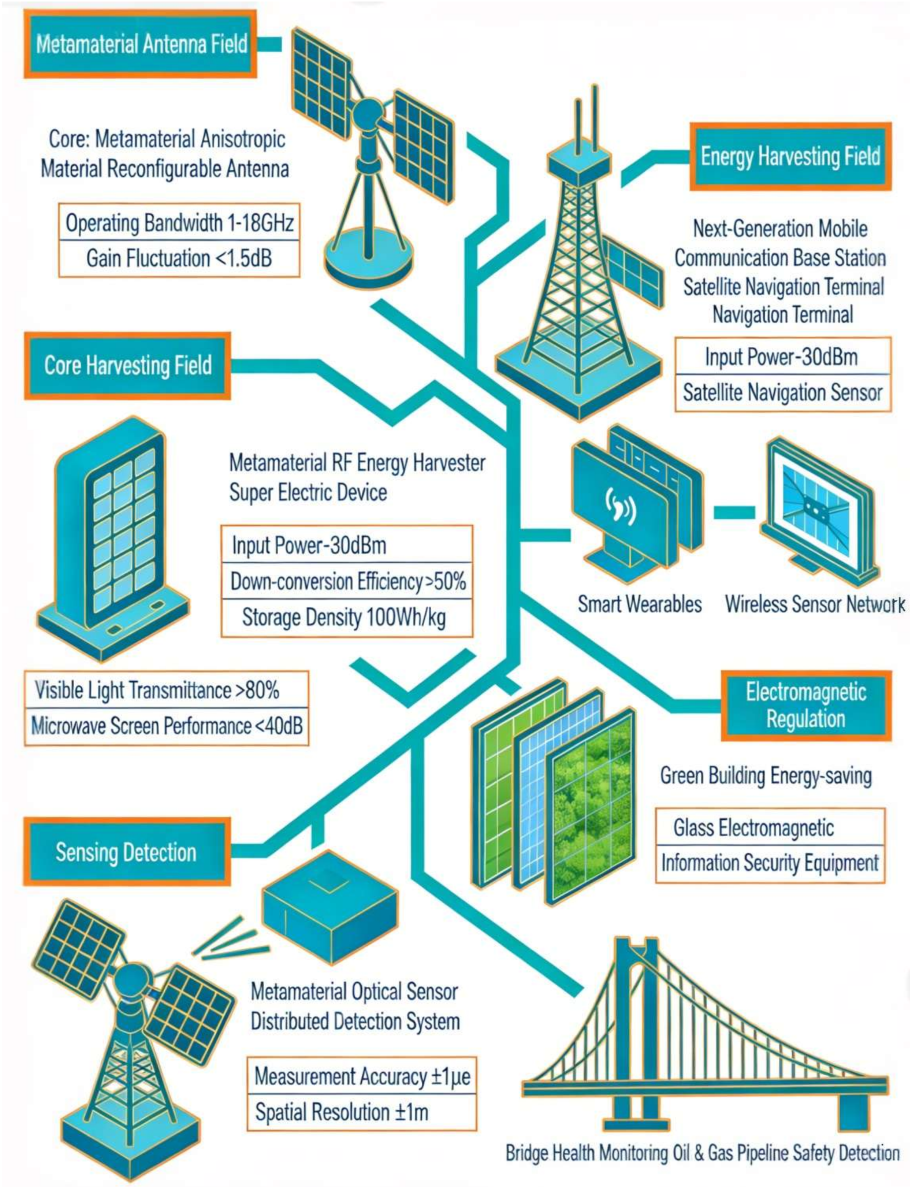

Figure 1. Correlation framework of metamaterials across four core application domains: communication antennas, energy harvesting, electromagnetic absorption and regulation, and sensing and detection.

Compared with conventional survey-type reviews that primarily summarize reported results, the present work aims to provide a mechanism-oriented and cross-domain analytical synthesis of metamaterial applications in IoT systems. Specifically, this review establishes a unified comparison framework across four major domains—communication, energy harvesting, sensing, and electromagnetic regulation—and systematically analyzes the underlying physical mechanisms and design strategies rather than merely listing individual studies. It highlights key performance trade-offs, such as miniaturization versus bandwidth and efficiency versus fabrication complexity, while identifying common bottlenecks and transferable design principles across domains.

Furthermore, this work places particular emphasis on very recent advances (2024–2026), thereby capturing the latest technological developments, emerging design strategies, and rapidly evolving application scenarios that are not yet comprehensively addressed in earlier reviews. Beyond qualitative discussions, it introduces a systematic quantitative comparison of key performance metrics—including gain, efficiency, bandwidth, sensitivity, and energy conversion efficiency—across multiple domains (Tables 1–4), enabling clearer benchmarking and facilitating the identification of intrinsic design trade-offs. In addition, by adopting a multi-domain integration perspective, this review simultaneously examines metamaterial-enabled communication, energy harvesting, sensing, and electromagnetic regulation within a unified framework, with particular attention to cross-domain coupling mechanisms and system-level integration for IoT applications.

Through this combination of mechanism-level insight, timeliness, quantitative rigor, and interdisciplinary synthesis, the present review not only serves as a comprehensive reference for the academic community but also provides practically actionable guidance for engineering design and real-world deployment of metamaterial-enabled IoT systems.

2. Metamaterial-enabled antenna design and communication applications

Metamaterials exhibit exceptional potential in antenna engineering and wireless communication systems. This is due to their unconventional electromagnetic properties, including negative permittivity and permeability, near-zero refractive index, and tailored dispersion characteristics. They have become a key enabling technology for addressing fundamental challenges in antenna miniaturization, performance enhancement, and multi-band adaptability, particularly in emerging application domains including 5G/6G communications, the IoT, and wearable electronics. To further strengthen the theoretical grounding of metamaterial-enabled communication systems, recent advances in reconfigurable intelligent surfaces (RIS) have introduced the concept of smart radio environments [29], in which the wireless propagation medium itself becomes programmable. Unlike conventional active transceivers, RIS function as nearly passive electromagnetic interfaces capable of dynamically shaping wavefronts through controllable reflection coefficients. Building on representative studies in this area [30–33], this paper systematically reviews recent research progress and evolving trends from five interrelated perspectives: research objectives, core technical approaches, representative achievements, existing challenges, and future development directions.

2.1. Research objectives and application scenarios

2.1.1. Core research objectives

(1) Size miniaturization: achieve substantial reductions in antenna physical dimensions while preserving satisfactory radiation performance, enabling seamless integration into space-constrained platforms such as wearable devices, IoT nodes, and automotive shark-fin antennas [34–37]. Specifically, Adawiah et al. [34] explored a compact tunable metamaterial unit cell featuring a trihexagon and tri-square split ring resonator structure designed for 5G communication applications. Musead et al. [35] introduced a wideband tunable metamaterial with a T-H-shaped symmetric resonator for body-centric

applications operating in the millimeter-wave frequency band centered at 28 GHz. Additionally, Singh et al. [36] studied an electromagnetic metamaterial–inspired simple monopole antenna on the RT/duroid 5880 substrate for millimeter-wave 5G applications.

(2) Performance optimization and matching technique: improve key performance indicators—including antenna gain, operating bandwidth, and port isolation—while suppressing sidelobe levels and specific absorption rate (SAR) and enhancing radiation directivity and operational stability [38–40].

(3) Function diversification and optimization: realize advanced functionalities such as multi-band operation, frequency reconfigurability, and polarization tunability to meet the demands of multi-standard wireless communication systems and heterogeneous application requirements [37,40,41].

(4) Scenario adaptability: Address communication challenges in complex and extreme environments, including signal instability in underwater communications, millimeter-wave propagation losses, and body-area network constraints [42–44].

2.1.2. Main application scenarios

Metamaterial-enabled antenna technologies target a broad range of application scenarios, including 5G/6G core communications in Sub-6 GHz and millimeter-wave bands, large-scale IoT device interconnection, wearable healthcare monitoring, V2X communications, underwater sensing and detection, satellite communications, and through-wall radar systems, as illustrated in Figure 2. Collectively, these applications provide critical communication support for emerging fields such as smart cities, sustainable industrial systems, and precision medicine. Representative studies further highlight the strong scenario adaptability of metamaterial-based antenna designs. For example, the antenna reported in [45] supports smart city infrastructure and sustainable industrial innovation; the design in [46] is well-suited for marine exploration and underwater navigation; the antenna presented in [8] targets wearable applications, including medical monitoring and fitness tracking; and the system reported in [47] is applicable to scenarios demanding enhanced protection and performance optimization, such as satellite communications, military radar, and telemetry systems.

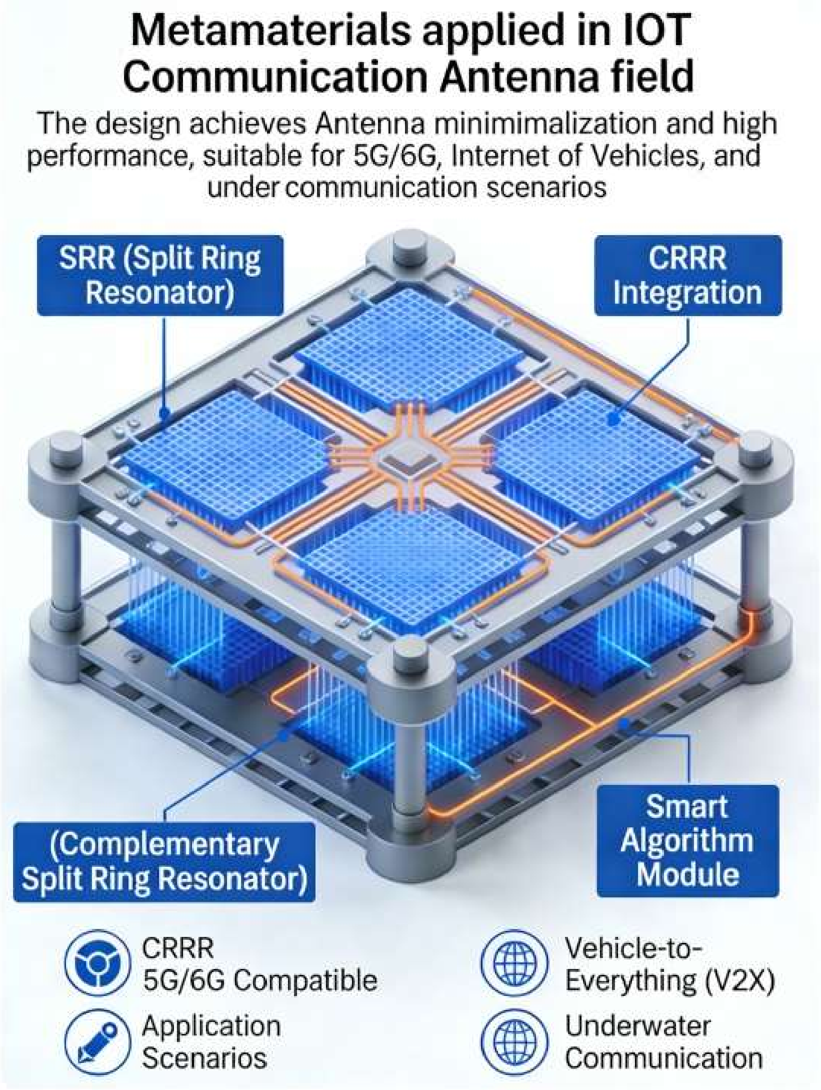

Figure 2. Schematic illustration of metamaterial-based antenna design and communication applications.

2.2. Core technical approaches and design strategies

2.2.1. Metamaterial selection and integration methods

(1) Representative metamaterial structures: typical metamaterial configurations—such as SRR, CSRR, AMC, double-negative (DNG), and epsilon-negative (ENG) metamaterials—are extensively employed in antenna engineering. Electromagnetic performance tailoring is primarily realized through systematic optimization of unit-cell geometries and array arrangements. For example, the structure reported in [9] adopted square SRR elements; the designs in [6,7] employed CSRR-based configurations; and the antenna in [8] integrated a 7 × 7 AMC array to significantly enhance radiation characteristics.

(2) Metamaterial–device integration schemes: common integration strategies include loading metamaterial units onto antenna patches or ground planes, utilizing metamaterials as reflective layers or superstrates, and embedding metamaterial elements within substrate-integrated structures. To achieve an optimal trade-off between electromagnetic performance and structural compactness, some

studies further adopt air-gap stacking or shared-aperture integration schemes. For instance, the configuration in [48] realized metamaterial–antenna stacking with a 6 mm air gap, whereas the design in [49] employed a shared-aperture architecture to enable coordinated operation across microwave and millimeter-wave frequency bands.

(3) Modeling assumptions and system abstraction: from a modeling and system abstraction perspective, programmable metasurfaces provide a critical bridge between physical electromagnetic design and communication-layer functionality. The work *Wireless Communications with Programmable Metasurfaces* [50] formalizes metasurfaces as software-defined electromagnetic platforms, where discrete tunable elements enable controllable scattering responses. This abstraction supports the development of system-level models that incorporate metasurface configurations into channel representations, enabling joint optimization of hardware structure and communication performance.

2.2.2. Multi-physical field coupling and optimization algorithms

(1) Innovative structural design strategies: by incorporating fractal geometries (e.g., Moiré and Koch curves), corrugated surfaces, and gradient structural designs, antenna bandwidth and radiation performance can be effectively enhanced. In addition, defected ground structures (DGS) and polarization rotators are introduced to improve impedance matching, inter-element isolation, and polarization control. Representative examples include the integration of Moiré and Koch fractal curves in [11], the adoption of corrugated structures in [9,51], and the application of DGS techniques in [52].

(2) Intelligent optimization and inverse design methods (not limited to antennas): advanced optimization techniques—such as genetic algorithms, Northern Goshawk Optimization (NGO), Bayesian optimization, and deep learning–based approaches (e.g., convolutional neural networks and generative adversarial networks)—are increasingly employed for efficient parameter optimization and inverse metamaterial design. These methods effectively mitigate convergence to local optima and significantly improve design efficiency. Specifically, genetic algorithms were used in [17] to optimize key structural parameters, NGO was applied in [53] for global optimization, and Bayesian optimization was adopted in [54] to further enhance prediction accuracy and design robustness.

2.2.3. Bandwidth and function expansion technologies

(1) Multi-band implementation: by exploiting the multi-resonant characteristics of metamaterial unit cells, controllable switching via Positive-Intrinsic-Negative (PIN) diodes, and multi-array integration strategies, broadband and multi-band operation is achieved across the S, C, X, and Ku bands, as well as key 5G New Radio (NR) frequency bands (n77, n78, n79, etc.). For example, the design in [11] enabled switching among seven resonant frequencies using PIN diodes, while the antenna reported in [55] achieved continuous coverage of the 5G NR C-band (3.2–4.4 GHz).

(2) Reconfigurable technology: by leveraging the phase-transition characteristics of vanadium dioxide (VO_2) and tunable metal stubs, dynamic regulation of operating frequency, polarization state, and radiation pattern can be realized, enabling adaptability to complex and time-varying communication environments. The incorporation of VO_2 facilitates real-time performance reconfiguration [15] and enables highly sensitive detection of hydrogen (H_2) and methane (CH_4) gases [20]. In addition, precise frequency tuning was achieved through the use of tunable metal stubs [12].

2.3. Key research outputs and performance breakthroughs

2.3.1. Miniaturization and integration achievements

(1) Extreme miniaturization: metamaterial loading enables antenna size reductions exceeding 92%, substantially advancing ultra-compact system integration. For example, the 3.5 GHz 5G antenna reported in [10] occupied only $12 \times 12 \times 1$ mm^3, while the millimeter-wave single-element antenna in [56] was further reduced to $6.15 \times 5.13 \times 0.8$ mm^3, fully satisfying the stringent integration requirements of micro-scale electronic devices.

(2) Multifunctional integration: antennas are increasingly co-designed with sensing and energy-harvesting functionalities to enable multifunctional integration. Representative wearable antennas simultaneously support wireless communication and physiological monitoring while maintaining mechanical flexibility and user comfort. In [8], communication and health-monitoring functions were integrated into a textile-based antenna platform, achieving both functional synergy and long-term wearability.

2.3.2. Enhancement of core performance metrics

(1) Gain and efficiency optimization: the introduction of metamaterials significantly enhances antenna gain and radiation efficiency. Reported gains reach up to 25.6 dBi in the terahertz band, with radiation efficiency generally exceeding 85%. Specifically, the metamaterial-enhanced antenna in [57] achieved a peak gain of 25.6 dBi, while the millimeter-wave antenna in [56] attained an exceptional radiation efficiency of 98%–99%. Moreover, by incorporating a metamaterial reflective layer, the average gain of the slot antenna in [30] was increased from 3.41 to 7.42 dBi.

(2) Isolation and interference suppression: for multiple-input multiple-output (MIMO) systems, metamaterial loading effectively suppresses mutual coupling, achieving inter-element isolation levels of $\geq$30 dB and envelope correlation coefficients (ECC) below 0.001. The four-element MIMO antenna in [56] demonstrated isolation exceeding 30 dB, while the design in [55] achieved an ECC of less than 0.0001, indicating excellent diversity performance and strong anti-interference capability. Furthermore, [42] systematically discussed metamaterial-based decoupling and focusing isolation techniques for planar millimeter-wave MIMO antennas.

(3) Bandwidth expansion: metamaterial-assisted designs substantially broaden antenna operating bandwidths. The enhanced antenna in [57] achieved an ultra-wide bandwidth of 44.8 THz, while the ultra-wideband antenna reported in [7] covered a frequency range from 0.38 to 20 GHz, effectively meeting the requirements of multi-standard and broadband wireless communication systems.

To ensure a more comprehensive and representative understanding of metamaterial-enabled antenna performance, it is important to consider results from multiple independent studies rather than relying on isolated reports. Across the literature [30,45,54–56], consistent trends can be observed in gain enhancement, bandwidth expansion, and isolation improvement, although the specific performance metrics vary depending on structural design, substrate selection, and operating frequency. For instance, while high-gain performance exceeding 20 dBi has been reported in millimeter-wave designs [56], other studies emphasize broadband characteristics or compactness [30,54], highlighting the inherent trade-offs among size, bandwidth, and radiation efficiency. Such cross-study comparisons provide a more balanced perspective on achievable performance limits and design strategies.

2.3.3. Adaptation breakthroughs in special scenarios

(1) Communication in extreme environments: metamaterial-enabled antennas demonstrate robust electromagnetic performance under harsh and unconventional operating conditions. In [46], an underwater MIMO antenna achieved a radiation efficiency of 81.3% at a water depth of 320 mm, with negligible performance degradation induced by Doppler frequency shifts. Additionally, the wearable antenna reported in [8] maintained stable operation under mechanical bending and on-body conditions, while achieving an average SAR reduction of 96.84%.

(2) High-frequency band adaptation: to address millimeter-wave communication requirements at frequencies such as 38 and 60 GHz, compact metamaterial-based antenna arrays have been developed to enable wide-angle coverage and 360° radiation-pattern diversity. The antennas reported in [9,51,58] are compatible with the 38 GHz millimeter-wave band. Furthermore, the 12-element array in [56] achieved full 360° pattern diversity, making it particularly suitable for high-data-rate communications in 5G small-cell deployments and V2X systems.

Beyond the reported performance metrics, it is essential to clarify the underlying physical mechanisms that enable these breakthroughs and to critically assess the associated trade-offs. For instance, antenna miniaturization achieved through SRR/CSRR loading primarily relies on effective wavelength compression induced by resonant metamaterial inclusions; however, this mechanism inherently introduces narrowband characteristics and increased loss sensitivity, leading to a fundamental trade-off between size reduction and bandwidth. In contrast, AMC-based or metasurface-assisted designs enhance gain and radiation efficiency by improving impedance matching and suppressing surface waves, yet they often require additional structural layers, thereby increasing fabrication complexity and system thickness. Similarly, multi-resonant and reconfigurable designs (e.g., PIN-diode-based or VO_2-enabled structures) provide functional flexibility and multi-band operation, but at the cost of higher control complexity, biasing requirements, and reduced reliability in dynamic environments.

From a system perspective, these strategies can be broadly categorized into resonance-dominated designs (favoring compactness and sensitivity) and wavefront-engineering designs (favoring efficiency and bandwidth). The former are more suitable for highly integrated IoT nodes with strict size constraints, whereas the latter are better aligned with high-performance communication scenarios such as 5G/6G base stations and MIMO systems. Therefore, optimal design selection should not be based solely on peak performance metrics but should instead consider the interplay between electromagnetic performance, structural complexity, and application-specific constraints.

2.4. Existing problems and technical bottlenecks

Despite significant progress, metamaterial-enabled antenna technologies continue to face several fundamental challenges that constrain large-scale deployment and long-term reliability.

In addition to fabrication and performance limitations, the practical deployment of RIS-based and metamaterial-enabled communication systems faces several system-level constraints that are often underemphasized. As discussed in [59], key challenges include control signaling overhead, scalability of real-time configuration, and the complexity of channel estimation in RIS-assisted environments. These factors impose non-negligible implementation costs and may limit achievable performance gains in realistic scenarios. Accordingly, a balanced assessment of RIS technologies must consider not only their theoretical advantages but also these practical constraints, particularly for large-scale IoT deployments requiring robust, low-latency, and energy-efficient operation.

To further enhance engineering interpretability and cross-domain comparability, the limitations in this section are refined into quantitative and design-relevant bottlenecks explicitly linked to representative studies summarized in Table 1. A fundamental constraint is the bandwidth–efficiency–profile trade-off inherent to metamaterial antennas. As evidenced by representative designs in Table 1, ultra-thin or conformal metasurface antennas (profile $< \lambda/20$) typically exhibit narrow impedance bandwidths (<5%–10%) and/or reduced radiation efficiency due to increased stored electromagnetic energy and ohmic losses. Conversely, broadband designs (>20%) often rely on thicker substrates or multi-resonant stacking strategies, which compromise low-profile integration. This trade-off imposes a fundamental limitation on simultaneous miniaturization and broadband performance and is now explicitly linked to the representative antenna configurations listed in Table 1.

2.4.1. Performance–cost trade-off

(1) Reliance on high-end substrates: most high-performance metamaterial antennas rely on specialized low-loss substrates, such as Rogers RT-5880, which substantially increase material costs and limit scalability. By contrast, antennas fabricated on low-cost FR4 substrates typically suffer from pronounced performance degradation at high frequencies. For example, the antennas reported in [45,58] were fabricated on Rogers RT-5880, and the design in [9] adopted an RT/duroid 5880 substrate, whereas the antennas in [10,48] employed FR4, resulting in notable disparities in high-frequency performance.

(2) Manufacturing complexity: the fabrication of metamaterial unit cells often requires high-precision processes—such as nanoscale lithography and three-dimensional micro-/nano-printing—which remain difficult to scale and are highly sensitive to dimensional deviations during mass production. These limitations undermine performance consistency and yield. As an illustrative example, the scheme in [60] employed maskless ultraviolet lithography–based optical 3D micro-printing, imposing stringent requirements on fabrication accuracy and process control.

2.4.2. Constraints on key performance metrics

(1) Bandwidth–gain trade-off: highly miniaturized antennas commonly exhibit limited impedance bandwidth, particularly in high-frequency metamaterial-based designs, where simultaneously achieving broadband operation and high gain remains challenging. The compact antenna reported in [10], with a bandwidth of only 200 MHz, exemplified the inherent difficulty in balancing bandwidth expansion with gain enhancement under strict size constraints.

(2) High-frequency loss and attenuation: metamaterial antennas operating in millimeter-wave and terahertz bands experience severe electromagnetic losses arising from conductor loss, dielectric loss, and surface-wave excitation. These losses substantially reduce effective transmission distance and restrict applicability in long-range communication scenarios. Although the D-band (110–170 GHz) antenna presented in [61] demonstrated encouraging performance, high-frequency attenuation remains a critical limiting factor.

2.4.3. System integration and reliability challenges

(1) Multi-module compatibility issues: the integration of metamaterial antennas with radio-frequency (RF) front ends, energy-harvesting units, and power-management modules is highly susceptible to electromagnetic interference, which can degrade overall system performance. Moreover, conventional intelligent reflecting surfaces typically exhibit single-function characteristics and low-resource utilization efficiency, limiting their suitability for highly integrated systems. For instance, in the four-port ultra-wideband MIMO antenna incorporating a metasurface in [62], mitigating inter-module coupling and electromagnetic interference remained a key challenge.

(2) Insufficient environmental adaptability: the electromagnetic responses of metamaterial structures are sensitive to environmental variations, such as extreme temperature and humidity, leading to parameter drift and degraded long-term stability. In addition, the sealing and corrosion resistance of underwater metamaterial antennas remain inadequate. Although the underwater antenna reported in [46] demonstrated stable short-term operation, further optimization of encapsulation and anti-corrosion strategies is required to ensure long-term reliability in harsh aquatic environments.

2.4.4. System integration and reliability challenges

While existing studies report significant performance improvements, a deeper analysis reveals that different metamaterial design strategies inherently involve non-trivial trade-offs:

(1) Miniaturization vs. bandwidth limitation: strongly resonant structures (e.g., SRR/CSRR-based designs) achieve substantial size reduction by exploiting localized electromagnetic resonance. However, such resonance is typically narrowband, leading to limited impedance bandwidth. In contrast, gradient or multi-resonant structures improve bandwidth but often increase structural complexity and footprint.

(2) Gain enhancement vs. loss mechanisms: high-gain performance is often achieved through metasurface superstrates or reflective layers that improve wavefront shaping. However, at millimeter-wave and terahertz frequencies, dielectric and conductor losses increase significantly, which can offset the gain improvement and reduce overall efficiency.

(3) Reconfigurability vs. system complexity: the introduction of tunable elements (e.g., PIN diodes, VO_2, microelectromechanical systems (MEMS)) enables dynamic control of frequency and radiation patterns. Nevertheless, this comes at the cost of increased biasing networks, control overhead, and reduced reliability, particularly in large-scale IoT deployments.

(4) Performance vs. manufacturability: high-performance designs frequently rely on complex geometries or high-end substrates (e.g., Rogers materials), which limit scalability. Simpler designs using FR4 substrates improve manufacturability but typically suffer from reduced high-frequency performance.

From a system perspective, these trade-offs indicate that no single design strategy is universally optimal. Instead, the selection of metamaterial configurations should be guided by application-specific priorities, such as compactness for wearable devices, efficiency for energy-constrained nodes, or robustness for harsh environments.

This comparative analysis highlights that future research should move beyond performance maximization of individual metrics toward multi-objective co-design frameworks that explicitly balance electromagnetic performance, cost, and system integration requirements.

2.5. Future research directions and development trends

2.5.1. 6G-oriented technological breakthroughs in high-frequency bands

(1) Targeted optimization for terahertz bands: leveraging the abundant spectrum resources in the 0.1–10 THz range, future research should prioritize the development of low-loss metamaterial antenna architectures to mitigate severe atmospheric absorption and transmission attenuation inherent to terahertz waves. Recent studies [15,20,26] have explored terahertz-band metamaterial designs, establishing an essential technical foundation for 6G-oriented communication scenarios.

(2) Convergent design for massive MIMO systems: by integrating gallium nitride (GaN) technologies with terahertz-compatible CMOS fabrication processes, chip-scale metamaterial-based massive MIMO arrays can be realized, enabling ultra-high-density integration and enhanced spatial multiplexing. For example, the 128-element massive MIMO architecture proposed in [56] provided valuable insights into scalable antenna system design for future high-capacity 6G networks.

2.5.2. Integration of intelligent metasurfaces and multifunctional systems

(1) Advancement of multi-dimensional reconfigurability: the development of intelligent metasurfaces with integrated control over radiation, scattering, and wavefront shaping is expected to enable real-time, multi-dimensional manipulation of electromagnetic waves. Such systems can seamlessly integrate communication, sensing, and energy-delivery functions within a unified platform. The programmable metasurface frameworks discussed in the review of information metamaterials [63] offer strong theoretical support for achieving multifunctional integration.

(2) High-precision adaptation to mobile scenarios: for highly dynamic platforms—such as unmanned aerial vehicles and autonomous driving systems—future metamaterial antenna designs should emphasize target-aware beam tracking, adaptive radiation control, and dynamic energy provisioning. Related studies focusing on V2X applications [62,64] provided practical design references for enhancing system adaptability in mobile and time-varying environments.

2.5.3. AI-driven innovation in design and manufacturing

(1) End-to-end inverse design frameworks: deep learning–based inverse design models enable the automated generation of metamaterial unit cells with customized operating bands and free-form reconfigurable geometries. The comprehensive review in [65] systematically summarized deep-learning methodologies for antenna inverse design and provided practical guidance for end-to-end implementation.

(2) Low-cost, large-scale manufacturing: emerging fabrication techniques—including maskless lithography, laser direct carbonization, and roll-to-roll printing—are being actively explored to facilitate scalable and cost-effective production of flexible metamaterial antennas. Notably, the laser-direct carbonization approach proposed in [66] for polymer substrates offers a promising pathway toward low-cost, high-throughput manufacturing.

2.5.4. Material innovation and cross-field collaboration

(1) Integration of novel functional materials: the hybrid integration of metamaterials with emerging functional materials—such as two-dimensional materials (e.g., graphene and molybdenum disulfide) and liquid metals—is being actively investigated to enhance electromagnetic performance, tunability, and reconfigurability. Studies in [53,67] on graphene-based metamaterials provided valuable references for material-level innovation.

(2) Advancement of interdisciplinary theoretical frameworks: multi-physics coupling models that integrate electromagnetics, materials science, and artificial intelligence are being increasingly developed to strengthen the theoretical foundation for metamaterial antenna design. In particular, the massive-electromagnetism-based framework (Proca theory) reported in [68] represents a compelling paradigm for advancing interdisciplinary theoretical research.

2.5.5. Expansion toward extreme scenarios and emerging fields

(1) Deep adaptation to extreme environments: metamaterial antennas are being engineered to operate reliably under harsh conditions, including radiation-intensive environments and ultra-high or ultra-low temperatures encountered in deep-space communication and polar exploration. In parallel, advanced sealing strategies and corrosion-resistant designs are being optimized for underwater applications. Studies on underwater antennas [46] and implantable medical antennas [69] provide valuable technical experience and design paradigms for extending metamaterial antenna applications to extreme scenarios.

(2) Cross-domain applications in emerging fields: beyond conventional wireless communications, metamaterial antennas are increasingly explored in frontier domains such as quantum communication, non-destructive biosensing, and holographic imaging. For example, [70] investigated terahertz communication security, while research on metamaterial-based biosensors [71] provided important insights into cross-disciplinary integration and functional expansion.

Metamaterial technology has enabled disruptive advances in antenna design and wireless communication systems, leading to substantial breakthroughs in miniaturization, performance enhancement, and multi-scenario adaptability. Consequently, metamaterial antennas have emerged as key enabling components for 5G IoT and next-generation communication infrastructures. Nevertheless, critical challenges remain, particularly in cost-effective fabrication, process reliability, and high-frequency loss mitigation. Looking ahead, sustained progress in material innovation, intelligent design methodologies, advanced manufacturing techniques, and interdisciplinary convergence is expected to further expand the application scope of metamaterial antennas across emerging domains such as 6G communications, smart terminals, and precision medicine. Table 1 summarizes representative research achievements in metamaterial antenna development. To improve consistency and comparability, the core performance indicators are reported with explicit units, and the direction of performance improvement (higher or lower being preferable) is clearly indicated. In addition, the specific metamaterial structure used in each study is explicitly listed.

Table 1. Comparative analysis of core performance and functional achievements of metamaterial antennas.

Ref.	Technical solution	Metamaterial structure	Core performance indicators	Application scenarios
[45]	Systematic integration of antenna design, metamaterial engineering, and MIMO configuration	I-shaped unit cell composed of seven circular ring resonators embedded within a square resonator	Gain (up to 11 dBi, ↑), bandwidth (5.3–11.3 GHz, ↑), isolation (up to 40 dB, ↑), efficiency (~70%–85%, ↑)	5G IoT, smart city, 5G wireless communication networks, WiMAX, and 5G Wi-Fi systems
[9]	Antipodal Vivaldi antenna array with optimized corrugations and SRR	Metamaterial unit cell with DNG properties	Frequency 37.9–45 GHz; gain 15.4–17 dBi (↑); efficiency > 89% (↑); SLL < −13.6 dB (↓)	Compact 5G devices, low-latency communication, and high-data-rate applications
[30]	Wideband slot antenna + reflector	Lattice of conducting wires embedded in a dielectric matrix	Gain 3.4→7.42 dBi (↑); bandwidth 1.4–6.5 GHz (↑); efficiency (not explicitly given, but inferred) (↑)	WLAN/Wi-Fi communication, IoT; WiMAX systems
[11]	Fractal antenna + PIN diode + SRR	Fractal radiating patch + SRR metamaterial	Bandwidth 2.85–11.3 GHz; (↑); gain 5.2 dBi (↑); size (mm^3 ↓)	Multi-standard communications; radar systems; IoT

3. Metamaterial-driven multifunctional energy harvesting and supply systems

Metamaterials, owing to their unconventional physical characteristics—such as local resonance, strong energy confinement, and negative Poisson's ratio—have enabled transformative advances in energy harvesting and power supply technologies. These properties facilitate efficient capture, conversion, and regulation of ambient energy, thereby providing green and sustainable power solutions for IoT devices, ultra-low-power sensors, and wearable electronics. Building upon representative studies [17,72–75], this section systematically reviews recent progress and emerging trends in metamaterial-enabled energy harvesting from five perspectives: research objectives, core technical approaches, key research outcomes, existing challenges, and future development directions. The aim is to establish a comprehensive and structured reference framework for researchers in this rapidly evolving field. In addition to summarizing representative studies, this section emphasizes comparative analysis and mechanism-driven insights to clarify performance differences among competing design strategies.

3.1. Research objectives and application scenarios

3.1.1. Core research objectives

(1) High-efficiency energy capture: enhance the conversion efficiency of multiple ambient energy forms—including electromagnetic, vibrational, acoustic, and solar energy—while overcoming the intrinsic efficiency limitations of conventional energy harvesting technologies [72,73,76].

(2) Compact and integrated system design: realize tightly integrated architectures that unify energy harvesting, storage, and power management within a single platform, thereby significantly

reducing system volume and satisfying the stringent size constraints of miniaturized electronic devices [73,77,78].

(3) Broadband operation and environmental adaptability: expand the effective energy harvesting bandwidth and improve operational robustness under complex and variable environmental conditions, such as indoor and outdoor settings, extreme temperatures, and fluctuating vibration spectra [72,77,79].

(4) Self-powered and maintenance-free operation: enable long-term, stable self-powered operation for low-power electronic systems, minimizing maintenance requirements and supporting large-scale deployment of wireless sensor networks [77–79].

3.1.2. Main application scenarios

Metamaterial-enabled energy harvesting technologies target a wide spectrum of application scenarios, including power supply for IoT nodes [6,17], low-power sensor systems [22,52], lifetime extension of wearable devices [13,80], energy recovery in smart manufacturing environments [14], and self-powered structural health monitoring systems [81,82], as illustrated in Figure 3. These applications provide essential energy support for low-power devices in emerging domains such as smart cities, sustainable industrial systems, and precision medicine. Beyond conventional electronic platforms, this framework further extends to high-speed optical communication systems within integrated photonics—such as data centers and long-haul optical fiber networks [83]—as well as nanoscale communication paradigms, including metamaterial-enabled nanonetworks operating in biomedical environments, such as within the human cardiovascular system [84].

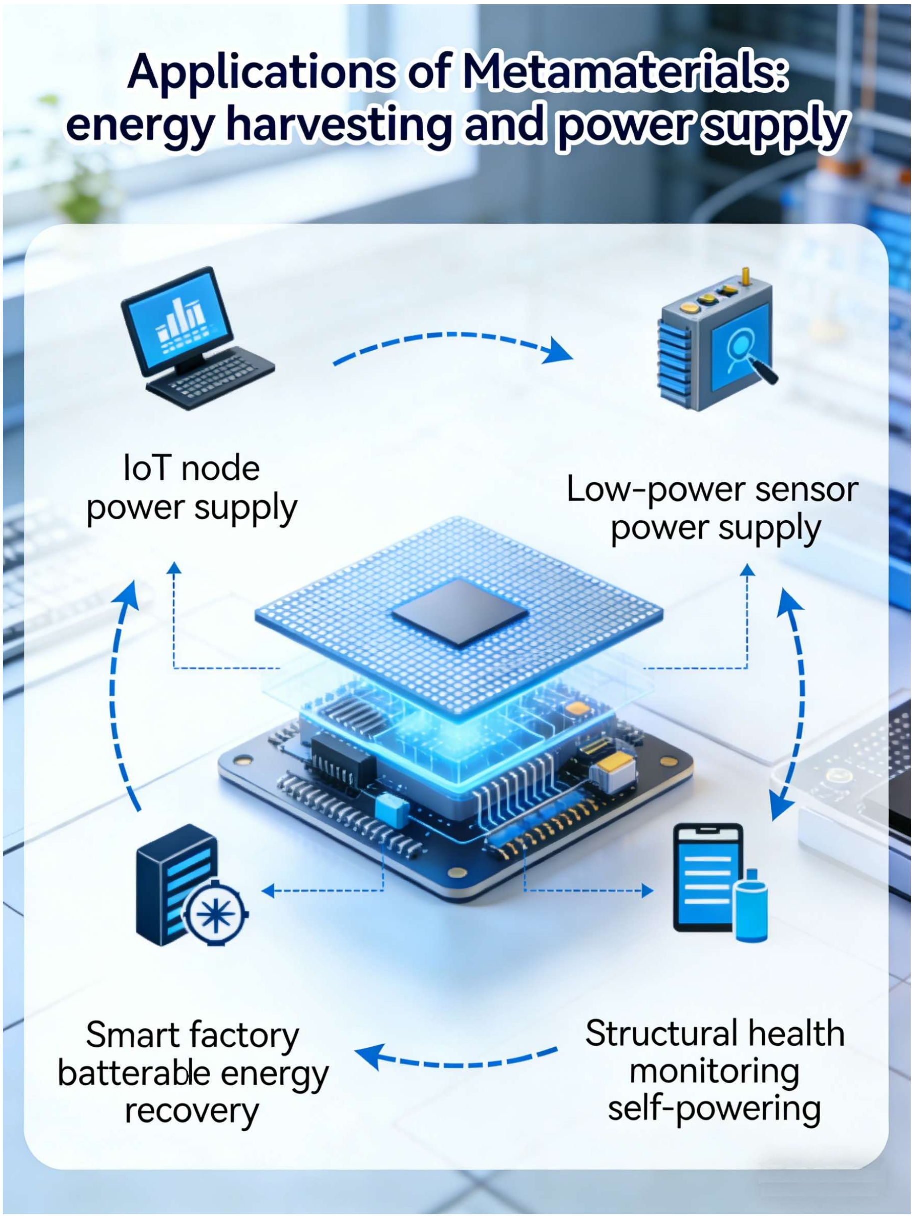

Figure 3. Schematic illustration of metamaterial applications in energy harvesting and power supply systems for the IoT.

3.2. Core technical means and design strategies

3.2.1. Metamaterial structure selection and energy enhancement mechanisms

(1) Representative metamaterial structures: widely adopted metamaterial configurations include DNG metamaterials [52], CSRR [6], gradient-index metamaterials [85], negative Poisson's ratio metamaterials [80,86], and acoustic metamaterials [14,87]. These structures enhance local energy density through mechanisms such as resonance amplification, energy confinement, and controlled wavefield manipulation.

(2) Energy enhancement mechanisms: electromagnetic metamaterials improve radio-frequency energy harvesting efficiency by enabling polarization-insensitive and wide-angle energy capture [17].

Acoustic metamaterials exploit local resonance to amplify sound pressure, thereby enhancing acousto-electric energy conversion efficiency [87,88]. Gradient metamaterials enable ultra-broadband and high-capacity vibration energy harvesting by tailoring spatial impedance distributions [85,89].

3.2.2. Multi-energy integration and system-level implementation technologies

(1) Multi-source energy complementarity: hybrid energy harvesting schemes that integrate radio-frequency and solar energy [6] and vibrational and acoustic energy [87], as well as triboelectric nanogenerators operating synergistically with capacitor-based storage units [13], are developed to ensure stable power output across diverse operating conditions while mitigating the intermittency of single-source harvesters.

(2) Integrated system design: system-level integration of energy harvesting, rectification, energy storage, and power management modules is a central design focus. For example, the energy management chip BQ25504 was employed to achieve stable voltage regulation and ultra-low-power startup [6], while broadband impedance-matched rectifier circuits are introduced to further improve overall energy conversion efficiency [22,39].

3.2.3. Optimization algorithms and modeling-driven empowerment

(1) Structural parameter optimization: advanced optimization algorithms—such as genetic algorithms [17,86] and the NGO algorithm [53]—were applied to optimize metamaterial unit-cell dimensions and array configurations, effectively avoiding local optima and maximizing energy harvesting performance.

(2) Efficient modeling framework: high-efficiency modeling approaches, including reduced-order harmonic balance (ROM-HB) frameworks [82], multi-physics coupled models [88], and distributed-parameter models [90], were established to enhance predictive accuracy and design efficiency while significantly reducing experimental iterations and computational cost.

(3) Mechanistic basis for tunability and wave control: to further strengthen the physical interpretation of tunability and wave/band-gap control mechanisms, additional representative studies with clear mechanistic foundations have been incorporated. In particular, the work of Pranno et al. [91] demonstrated that band-gap characteristics can be actively tuned through deformation-induced microscopic instabilities in nacre-like composite metamaterials. Their results reveal that instability-triggered pattern transformations under compressive loading directly modify wave propagation behavior, thereby providing a rigorous nonlinear and multiscale framework for understanding adaptive tunability. In addition, the study by De Maio et al. [92] proposed a microstructural design strategy—such as the introduction of hollow platelets and pre-stress states—to regulate elastic wave attenuation and band-gap formation. Their findings indicate that band gaps can be effectively tuned through internal architecture and pre-stress without altering the global structural length scale, supported by Bloch–Floquet analysis and validated numerical modeling. These studies collectively clarify that tunability in metamaterial-based IoT components is not limited to geometric or parametric variations but can also arise from nonlinear instability mechanisms and microstructure–pre-stress coupling. Moreover, they provide validated computational frameworks—combining finite element modeling with Bloch-wave analysis—that directly support applications in vibration control, sensing, and energy harvesting.

3.3. Key research outputs and performance breakthroughs

3.3.1. Substantial enhancement in energy harvesting efficiency

(1) Electromagnetic energy harvesting: a dual-band Wi-Fi energy harvester achieved peak harvesting efficiencies of 96.9% and 95% at 2.45 and 5.8 GHz, respectively [17]. In addition, a metamaterial-based rectenna array enhances harvested power in the sub-1 GHz band by approximately 60 times compared with conventional designs [93].

(2) Vibrational energy harvesting: a gradient-structured metamaterial energy harvester delivers an output power 489% higher than that of a traditional single-cantilever configuration [85]. Furthermore, a negative Poisson ratio metamaterial-enhanced piezoelectric nanogenerator (MM-PENG) achieves a 6.7-fold increase in output power [86].

(3) Acoustic energy harvesting: an acoustic metamaterial piezoelectric harvester exhibits a voltage sensitivity of 0.11 V/Pa under factory noise conditions, with output power 4.4–12.7 times greater than that of conventional structures [14]. The MetaSonicell system further generates 0.17 mW of electrical power under 90 dB acoustic excitation [87].

(4) Hybrid power supply system: a hybrid radio-frequency and solar energy harvesting system maintains a stable output voltage of 2.9 V across four representative environmental scenarios, successfully meeting the power requirements of typical IoT sensor nodes [6].

3.3.2. Breakthroughs in system miniaturization and integration

(1) Ultimate size reduction: a metamaterial-integrated wireless power and information transfer system achieves an ultra-compact footprint of only 25×25 mm^2 [52]. In parallel, a gradient E-shaped metamaterial energy harvester realizes high-capacity energy capture over a broad low-frequency range of 20–400 Hz while maintaining a compact structural configuration [89].

(2) Multifunctional integration: a triboelectric metamaterial platform integrates mechanical energy conversion, charge storage, and short-range sensing functionalities, delivering a maximum open-circuit voltage of up to 3860 V [13]. Meanwhile, a thermoacoustic metastructure enables synergistic acoustic–thermal–electrical energy conversion while simultaneously achieving effective noise suppression [94].

3.3.3. Enhanced environmental adaptability and stability

(1) Broadband operational capability: vibration-based energy harvesters demonstrated effective operating bandwidths spanning 60–160 Hz [85] and 20–400 Hz [89], while acoustic energy harvesters achieved a tunable resonant frequency range of 41–71 Hz [95].

(2) Tolerance to complex environments: hybrid energy supply systems ensure stable power delivery under diverse conditions, including indoor light/dark environments and outdoor sunny/cloudy scenarios [6]. Flexible metamaterial energy harvesters exhibit robust adaptability to bending deformations and wearable, on-body applications [8,96]. In addition, wireless power transfer systems maintain high transmission efficiency over distances of 5–25 cm and under lateral misalignment conditions [97].

3.4. Existing problems and technical bottlenecks

To improve practical relevance, the limitations in this section are reformulated into three core engineering bottlenecks based on the representative systems summarized in Table 2. First, the variability of ambient energy sources leads to unstable power output. As shown in Table 2, RF and vibration energy harvesting outputs vary by orders of magnitude across different environments, resulting in highly inconsistent power budgets for IoT devices. Second, packaging and durability constraints significantly affect performance. Many reported devices rely on delicate resonant structures or impedance matching layers, which are prone to degradation under mechanical fatigue, humidity exposure, and temperature cycling. Third, aging and long-term reliability issues remain insufficiently addressed. In particular, there is a lack of reported lifetime performance data for flexible or hybrid metamaterial systems, limiting confidence in long-term deployment. These bottlenecks are now explicitly correlated with representative devices in Table 2 to highlight real-world engineering constraints.

3.4.1. Constraints on energy density and output power

(1) Limited adaptability under low-power excitation: for low-intensity ambient energy sources—such as weak radio-frequency signals and microscale vibrations—the energy conversion efficiency of current systems remains insufficient, hindering reliable power supply for medium- to high-consumption electronic devices.

(2) Severe losses at high-frequency bands: metamaterial energy harvesters operating in millimeter-wave and terahertz regimes suffer from pronounced electromagnetic losses, which limit the simultaneous realization of long-range energy transmission and high harvesting efficiency [26,61].

3.4.2. Challenges in cost and large-scale manufacturing

(1) Dependence on high-end materials and advanced fabrication: many high-performance metamaterial energy harvesters rely on specialized substrates (e.g., Rogers-series laminates) and advanced fabrication techniques, such as 3D microprinting and laser-induced carbonization [60,66]. These requirements substantially increase production costs and restrict scalability.

(2) Insufficient consistency in mass production: minor dimensional deviations in metamaterial unit cells can induce significant performance fluctuations at the array level. Existing manufacturing processes still struggle to maintain tight tolerance control and uniformity during large-scale production [23,60].

3.4.3. Challenges in system integration and reliability

(1) Multi-module compatibility issues: the integration of energy harvesting, rectification, and storage modules often introduces electromagnetic interference and parasitic energy losses, thereby degrading overall system efficiency [93].

(2) Insufficient long-term stability: the mechanical and electromagnetic properties of flexible metamaterials tend to drift under repeated bending cycles and harsh temperature–humidity conditions [8,98]. In addition, the wear resistance and cyclic durability of triboelectric metamaterial structures remain inadequate and require further improvement [13].

3.5. Future research directions and development trends

3.5.1. Multi-mechanism integration and performance limit breakthroughs

(1) Cross-modal energy integration: future systems should integrate electromagnetic, vibrational, acoustic, and thermal energy harvesting mechanisms within unified platforms to improve power stability, robustness, and redundancy.

(2) Low-loss material innovation: the hybrid integration of metamaterials with emerging material systems—such as two-dimensional materials (e.g., graphene and MXene) [67,99] and liquid metals [100]—offered promising pathways to suppress high-frequency losses and enhance overall energy conversion efficiency.

3.5.2. Intelligent adaptation and precise regulation

(1) Adaptive energy harvesting: programmable metamaterial architecture [63,70] can enable real-time reconfiguration of operating frequency bands and harvesting directions, allowing dynamic adaptation to fluctuating ambient energy environments.

(2) AI-enabled full-process empowerment: deep learning–based inverse design frameworks [65], combined with digital twin technologies [101], were expected to support rapid design iteration, accurate performance prediction, and intelligent fault diagnosis throughout the entire lifecycle of metamaterial energy harvesting systems.

3.5.3. Low-cost scaling and engineering applications

(1) Manufacturing process innovation: to enable cost-effective scalability, emerging fabrication routes—including roll-to-roll printing [102], laser direct carbonization [66], and maskless lithography [60]—have been actively explored to improve production efficiency, dimensional consistency, and yield in large-scale manufacturing.

(2) Scenario-specific customized development: application-tailored metamaterial energy harvesting solutions are being developed for smart factories, smart cities, and wearable medical devices, with a strong emphasis on system-level compatibility and seamless integration with terminal equipment [14].

3.5.4. Enhancement of theoretical and modeling frameworks

(1) Advancement of multi-field coupling theory: a unified theoretical framework encompassing electromagnetic, mechanical, thermal, and acoustic multi-field coupling is required to accurately describe energy conversion mechanisms under complex and dynamic operating conditions [88,90].

(2) Reliability modeling and lifecycle optimization: long-term reliability models for metamaterial energy harvesting systems should be established to quantitatively assess environmental impacts on performance degradation and to guide lifespan-oriented optimization strategies.

In summary, metamaterial technology has driven disruptive advances in multi-modal energy harvesting and power supply systems, achieving notable progress in efficiency enhancement, miniaturization, and multifunctional integration. These developments provide effective solutions for the self-powered operation of low-power electronic devices. Nevertheless, key challenges remain, including limited energy density, high fabrication costs, scalability constraints, and insufficient long-term stability. Looking forward, continued progress through multi-mechanism integration, material innovation, intelligent design methodologies, and manufacturing process optimization is expected to substantially expand the engineering applicability of metamaterial energy-harvesting technologies in the Internet of Things, wearable electronics, and smart infrastructure, thereby supporting green and sustainable technological development. Table 2 summarizes representative metamaterial-based energy-harvesting systems reported in the literature, with a focus on their operating mechanisms, structural configurations, and key performance metrics. Specifically, the table provides a comparative overview of parameters such as operating frequency and bandwidth, harvested power or power density, conversion efficiency, system architecture, and targeted application scenarios. This structured comparison ensures consistency with the scope of this section and facilitates a clear understanding of current technological capabilities and design trade-offs in metamaterial-enabled energy harvesting.

Table 2. Comparative analysis of core performance and functional characteristics of representative metamaterial-based energy-harvesting systems.

Ref.	Technical solution	Key energy-harvesting performance metrics	Application scenarios
[52]	Dual-band (405/900 MHz) metamaterial-integrated WIPT system, defected ground structure (DGS) resonator + DNG metamaterials	Power transfer efficiency (PTE) is improved by 14% in the 405 MHz frequency band and 7% in the 900 MHz frequency band	Wireless power supply and data transmission for low-power IoT sensors
[6]	Hybrid power supply–system integrated with metamaterial antenna (CSRR + 4×1 array) and solar cells, equipped with energy management chip BQ25504	Stably outputs a voltage of 2.9 V, with the antenna delivering a maximum output voltage of 1.63 V	Power supply for IoT nodes (under indoor light/dark and outdoor sunny/cloudy environments)
[17]	Electromagnetic metamaterial dual-band (2.45/5.8 GHz) Wi-Fi energy harvester, optimized by genetic algorithm	The harvesting efficiency reaches 96.9% and 95% under normal incidence, with excellent half-power bandwidth	Self-power supply for IoT devices and power supply for low-power sensors
[82]	Electromechanical tribo-induced metamaterial node (EMetaNode), mechanical metamaterial + synchronized switch interface circuit	The computational efficiency of the modeling framework is approximately 100 times higher than that of the full-scale model, and it can stably convert vibrational energy into direct current (DC)	Self-powered sensing for IoT and structural health monitoring

4. Metamaterial absorbers and electromagnetic regulation mechanisms

As key functional elements in electromagnetic regulation systems, metamaterial absorbers have enabled substantial advances across a broad spectrum of applications, including electromagnetic shielding, energy harvesting, spectrum management in wireless communications, and radiation protection. These advances are primarily attributed to their highly tailorable electromagnetic responses, near-unity absorption efficiency, and flexible structural design. Building upon representative studies such as [15,16,21], this section systematically reviews recent progress and emerging trends in metamaterial absorbers from five complementary perspectives: research objectives, core technical approaches, key achievements, existing challenges, and future development directions. The discussion aims to provide a comprehensive and structured reference framework for researchers and practitioners in this field.

To ensure conceptual clarity, the term "electromagnetic regulation" as used in this review is defined as a broad category encompassing multiple functionalities, including electromagnetic absorption, shielding, and wavefront manipulation. Among these, metamaterial absorbers represent the most mature and widely implemented approach in current IoT-related applications. Therefore, while this section situates electromagnetic regulation within a broader functional framework, the primary focus is placed on metamaterial absorbers, with other related mechanisms discussed in a complementary and contextual manner.

4.1. Research objectives and application scenarios

4.1.1. Core research objectives

(1) High-efficiency electromagnetic absorption: achieve near-perfect electromagnetic wave absorption (approaching 100%) within targeted or broadband frequency ranges, thereby overcoming the intrinsic limitations of conventional absorbing materials, such as narrow operating bandwidths and limited absorption efficiency [103,104].

(2) Synergistic multi-parameter optimization: realize coordinated optimization of polarization insensitivity, wide-angle incidence stability, and structural miniaturization, enabling robust electromagnetic regulation under complex and dynamically varying application conditions [105].

(3) Functional diversification and integration: integrate auxiliary functionalities—including energy harvesting, infrared shielding, and optical transparency—so as to transcend the single-function limitations of traditional electromagnetic absorbers and enable multifunctional system-level applications [88,103].

(4) Scenario-oriented precise adaptation: enable tailored electromagnetic responses to satisfy the specific performance requirements of diverse application scenarios, such as 5G/6G wireless communications, electromagnetic radiation protection, stealth technology, and thermal management in electronic devices [106,107].

4.1.2. Main application scenarios

The proposed research framework supports a wide range of practical application scenarios, including 5G electromagnetic radiation protection [21], 6G terahertz communication and imaging [15], optical window design for electronic devices [16], satellite communication and radar stealth [108], non-invasive microwave medical imaging [109], and electromagnetic interference shielding [110,111], as illustrated in Figure 4. Collectively, these applications provide critical technical support for intelligent communication systems, national defense security, and the high-density integration of advanced electronic equipment.

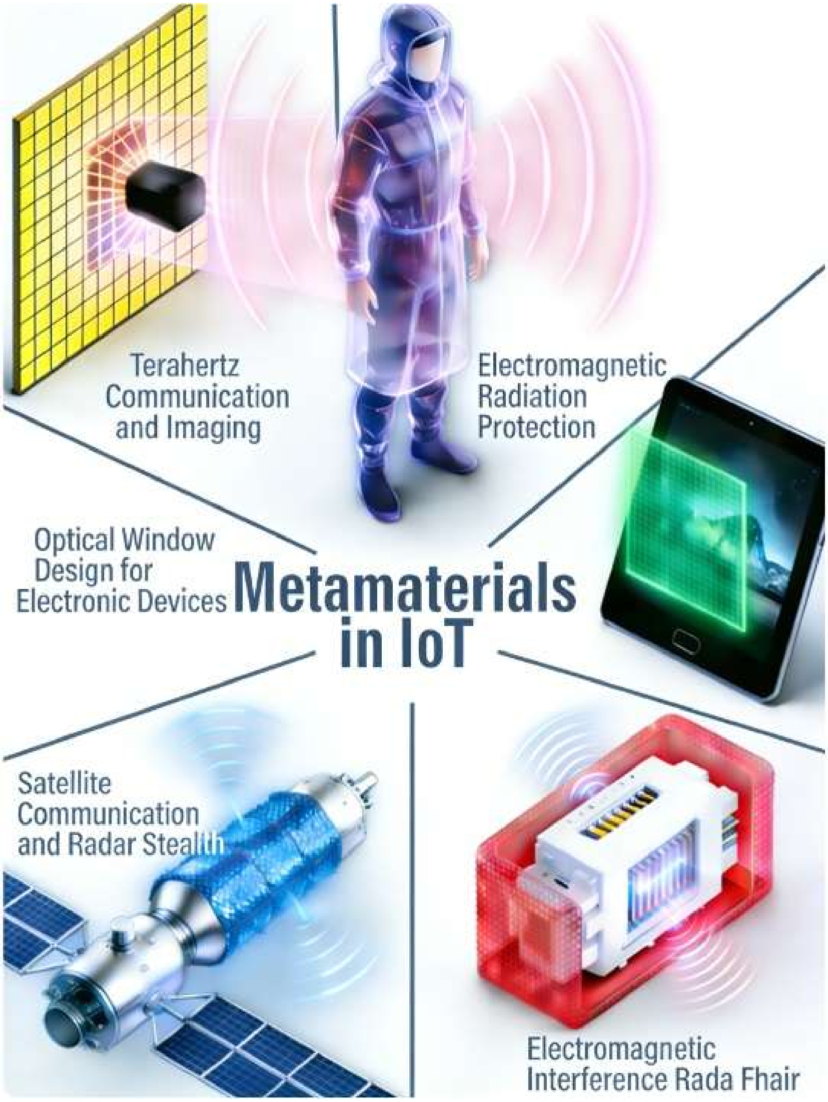

Figure 4. Schematic illustration of metamaterial applications in electromagnetic regulation and electromagnetic absorption for the IoT.

4.2. Core technical means and design strategies

4.2.1. Metamaterial structure design and electromagnetic regulation mechanisms

(1) Typical structural configurations: commonly adopted metamaterial absorber architectures include metal–insulator–metal (MIM) sandwich structures [108,112], nested ring structures [15], cross-shaped resonators [49], and periodic grating structures [113]. These designs achieve high-efficiency electromagnetic absorption through resonance excitation, polarization coupling, and intrinsic electromagnetic energy dissipation mechanisms. For example, [15] realized ultra-broadband terahertz absorption using a 2 × 2 array of VO_2 nested rings, while [108] achieved triple-band high absorption through a solar system–inspired double split-ring resonator configuration.

(2) Key regulation technologies: various electromagnetic effects—including DNG behavior [114], near-zero-index (NZI) characteristics [115], and Fano resonance [20]—were exploited to tailor the effective permittivity and permeability of metamaterials, thereby inducing strong absorption within

designated frequency bands. Notably, the compact CSRR-based absorber reported in [114] achieved high absorption efficiency in the S and C bands by leveraging its DNG properties.

4.2.2. Material selection and functional composite technology

(1) Core material systems: low-loss dielectric materials such as Rogers RT5880, silicon dioxide, and FR-4 were widely employed as substrates [15,55], while metals (including gold, nickel, and copper) serve as resonant layers [112,116]. In addition, phase-change materials—particularly VO_2—were incorporated in selected designs to enable dynamic and reversible tuning of absorption performance [15,20].

(2) Functional material integration: to achieve multifunctional performance, metamaterial absorbers were frequently integrated with gas-sensitive films [20], infrared shielding layers [16], photovoltaic materials [116], and other functional components. This integration enables the simultaneous realization of electromagnetic absorption, sensing, energy conversion, and shielding. For instance, [16] combined an infrared shielding layer with a water-based matrix, achieving synergistic broadband microwave absorption alongside effective suppression of infrared thermal radiation.

4.2.3. Structural optimization and simulation-driven design methods

(1) Topological structure innovation: advanced structural topologies—including fractal geometries [112], gradient architectures [110], and porous configurations [94]—were introduced to enhance resonant coupling, broaden absorption bandwidths, and improve angular stability. As a representative example, [112] achieved ultra-broadband absorption spanning the ultraviolet to near-infrared spectrum using a Sierpiński carpet-based fractal design.

(2) Simulation-assisted optimization techniques: electromagnetic simulation tools such as CST and High Frequency Structure Simulator (HFSS) [15,21], equivalent Resistor–Inductor–Capacitor (RIC) circuit modeling approaches [15,108], and optimization algorithms including genetic algorithms [17] were widely employed to accurately tune structural parameters and improve design efficiency. Notably, [54] integrated an equivalent circuit model with a deep neural network to accurately predict the resonant frequencies of metamaterial unit cells, significantly accelerating the design and optimization process.

4.3. Key research outputs and performance breakthroughs

4.3.1. Significant improvement in absorption efficiency and bandwidth

(1) Ultra-broadband and high-efficiency absorption: substantial breakthroughs have been achieved in both absorption bandwidth and efficiency across multiple spectral regimes. In the terahertz domain, an ultra-broadband absorber exhibits effective absorption from 2.5 to 9.5 THz, maintaining absorption above 90% throughout the entire band and approaching unity absorption within the 4.0–6.8 THz range [15]. In the microwave regime, a broadband absorber operates over 6.0–39.4 GHz, achieving an exceptionally large relative absorption bandwidth of 147.1% [16]. In the visible–near-infrared region, a nanoscale absorber demonstrates a bandwidth of 516 nm with an average absorption efficiency of 90.08% [116].

(2) Narrowband and high selective absorption: for applications requiring frequency selectivity, notable progress has also been reported. A sub-6 GHz absorber designed for 5G electromagnetic radiation achieves absorption exceeding 80% across the 3.1–5.0 GHz band, resulting in a reduction of the SAR by more than 95% [21]. Additionally, a triple-band absorber exhibits near-unity absorption efficiencies of 99.86%, 97.58%, and 97.46% at 3.02, 5.71, and 8.36 GHz, respectively [108].

4.3.2. Synergistic performance enhancement and functional expansion

(1) Enhanced environmental adaptability: most reported metamaterial absorbers exhibit intrinsic polarization insensitivity, and those presented in [15,21] maintained high absorption performance under oblique incidence angles ranging from 60° to 90°. Furthermore, flexible metamaterial absorbers demonstrate strong adaptability to bending deformations and retain stable absorption characteristics when conformally attached to complex or curved carrier surfaces [98,110].

(2) Breakthroughs in multifunctional integration: multifunctional absorber designs have significantly expanded the application scope of metamaterials. For example, [16] achieved the synergistic integration of broadband microwave absorption (absorption rate >0.9), suppressed infrared thermal radiation, and optical transparency of 51.38%. In [114], an absorber realized energy harvesting functionality, delivering a load output equivalent to 98% of the absorbed electromagnetic energy. Moreover, [117] demonstrated a polarization-insensitive and wide-angle-stable absorber based on low-cost nickel materials, effectively reducing reliance on precious metals without compromising performance.

4.3.3. Advances in miniaturization and integration

(1) Ultimate size reduction: metamaterial absorber unit dimensions have been reduced from the millimeter scale to the nanoscale. The terahertz absorber reported in [15] featured a highly compact unit-cell geometry, while the visible–near-infrared absorber in [116] achieved an ultra-small unit size of only $1000 \times 1000 \times 165$ nm^3. Moreover, co-aperture integration strategies enable seamless incorporation of absorbers with antennas, sensors, and other functional devices, eliminating the need for additional system footprint [49,114].

(2) Improved fabrication compatibility: mature fabrication techniques—including photolithography, three-dimensional printing, and laser-induced carbonization—are increasingly adopted to enhance process compatibility. In particular, single-layer absorber design [22] and flexible-substrate-based implementations [110] significantly reduced fabrication complexity and overall manufacturing costs.

4.4. Existing problems and technical bottlenecks

To strengthen engineering insight, this subsection further identifies tolerance sensitivity and environmental robustness as critical bottlenecks based on Table 3. Many high-performance absorbers rely on precise geometric resonances, making them highly sensitive to fabrication tolerances. As indicated by representative designs in Table 3, dimensional variations on the order of ±5%–10% can significantly degrade absorption performance. In addition, limited robustness to incident angle variation, polarization diversity, and temperature fluctuations reduces real-world effectiveness compared to idealized simulation conditions. These limitations are now explicitly connected to the absorber configurations summarized in Table 3, highlighting the gap between laboratory performance and practical deployment.

4.4.1. Limitations in performance trade-offs and scenario adaptability

(1) Conflicting performance requirements: inherent trade-offs persist among key absorber characteristics, such as broadband absorption versus high gain and structural miniaturization versus operational stability. For instance, some broadband absorbers were unable to simultaneously achieve wide-angle stability, polarization insensitivity, and ultra-thin profiles [15,108].

(2) Performance degradation at high-frequency bands: absorbers operating in high-frequency regimes, particularly in the terahertz band, suffer from pronounced metallic and dielectric losses. These losses severely constrain the concurrent optimization of absorption efficiency and operational bandwidth [15,26].

4.4.2. Manufacturing complexity and cost constraints

(1) High-precision fabrication challenges: metamaterial unit cells at nanometer- and micrometer-scale dimensions demand extremely high fabrication accuracy, relying on advanced techniques such as photolithography and micro/nanoscale three-dimensional printing. Even minor dimensional deviations during large-scale production can induce substantial performance non-uniformity and poor repeatability [60,112].

(2) Dependence on high-cost materials: many high-performance absorbers still depend on noble metals (e.g., gold and silver) and specialized dielectric substrates (e.g., Rogers-series laminates), resulting in elevated material costs that hinder scalability and large-scale commercial deployment [15,71].

4.4.3. Insufficient reliability and environmental robustness

(1) Long-term stability limitations: in flexible absorber systems, metallic layers are prone to oxidation, while dielectric substrates experience mechanical degradation under repeated bending cycles and harsh temperature–humidity conditions [98,110]. Furthermore, phase-change materials such as VO_2 exhibited limited cyclic phase-transition stability, restricting their suitability for long-term operation [15,20].

(2) Challenges under realistic operating environments: when integrated into complex electronic systems, metamaterial absorbers may introduce electromagnetic interference, and their absorption performance can degrade in environments characterized by multi-band coupling and strong external electromagnetic disturbances [62,111].

4.5. Future research directions and development trends

4.5.1. Breakthroughs in high-performance absorption technology

(1) Targeted optimization for high-frequency regimes: future efforts should prioritize the development of low-loss metamaterial architectures and novel dielectric materials to address efficiency and bandwidth limitations in terahertz and infrared absorbers [15,26]. In parallel, emerging physical

mechanisms—such as quasi-bound states in the continuum (QBIC)—offered promising pathways for significantly enhancing the figure of merit of high-frequency absorbers [118].

(2) Enhancement of multi-physics coupling performance: incorporating electromagnetic–thermal–mechanical multi-field coupling into absorber design is essential for mitigating high-frequency losses, suppressing temperature-induced performance drift, and improving operational stability under complex environmental conditions [88,94].

4.5.2. Multifunctional and intelligently tunable design

(1) Deep functional integration and synergy: future absorber architectures are expected to deeply integrate electromagnetic absorption with energy harvesting, sensing, and communication functions, enabling compact *absorption–conversion–application* systems [93,114]. The inclusion of complementary attributes such as optical transparency and infrared shielding will further expand applicability in smart buildings and vehicle-mounted electronic systems [16,64].

(2) Programmable and adaptive electromagnetic regulation: by leveraging tunable materials and reconfigurable structures—including graphene, liquid metals, and MEMS—dynamic control over absorption frequency bands and intensity can be achieved, addressing the stringent requirements of adaptive spectrum management in emerging 6G communication systems [70,119].

4.5.3. Low-cost scalability and engineering deployment

(1) Manufacturing technology innovation: the advancement and industrial adoption of scalable, cost-effective fabrication techniques—such as roll-to-roll printing, laser direct writing, and maskless lithography—are critical to reducing barriers to commercialization [66,102]. Concurrently, the exploration of low-cost alternative materials can alleviate dependence on precious metals and specialized substrates [111,117].

(2) System-level integration optimization: optimized co-design and integration of absorbers with antennas, sensors, and electronic systems are required to suppress electromagnetic interference and enhance overall system-level performance [62,93]. Application-specific absorber solutions tailored to scenarios such as new-energy safety and medical imaging represent important directions for future engineering deployment [20,71].

4.5.4. Cross-disciplinary integration and theoretical advancement

(1) Interdisciplinary technology convergence: the integration of artificial intelligence and digital twin technologies provides powerful tools for inverse design, performance prediction, and fault diagnosis of metamaterial absorbers [65,101]. Moreover, combining electromagnetic design with acoustic and thermal theories can enable the development of next-generation absorbers with coordinated multi-physics field regulation capabilities [88,94].

(2) Advancement of theoretical frameworks: establishing comprehensive electromagnetic response models that account for multi-band operation, wide-angle incidence, and complex environmental conditions is essential to provide robust theoretical foundations for systematic performance optimization of metamaterial absorbers [15,108].

In summary, metamaterial absorbers demonstrate considerable potential for electromagnetic regulation applications. Through sustained structural innovation and technological refinement, remarkable progress has been achieved in absorption efficiency, bandwidth expansion, and multifunctional integration. Nevertheless, critical challenges—including high-frequency losses, fabrication complexity, elevated costs, and limited long-term reliability—remain to be addressed. Looking forward, continued advances in material innovation, intelligent design methodologies, scalable manufacturing, and interdisciplinary integration are expected to accelerate the engineering deployment of metamaterial absorbers in areas such as 6G communications, national defense, and intelligent electronic systems. Table 3 summarizes representative metamaterial absorber designs and their key performance metrics within the broader context of electromagnetic regulation applications.

Table 3. Comparison of key performance metrics for representative metamaterial absorber designs within electromagnetic regulation applications.

Ref.	Technical solution	Core performance indicators	Application scenarios
[21]	Ring + split ring + meander crossed dipole + lumped resistor, broadband metamaterial absorber	Operating band: 3.1–5 GHz (bandwidth: 1.9 GHz), polarization-insensitive, absorption rate >80% under 60° oblique incidence, SAR reduction ≥95%	Sub-6 GHz 5G electromagnetic radiation protection
[22]	4 × 4 unit array metamaterial perfect absorber (MPA) + Coplanar Waveguide (CPW)-structured broadband full-wave rectifier	Absorption efficiency of 99% at 5.2 GHz band; rectifier bandwidth >5 GHz, conversion efficiency of 65%; received power increased by 7.8 dBm	Self-power supply for IoT devices (ultra-low power signal scenarios)
[15]	VO_2 nested ring 2×2 array tunable terahertz metamaterial absorber	Operating band: 2.5–9.5 THz; absorption rate >90% across the entire band, nearly 100% in the 4.0–6.8 THz range; fractional bandwidth: 116.66%	6G terahertz communication, sensing, and imaging
[16]	Water matrix + Indium Tin Oxide (ITO)-patterned metasurface multi-band tunable absorber	Absorption rate >0.9 in the 6.0–39.4 GHz band; relative absorption bandwidth: 147.1%; optical transmittance: 51.38%; low infrared thermal radiation	Optical windows for electronic communication devices and detectors

5. Metamaterial-enhanced sensing technology

By exploiting distinctive physical properties—such as tailored electromagnetic responses, localized resonance, and subwavelength energy confinement—metamaterials have effectively addressed critical performance limitations of conventional sensors in terms of sensitivity, selectivity, and limits of detection. Consequently, metamaterial-enhanced sensing technologies have demonstrated strong potential across a broad spectrum of applications, including biomedicine, food safety, environmental monitoring, and structural health monitoring. Building on representative studies (e.g., [20,60,120]), this paper systematically reviews recent advances and emerging trends in metamaterial-based sensing from five perspectives: research objectives, core technical approaches, key research outcomes, existing challenges, and future development directions, thereby providing a comprehensive and structured reference framework for researchers in this field.

5.1. Research objectives and application scenarios

5.1.1. Core research objectives

(1) Sensitivity enhancement: surpass the detection limits of conventional sensing technologies to enable reliable identification of low-concentration or low-abundance analytes, thereby supporting trace-level detection and high-resolution sensing [32,121].

(2) Specificity improvement: achieve highly selective recognition of target analytes while suppressing environmental interference through rational metamaterial structural design and targeted functional surface modification.

(3) Miniaturization and system integration: reduce sensor footprint while realizing highly integrated sensing platforms that combine sensing units with signal processing and data transmission modules, facilitating portable, wearable, and embedded sensing applications.

(4) Multi-scenario adaptability: ensure stable and reliable sensing performance under complex and harsh conditions—including extreme temperature and humidity, strong electromagnetic or mechanical interference, and in vivo environments—thereby extending the operational boundaries of sensing technologies.

5.1.2. Main application scenarios

Metamaterial-enhanced sensing technologies have been successfully applied in diverse scenarios, including food contaminant detection [18,120], biomedical sensing [71,113,118], environmental monitoring [113,115], structural health monitoring [19,82,122], and gas detection [20,115]. In addition, flexible metamaterial-based sensors support low-power positioning and continuous monitoring applications [74], as illustrated in Figure 5. Collectively, these technologies provide essential technical support for precision medicine, food safety supervision, intelligent manufacturing, and environmental protection.

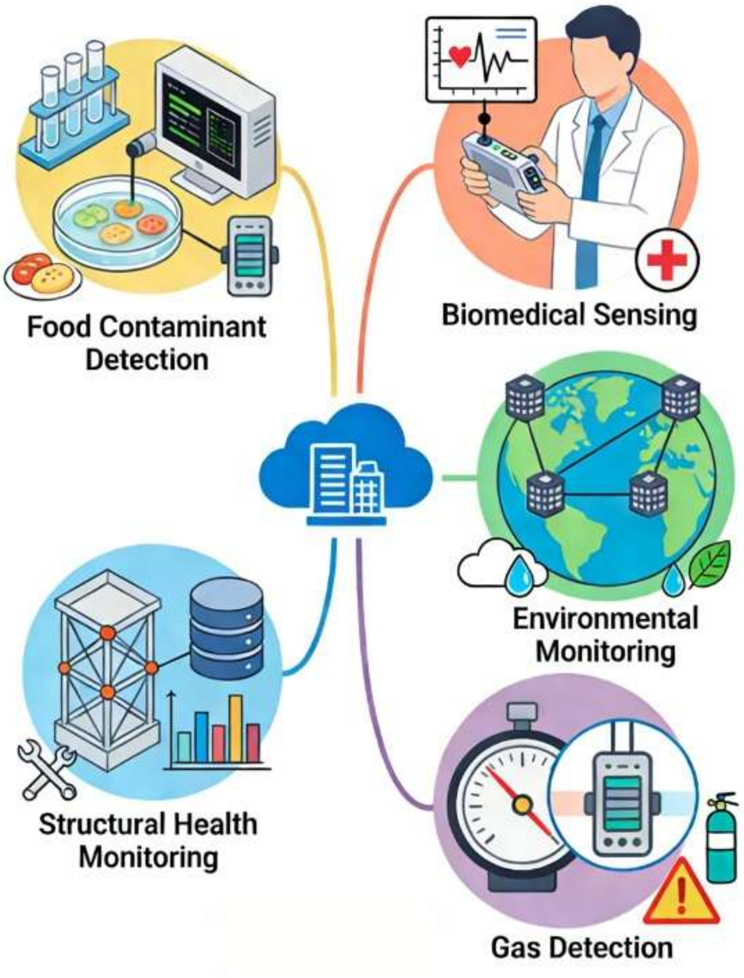

Figure 5. Schematic illustration of metamaterial-enabled enhanced sensing for the IoT.

5.2. Core technical means and design strategies

5.2.1. Metamaterial structure selection and sensing mechanisms

(1) Representative metamaterial architectures: commonly employed metamaterial configurations include SRRs [18,27], CSRRs [123], terahertz metasurfaces [20,120], negative Poisson's ratio metamaterials [19,60], and AMCs. Sensing functionality is primarily realized through resonance-related responses, such as resonant frequency shifts, amplitude modulation, and phase variations.

(2) Fundamental sensing principles: metamaterial sensors exploit the extreme sensitivity of resonant electromagnetic responses to variations in analyte-related physical parameters, including dielectric constant and refractive index. External stimuli are transduced into measurable signals via mechanisms such as resonant peak shifts [18,20], absorption efficiency variations [22,114], and scattering signal modulation [124].

5.2.2. Material functionalization and performance enhancement strategies

(1) Integration of sensitive functional materials: selectivity and recognition capability toward specific analytes are significantly enhanced by functionalizing metamaterial surfaces with gas-sensitive

films [20], biological probes, or nanoparticles [18,115]. For example, the study reported in [20] achieved highly sensitive detection of H_2 and CH_4 by coating Pd–WO_3 or Ultraviolet-Curable Functional Sensitive (UVCFS) gas-sensitive layers onto metamaterial resonant structures.

(2) Multi-physics coupling enhancement: sensing performance can be further amplified through synergistic coupling of multiple physical fields, such as piezoelectric effects [19,60], plasmonic effects [71,98], and thermoacoustic coupling [94]. These multi-field interaction mechanisms enable substantial improvements in signal strength, detection sensitivity, and response robustness.

5.2.3. Structural design and simulation-based optimization methods

(1) Topological and structural innovation: advanced metamaterial unit-cell designs—including fractal geometries [112], nested ring structures [15], and gradient configurations [121]—were proposed to tailor resonance characteristics and amplify sensing responses. Notably, the work in [121] demonstrated programmable piezoelectric and pyroelectric properties using ferroelectric metamaterials with shell-type topological architectures.

(2) Intelligent modeling and optimization approaches: geometric parameter optimization and sensing performance enhancement were increasingly supported by intelligent design tools, including genetic algorithms [86], deep learning–based models [65,125], and finite element simulations [19,122]. For instance, [54] combined equivalent circuit modeling with deep neural networks to accurately predict resonant frequencies of metamaterial unit cells, substantially improving design efficiency and predictive accuracy.

5.3. Key research outputs and performance breakthroughs

5.3.1. Significant improvement in detection sensitivity and specificity

(1) Breakthroughs in trace-level detection: terahertz metamaterial sensors have enabled ultra-low-concentration detection of food contaminants, including pesticides and antibiotics [120]. Formaldehyde sensors achieve sensitivities as high as 37.38–48.80 MHz/RIU [18], while gas sensors demonstrate sensitivities of 1.36 GHz/% for H_2 and 7.13 GHz/% for CH_4 [20], demonstrating substantial improvements in trace-gas detection performance.

(2) Highly specific target recognition: through functional material modification and precise structural optimization, accurate discrimination of specific analytes—such as gases [20], bacteria [71], and chemical substances [115]—has been achieved. In representative studies, the relative detection error is reduced to below 1% [18], indicating markedly enhanced sensing specificity.

5.3.2. Expansion of detection range and scenario adaptability

(1) Multi-band and multi-target detection capability: metamaterial sensors now operate across an extended spectral range, covering terahertz [20,120], microwave [18,115], and visible–near-infrared bands [112,117]. Moreover, multi-resonant designs enable simultaneous detection of multiple analytes; for example, the work in [115] reported concurrent identification of ethanol–methanol mixed solutions.

(2) Adaptability to complex environments: flexible metamaterial sensors can conform to the human body or curved structural surfaces for applications such as motion monitoring and structural

health assessment [19,60]. Underwater sensors maintain stable performance at depths of up to 320 mm [46], while reliable sensing operation has also been demonstrated under high-temperature and high-humidity conditions.

5.3.3. Advances in miniaturization and system integration

(1) Extreme size reduction: the characteristic dimensions of metamaterial sensing units have been scaled down to the nanoscale [112,116], enabling highly compact sensing architectures. For instance, the terahertz metasurface reported in [20] occupied only 30.2 × 30.2 × 0.97 μm^3, while the flexible sensor presented in [18] achieved lightweight and miniaturized system integration.

(2) Multifunctional and system-level integration: metamaterial sensors increasingly integrate sensing with complementary functionalities, including energy harvesting [19,82], wireless communication [75], and noise suppression [87,94]. A representative example is the self-powered strain sensor reported in [19], which combines solar energy harvesting with integrated Bluetooth data transmission.

5.4. Existing problems and technical bottlenecks

To enhance reliability-oriented analysis, this section now emphasizes three key challenges based on the representative sensors in Table 4. First, drift and calibration requirements are significant. Many metamaterial sensors exhibit resonance shifts that are difficult to distinguish from environmental drift without frequent recalibration. Second, repeatability and noise sensitivity remain critical issues. As reflected in Table 4, high sensitivity is often accompanied by reduced signal-to-noise robustness, particularly in real-world conditions. Third, long-term stability limitations persist. There is a clear lack of studies reporting multi-cycle or long-duration testing, which constrains confidence in practical deployment. These issues are now directly linked to representative sensing systems in Table 4.

5.4.1. Limitations in performance and environmental robustness

(1) Insufficient anti-interference capability: in complex sensing environments—such as multicomponent analyte mixtures and conditions involving fluctuating temperature and humidity—metamaterial sensors are highly susceptible to external disturbances, resulting in degraded selectivity and sensing accuracy [27,120].

(2) Inadequate long-term stability: flexible metamaterials often exhibit drift in mechanical and electromagnetic properties under repeated deformation and harsh environmental conditions [8,98]. In addition, functional modification layers are prone to aging, delamination, and degradation, significantly shortening sensor lifespan [18,20].

5.4.2. Manufacturing constraints and cost challenges

(1) High-precision fabrication bottlenecks: nanoscale fabrication of metamaterial unit cells—typically relying on lithography or micro/nanoscale 3D printing—poses substantial technical challenges. Small dimensional deviations during large-scale manufacturing can lead to pronounced device-to-device performance variations [23,60].

(2) Dependence on high-end materials: many high-performance metamaterial sensors rely on noble metals [15,71] and specialized substrates [20,120], resulting in elevated material costs that limit scalability and widespread deployment.

5.4.3. System integration and signal processing challenges

(1) Weak signal extraction and processing difficulty: at low analyte concentrations, sensing signals are often weak and highly susceptible to noise, necessitating complex amplification, filtering, and signal-conditioning circuits [22,71].

(2) Insufficient system-level integration: compatibility between metamaterial sensing elements and modules for signal processing, wireless communication, and power management remains limited. This is frequently accompanied by electromagnetic interference, hindering the realization of compact, highly integrated sensing systems [62,93].

5.5. Future research directions and development trends

5.5.1. Breakthroughs in high-performance sensing technology

(1) Multi-target cooperative detection: metamaterial architectures with multiple resonance modes or spectral features should be developed to enable simultaneous detection of multicomponent and multiparameter analytes, thereby improving detection throughput and system efficiency [115,118].

(2) Ultimate sensitivity enhancement: emerging concepts such as quantum sensing, topological protection mechanisms [25], and quasi-bound states in the continuum (QBIC) [118] are expected to overcome fundamental sensitivity limitations and push sensing performance toward theoretical limits.

5.5.2. Intelligent and adaptive sensing systems

(1) Programmable and tunable sensor designs: dynamically reconfigurable metamaterial sensors incorporating phase-change materials [15,20] and two-dimensional materials [67,70] could enable real-time tuning of operating frequency, resonance characteristics, and sensitivity.

(2) AI-enabled sensing frameworks: deep learning and data-driven approaches [65,125] would play an increasingly important role in intelligent signal interpretation, interference suppression, adaptive calibration, and fault diagnosis, thereby improving detection accuracy and robustness.

5.5.3. Miniaturization and engineering-oriented development

(1) Low-cost and scalable manufacturing processes: cost-effective, large-area fabrication techniques—such as maskless lithography [60], laser direct writing or processing [66], and roll-to-roll printing [102]—are essential for reducing production costs and accelerating industrial deployment.

(2) System-level integration and optimization: seamless integration of metamaterial sensing units with microprocessors, wireless communication modules, and energy-harvesting components [19,93] will facilitate the development of compact, portable, and self-powered sensing platforms suitable for real-world applications.

5.5.4. Cross-disciplinary integration and scenario expansion

(1) Interdisciplinary technology convergence: by integrating advances from biomedicine, materials science, artificial intelligence, and communication engineering, metamaterial sensing technologies are evolving toward multifunctional and intelligent sensing systems with enhanced perception, analysis, and decision-making capabilities [118,126].

(2) Extension to emerging application domains: ongoing research is extending metamaterial sensors into frontier fields such as deep-space exploration, marine and extreme-environment monitoring, implantable in vivo sensing [69,101], and quantum sensing, thereby transcending the limitations of conventional sensing paradigms.

In summary, through sustained structural innovation and functional optimization, metamaterial-enhanced sensing technologies have achieved substantial advances in sensitivity, selectivity, and device miniaturization, establishing themselves as key enabling technologies for high-precision detection across multiple disciplines. Nevertheless, challenges remain in terms of anti-interference robustness, long-term stability, fabrication complexity, and cost. Looking ahead, progress driven by advanced materials, intelligent design methodologies, scalable manufacturing processes, and deep interdisciplinary integration is expected to enable broad engineering deployment of metamaterial sensors in areas such as precision medicine, food safety, intelligent manufacturing, and environmental monitoring. Table 4 summarizes the core performance parameters of representative metamaterial sensors.

Table 4. Comparison of key performance parameters of metamaterial-based sensors.

Ref.	Technical solution	Core performance indicators	Application scenarios
[20]	VO_2 dual-peak terahertz metasurface + Pd-WO_3/UVCFS gas-sensitive film	Figure of merit: 168.99; refractive index sensitivity: 8635.43 GHz/RIU; H_2 sensitivity: 0.98/1.36 GHz/%; CH_4 sensitivity: 3.73/7.13 GHz/%	Hydrogen and methane concentration detection (new energy safety field)
[18]	Flexible substrate with $Mg_xCo_{(0.9-x)}Ni_{0.1}Fe_2O_4$ nanoparticles + SRR	Resonant frequency: 6.14 GHz; formaldehyde detection range: 1%–10%; sensitivity: 37.38–48.80 MHz/RIU (simulation), 38.25–42.57 MHz/RIU (actual measurement); relative error: <1%	Food safety (rapid formaldehyde detection)
[71]	Epsilon-near-zero (ENZ) metamaterials + dual plasmon-induced transparency (D-PIT), dielectric-metal-dielectric (DMD) structure	Operating frequency band: 40–45 GHz; sensitivity: 17.2–17.6 GHz/RIU; maximum figure of merit (Q): 4285	Non-invasive detection of intestinal pathogenic bacteria (*E. coli*, *Staphylococcus*)
[19]	Gold-plated elastomer rotational square structure (GDE-R) mechanical metamaterial, self-powered strain sensor	Gauge factor (GF): ≈10.5; low hysteresis: 0.508%; stability: >10,000 cycles; response time: <20 ms; limit of detection: 0.01%	Structural health monitoring, human motion monitoring, soft airbag inflation/deflation monitoring

6. Research progress, reviews, and fundamental theories of metamaterials

As a cutting-edge interdisciplinary research field, metamaterials span multiple physical domains—including electromagnetism, acoustics, mechanics, and thermodynamics—and support a wide range of application scenarios, such as antenna engineering, energy harvesting, sensing and detection, and electromagnetic regulation. The fifth category of studies focuses on review articles and fundamental theoretical investigations. These works systematically consolidate the research landscape of metamaterials by clarifying theoretical foundations, summarizing key technological breakthroughs, identifying unresolved challenges, and outlining future development trends. As such, they provide both comprehensive academic references and forward-looking guidance for industrial applications. Drawing on representative contributions (e.g., [31,127–129]), this paper reviews research progress in metamaterial reviews and fundamental theories from five perspectives: research objectives, core theoretical content, major achievements, existing limitations, and prospective research directions.

6.1. Research objectives and core values

6.1.1. Core research objectives

(1) Systematic synthesis: to consolidate research achievements on metamaterials across multiple domains, clearly delineating technical pathways, key performance parameters, and application boundaries of major subfields.

(2) In-depth theoretical advancement: to refine the underlying physical mechanisms, modeling approaches, and design theories of metamaterials, thereby providing a solid theoretical foundation for sustained technological innovation.

(3) Academia–industry integration: to examine patent landscapes, industrial deployment patterns, and key bottlenecks in technology transfer within the metamaterials field, strengthening the linkage between fundamental research and engineering applications.

(4) Prospective trend forecasting: to identify existing research gaps and anticipate future development directions—such as interdisciplinary convergence and intelligent technology empowerment—so as to guide topic selection and strategic research planning.

6.1.2. Core values

This body of work provides an introductory reference framework for early-career researchers, enabling rapid comprehension of the overall field landscape [28,127], clarifies critical technical bottlenecks and promising innovation pathways for experienced researchers [23,26], and offers a decision-making basis for technology selection and market positioning in industrial contexts [24,130]. Collectively, these contributions facilitate the transition of metamaterials from laboratory-scale studies toward practical engineering implementations and industrial applications.

6.2. Core research content and technical context

6.2.1. Review of subfields and integration of research findings

(1) Application scenario–oriented review: this strand emphasizes the application progress of metamaterials in representative scenarios, including antenna and wireless communication [24,127,131], energy harvesting and management [25,28], sensing and detection [27,118,120], and biomedical engineering [69,132]. These studies systematically synthesize technical routes, key performance metrics, and scenario adaptability. For example, [127] summarized advances in metamaterial-enabled antenna gain enhancement and miniaturization, whereas [120] focused on metamaterial-enhanced terahertz sensing for food contaminant detection.

(2) Material- and structure-oriented review: this line of research covers functional metamaterials [128], carbon-based metamaterials [99], negative Poisson ratio metamaterials [132–134], and reconfigurable terahertz metamaterials [26], among others. The characteristics and advantages of different material systems and structural configurations are comparatively analyzed. In particular, [128] reviewed structural innovations and adaptive response characteristics of functional metamaterials from 2020 to 2025, while [99] summarized the application of carbon-based materials—such as graphene and MXene—in metamaterial devices.

6.2.2. Research on fundamental theories and design methodologies

(1) Advances in core theories: research in this area focuses on electromagnetic properties [23,68], multi-physics coupling mechanisms [28,88], and energy regulation principles [25,79] of metamaterials, aiming to enrich and refine the theoretical framework. For instance, based on massive electromagnetism (Proca theory), [68] demonstrated that nonlocal Proca metamaterials can achieve perfectly isotropic radiation, thereby overcoming fundamental limitations of conventional electromagnetic theory.

(2) Design and optimization approaches: this subsection reviews the integration of intelligent techniques—such as deep learning [65], artificial intelligence and machine learning [128], and genetic algorithms [135]—into metamaterial design workflows, including forward modeling, inverse design, and topological optimization. As a representative example, [65] detailed the application of convolutional neural networks and generative adversarial networks in antenna design.

(3) Mechanics-oriented artificial intelligence/machine learning (AI/ML) design example: to further demonstrate the generality of AI/ML-assisted design methodologies beyond electromagnetic applications, a representative mechanics-oriented study has been incorporated. Specifically, Pranno [91] presented a complete and physically grounded workflow integrating finite element (FE)-based dataset generation, genetic algorithm (GA) optimization, and neural network (NN) surrogate modeling and classification. Unlike purely performance-driven optimization, this study explicitly incorporates instability-aware criteria, including buckling and local collapse, as penalization terms within the optimization loop, thereby embedding physically meaningful constraints into the design process. This example highlights that data-driven approaches are not limited to electromagnetic metamaterials but are equally powerful in structural and mechanics-driven metamaterial design, enabling efficient exploration of high-dimensional design spaces while respecting domain-specific physical constraints. A generalized, domain-independent workflow for AI/ML-assisted metamaterial design is shown in Figure 6.

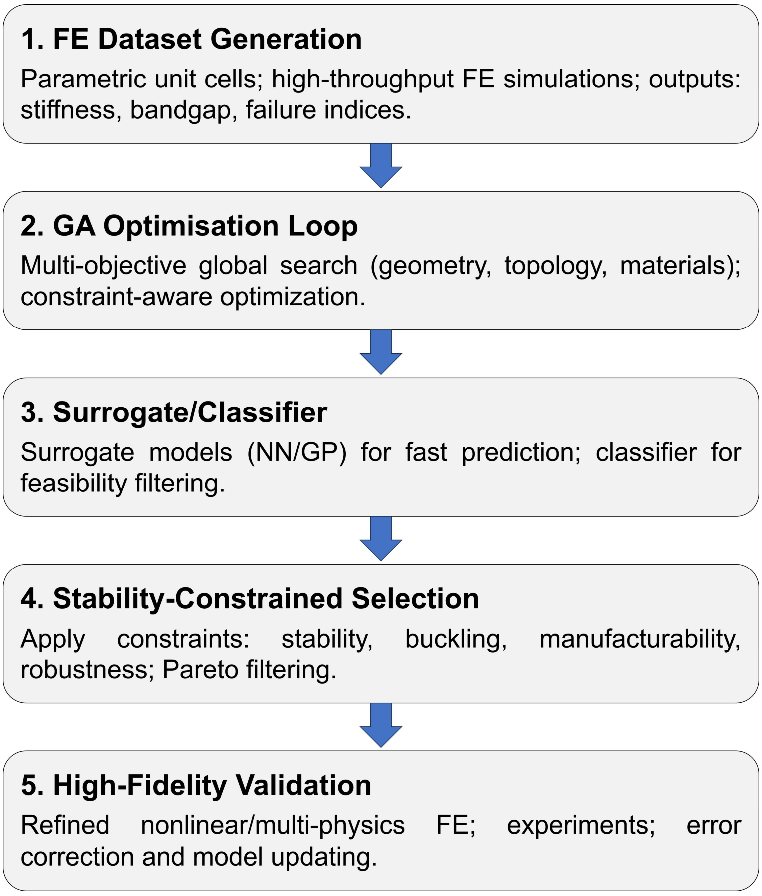

Figure 6. AI-assisted design loop integrating finite element dataset generation, genetic algorithm optimization, surrogate modeling, stability-constrained selection, and high-fidelity validation. The closed-loop feedback enables continuous improvement of model accuracy and design optimality.

6.2.3. Analysis of industrial development and patent trends

(1) Patent landscape analysis: through systematic analysis of patent data, this section delineates the competitive technological landscape of the metamaterials field, identifying leading applicants, technical focal points, and emerging trends. According to [24], the United States dominates patent filings in metamaterial antenna technologies, with companies such as Samsung and Kymeta among the major applicants, and patent activity exhibiting rapid growth between 2021 and 2023.

(2) Technology translation and commercialization: this subsection examines the key constraints hindering the transition of metamaterials from laboratory research to engineering practice and industrial deployment. It further discusses potential pathways for advancement, including scalable manufacturing, cost reduction, and reliability enhancement [23,128].

6.3. Key research outputs and academic contributions

6.3.1. Establishment of a systematic knowledge framework

(1) Mapping the overall landscape of the field: existing studies clearly delineate the classification of metamaterials into electromagnetic, acoustic, mechanical, and thermodynamic categories [65,127], together with their defining characteristics—such as double-negative electromagnetic parameters and negative Poisson's ratio [23,134]. Key enabling technologies, including metamaterial integration strategies, intelligent optimization methods, and scalable manufacturing techniques, are also systematically summarized [102,128]. Collectively, these efforts contribute to the construction of a coherent and comprehensive knowledge framework for the metamaterials field.

(2) Focused analysis of subfields: for specific application scenarios, core technical routes and performance metrics are systematically reviewed and compared. For example, [131] evaluated the relative effectiveness of metamaterials and metasurfaces in improving gain and isolation in MIMO antenna systems, while [130] reviewed metamaterial-enabled integration schemes for wireless power transfer in electric vehicles. Such targeted analyses facilitate clearer technical benchmarking and application-oriented understanding.

6.3.2. Synthesis of theoretical and methodological innovations

(1) Advances in fundamental theory: key physical mechanisms underlying metamaterials—including energy localization, local resonance, and wavefield manipulation—are extensively elucidated, providing a solid theoretical basis for the design of next-generation metamaterial structures [25,28]. Notably, [25] highlighted the roles of defect modes and gradient refractive-index configurations in enhancing energy-harvesting performance.

(2) Innovations in design methodologies: the applicability and advantages of emerging design approaches, such as intelligent optimization algorithms and multiphysics modeling, are systematically clarified. For instance, [65] demonstrated that deep learning–based frameworks can significantly improve antenna design efficiency, while [54] verified the high predictive accuracy of Bayesian optimization in resonant-frequency estimation for metamaterial unit cells.

6.3.3. Identification of challenges and outlook on future trends

(1) Synthesis of core challenges: widely acknowledged challenges include difficulties in large-scale manufacturing [23,128], pronounced losses at high-frequencies [26,127], persistently high costs [102,111], and inadequate long-term stability [98,119]. In addition, application-specific limitations remain, such as insufficient sensitivity in terahertz sensing [118] and biocompatibility concerns in wearable metamaterials [69].

(2) Projection of future directions: major development trends—encompassing interdisciplinary integration [23,126], intelligent and tunable design strategies [63,126], materials innovation [99,111], and deeper scenario-oriented applications [126,130]—are identified, offering clear guidance for future research and technological advancement.

6.4. Existing problems and academic gaps

To address cross-domain consistency, the limitations in this section are further defined from a system-level perspective. While existing reviews provide valuable summaries, they often lack quantitative, engineering-oriented bottleneck analysis and explicit linkage to representative implementations. This limits their usefulness for design translation and cross-domain comparison. In particular, the absence of standardized evaluation metrics and insufficient integration of experimental constraints (e.g., fabrication tolerance, environmental robustness, and lifecycle performance) hinder the development of unified design guidelines across metamaterial-enabled IoT systems.

6.4.1. Limitations of review research

(1) Uneven topical coverage: review articles addressing emerging areas, such as metamaterial applications in quantum communication and niche material systems, remain relatively scarce. In contrast, existing reviews predominantly focus on mainstream applications and well-established material platforms.

(2) Imbalance between timeliness and depth: some reviews emphasize the compilation of research outcomes while lacking in-depth discussion of underlying physical mechanisms and systematic comparisons of different technical approaches. Moreover, given the rapid evolution of the field, the timeliness of a portion of the existing literature requires further improvement.

(3) Insufficient cross-disciplinary integration: most reviews concentrate on single application scenarios or material categories, with limited integrative analysis of cross-domain topics such as multi-field coupling and multifunctional integration [28,126].

6.4.2. Weaknesses in fundamental theories

(1) Incomplete multi-field coupling frameworks: current understanding of metamaterial response mechanisms under coupled electromagnetic, mechanical, thermal, and acoustic fields remains fragmented, and a unified theoretical framework has yet to be established [28,88].

(2) Lack of high-frequency theoretical models: theoretical investigations into loss mechanisms and radiation characteristics in high-frequency regimes—such as terahertz and millimeter-wave bands—lag behind experimental progress, limiting the optimization of high-frequency metamaterial devices [26,118].

(3) Deficiency in reliability theories: systematic studies on performance degradation mechanisms and lifetime prediction models for metamaterials operating under extreme environments and long-term service conditions remain insufficient [98,119].

6.4.3. Gaps between theories and application

(1) Limited emphasis on industrialization-oriented issues: existing reviews and theoretical studies primarily focus on academic performance metrics, with inadequate attention to industrialization challenges such as cost control, large-scale manufacturing consistency, and system-level integration [102,128].

(2) Absence of standardized evaluation systems: comprehensive discussions on standardized testing protocols and performance evaluation methodologies for metamaterial devices are scarce, resulting in limited comparability across reported studies [111,135].

6.4.4. System-level and RIS-enabled challenges

In addition to the aforementioned theoretical and review-related limitations, system-level challenges associated with RIS in IoT deployments have been further identified:

(1) Control overhead and scalability: large-scale RIS implementations require high-dimensional and frequently updated control signals to configure numerous meta-atoms in real time. This leads to substantial signaling overhead, increased system complexity, and elevated energy consumption, particularly in dense IoT networks. These limitations are consistent with the scalability constraints observed in programmable metasurface systems discussed earlier in this manuscript (see related discussions in Sections 2 and 6.2, and performance implications summarized in Tables 1–4).

(2) Channel estimation burden: accurate RIS configuration depends critically on real-time channel state information (CSI), which necessitates frequent channel estimation. In dynamic IoT environments—characterized by mobility, multipath effects, and low-power devices—this process becomes computationally expensive and often impractical. The resulting trade-off between estimation accuracy and system efficiency represents a key bottleneck for real-world deployment.

(3) Implications for system integration: these challenges highlight a fundamental gap between theoretical RIS performance gains and practical IoT implementation. Specifically, they reinforce the need for low-overhead control strategies, efficient channel estimation methods, and co-design frameworks that jointly optimize hardware, algorithms, and network architecture.

6.5. Research directions and development recommendations

6.5.1. Optimization directions for review research

(1) Reviews on emerging and interdisciplinary topics: future reviews should place greater emphasis on emerging application domains, including quantum communication, space exploration, and brain–computer interfaces. Concurrently, interdisciplinary themes such as multi-field coupling and multifunctional integration should be systematically analyzed to uncover cross-domain synergies and shared design principles [70,126].

(2) Enhancing depth and timeliness: review studies should more comprehensively incorporate recent advances, with increased emphasis on fundamental physical mechanisms. The inclusion of quantitative comparisons—such as performance benchmarking tables and technology roadmaps—would further enhance their practical value.

(3) Industrialization-oriented reviews: dedicated reviews addressing industrialization-related issues, including scalable manufacturing, cost optimization, and metamaterial supply-chain organization, are essential for bridging the gap between academic research and industrial practice [128,130].

6.5.2. Key breakthroughs in fundamental theories

(1) Advancement of multi-field coupling and high-frequency theories: priority should be given to developing comprehensive theoretical models for metamaterials under multiphysics coupling conditions. Further investigation of loss mechanisms and radiation characteristics in high-frequency regimes—such as terahertz and infrared bands—is critical for device optimization [26,118].

(2) Development of reliability and service-life theories: systematic research on performance degradation mechanisms under extreme temperature, humidity, mechanical deformation, and prolonged operation should be strengthened, enabling the establishment of service-life prediction models and reliability evaluation frameworks [98,119].

(3) Integration of emerging theories and technologies: the incorporation of advanced theoretical paradigms, including topological physics and quantum mechanics, should be further explored to stimulate conceptual innovation and enable novel metamaterial functionalities [24,130].

6.5.3. Strengthening the link between theory and application

(1) Standardization and evaluation frameworks: future research should address standardized performance testing protocols, evaluation metrics, and characterization methodologies, facilitating the establishment of unified and widely accepted industry standards [111,135].

(2) Engineering-oriented theories and methods: greater emphasis should be placed on theoretical frameworks that support the integration of metamaterials with existing electronic and communication systems, as well as on optimization strategies for low-cost, scalable manufacturing [66,102].

(3) Industry–university–research collaboration: strengthened collaboration between academia and industry is encouraged to jointly identify critical practical challenges and develop theory-driven solutions, thereby enhancing the translational impact of metamaterial research [24,130].

Overall, review and fundamental theoretical studies play a pivotal role in sustaining the development of metamaterials by synthesizing knowledge, clarifying technical pathways, and anticipating future trends. Despite notable progress, challenges such as uneven topical coverage, insufficient analytical depth, and weak theory–application linkage persist. By prioritizing emerging research areas, deepening theoretical investigations, and reinforcing industry–university–research collaboration, future efforts can provide stronger support for technological innovation and industrial deployment, ultimately enabling broader breakthroughs in fields such as 6G communications, precision medicine, and intelligent manufacturing.

7. Conclusions

As artificially engineered functional composite materials, metamaterials possess an exceptional ability to precisely manipulate physical fields—including electromagnetic waves, acoustic waves, and mechanical vibrations. Leveraging these capabilities, a relatively mature technological framework has been established for their application in four core IoT domains: communication antennas, energy harvesting, electromagnetic regulation, and sensing and detection. Continuous progress in fundamental theory, together with systematic review studies, has provided a robust knowledge foundation that supports both technological innovation and the gradual transition toward practical engineering deployment.

In the field of communication antennas, metamaterials have enabled synergistic advances in antenna miniaturization, high performance, and multi-scenario adaptability. Representative achievements include ultra-compact antenna dimensions as small as 12 × 12 × 1 mm^3 and maximum gains reaching 25.6 dBi. These improvements are primarily realized through the incorporation of canonical metamaterial structures—such as SRRs and CSRRs—in combination with intelligent optimization algorithms, effectively addressing diverse communication requirements in emerging scenarios such as 5G/6G systems, the IoV, and underwater communications. In energy-harvesting applications, the exploitation of localized resonance phenomena and multi-source energy fusion strategies has significantly enhanced the conversion efficiency of electromagnetic, vibrational, and acoustic energy, with reported efficiencies of up to 96.9%. Such advances offer green, sustainable, and self-powered solutions for low-power IoT nodes. In electromagnetic regulation, customized metamaterial absorbers have demonstrated broadband and high-efficiency absorption, with absorptivity exceeding 90%, thereby providing effective mitigation of electromagnetic interference and radiation exposure associated with dense 5G/6G deployments. In sensing and detection, metamaterial-induced local field enhancement and signal amplification have enabled trace-level detection and high-specificity recognition, with sensitivities ranging from 37.38 to 8635.43 MHz/RIU, supporting critical applications in food safety, biomedicine, and structural health monitoring. Concurrently, fundamental theoretical investigations and review studies have systematically summarized technical evolution paths, performance benchmarks, and prospective industrialization routes across these subfields, offering coherent academic guidance for future research and development.

Despite these notable advances, the large-scale deployment of metamaterials in IoT systems continues to face several common challenges. Key bottlenecks include the persistently high costs associated with advanced substrates and precision fabrication processes, pronounced electromagnetic losses in millimeter-wave and terahertz frequency regimes, electromagnetic interference and compatibility issues arising from multi-module system integration, and inadequate long-term stability of flexible metamaterials under extreme or prolonged service conditions. Addressing these challenges remains essential for bridging the gap between laboratory-scale demonstrations and robust, scalable, and economically viable engineering applications, thereby unlocking the full potential of metamaterials in next-generation IoT systems.

Beyond application-specific advances, the future development of metamaterial-enabled IoT systems critically depends on addressing several cross-cutting theoretical and methodological challenges. In particular, the establishment of unified multi-physics coupling frameworks—encompassing electromagnetic, mechanical, thermal, and acoustic interactions—remains essential for accurately predicting device behavior under realistic operating conditions. Furthermore, the development of high-frequency theoretical models for millimeter-wave and terahertz regimes is urgently needed to mitigate intrinsic loss mechanisms and enable efficient long-range operation. Reliability-oriented research, including performance degradation modeling and lifecycle prediction under complex environmental conditions, also represents a key bottleneck for large-scale deployment.

From a technological perspective, future research should emphasize the convergence of artificial intelligence with metamaterial design, enabling data-driven inverse design, real-time adaptability, and system-level optimization. At the same time, the advancement of scalable, low-cost manufacturing technologies and standardized evaluation frameworks will be crucial to bridge the gap between laboratory-scale innovation and industrial implementation. These directions, together with deeper interdisciplinary integration, will define the next stage of metamaterial research and accelerate its transition toward practical, high-impact IoT applications.

Use of AI tools declaration

The authors declare they have not used Artificial Intelligence (AI) tools in the creation of this article.

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Author contributions

Qinghua Qin: supervision, writing—original draft, formal analysis, revision, comment; Qiuhuang Chen: methodology, revision, comment.

Conflict of interest

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