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Power-Efficient Nanodevices Enabling Scalable IoT Solutions for Smart Factory Environments

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ABSTRACT

This paper conducts a systematic review of efficient nanodevices to enable IoT solutions for smart factories. Using a literature review of relevant articles from 2017-2025, the review provides critical evaluations of the performance and efficiency of the nano-technological components used to build IoT devices, specifically on four main nanotechnologies such as nano-sensors, nano-antennas, nano-processors, and nanobatteries, which provide more benefits compared to current traditional electronics. In addition, we analyze the properties of nanomaterials, particularly carbon nanotubes (CNTs), graphene, MXenes, quantum dots, and other nanomaterials, and their benefits in energy efficiency, miniaturization, sensing, and communication bandwidth. An example of the qualitative Performance Index (PI) heuristic framework is introduced for conceptualizing the comparison between nanoelectronics and traditional electronics as a graphical visualization technique only. This review is not a model based on physical laws and calculations or experimental data since the qualitative framework does not include all variables. A critical evaluation of existing literature has found that nano-sensors, nano-antennas, and nano-processors have some benefits, although some barriers need to be overcome, such as scalability, air stability, co-integration, and standardization, before being implemented in smart factories. Finally, research directions are provided in the future work section, which mainly focus on future research. In this paper, key future research areas have been highlighted for consideration, including system-level experimental validation, TCAD/COMSOL-based simulation for design, and environmentally sustainable methods of nanomaterial synthesis.

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1. INTRODUCTION

The fusion of nanotechnology with the IoT stands out among the most significant advances in technology in the early twenty-first century. A nanomaterial is characterized by having at least one dimension that falls in the range of 1-100 nanometers and has unique characteristics compared to bulk materials due to its small size and surface effects. Several nanomaterials have outstanding mechanical strength and hardness, and the properties of these materials may be designed by manipulating the size, shape, and structure of the material surfaces [1]. This is further enhanced by the outstanding electrical, optical, and thermal properties associated with quantum size effects, which makes these materials ideal for designing sensors, low-power processors, antennas, and energy storage devices [2,3]. The role of nanotechnology in contributing to Society 5.0 a future sustainable and digital society characterized by a human-centric approach to sustainability – has been established on the basis of three aspects: digitalization, sustainability, and healthcare [4]. Nanotechnology facilitates IoT, artificial intelligence, autonomous robotics, and intelligent manufacturing by means of nano-sensors, nanodevices, and functional nanomaterials that ensure integration between the real world and the cyberspace/cyber-physical system [5]. Regarding sustainability, nanomaterials can be applied to clean water purification, emission reductions of CO_2, and support to circular economy initiatives [6]. In the field of health, advances in nanobiotechnology, wearable biosensors, and biomaterials contribute to prevention, diagnostics, and therapies [7]. There are many studies indicating an increasing convergence of nanotechnology, artificial intelligence and sustainable technologies across a wide range of scientific and engineering disciplines. Significant promise has been shown by cognitive systems and data-centric methodologies in the improvement of the synthesis and performance of inorganic nanomaterials. The merger of nanotechnology and machine learning has highlighted the need for computational approaches to advance the research of nanomaterials and to improve the properties of materials. The study of nanomaterials and nanoelectronics has focused on the fabrication, properties and uses of these materials in advanced electronic devices [8-10], while polymer nanocomposites have been studied for their role in green and sustainable technologies [11]. In ecological settings, nanotechnology has shown promise in promoting sustainability of agriculture and improving farming practices [12-15]. The progress in quantum-dot cellular automata has stimulated the development of universal and reversible logic gates for nanoscale computing applications. Intelligent nanoparticles have also been developed as useful tools for targeted fertilization, with the promise of better management of agricultural resources and fertilizer efficiency. The recent developments and patents demonstrated the growing importance of nanotechnology in electronics and its potential for technological innovation and complex electronic applications. The Internet of Nano-Things (IoNT) resulting from the synergy between nanotechnology and IoT has become a research paradigm with its own practical applications in health monitoring, environmental surveillance, and manufacturing automation [16,17]. The IoNT exploits the unique physical and chemical properties of nanomaterials to design ultra-sensitive, power-efficient, and tiny sensors that interact directly with living organisms and the physical world [18]. They allow for instantaneous diagnoses of diseases, detection of environmental pollutants, and context-driven machine-to-machine interactions, marking a qualitative leap from conventional MEMS-based sensor networks [19]. Moreover, the use of nanomaterials in IoT wearables has expanded their application area to healthcare, environmental sensing, smart fabrics, and fast data transmission via wireless connections [21].

Nevertheless, despite the significant promise of nano-IoT technology, several key reviews highlight the disparity between individual component performances and industry-ready system deployment. The scalability in fabricating CNT networks, air stability in MXene-based sensors, yield of CNT field-effect transistors at the circuit level, and cyclic capacity of electrodes based on nanostructured batteries are among the obstacles that must be overcome to facilitate the smart factory of the future [22–25]. Finally, the importance of 5G and prospective 6G communication networks in delivering low-latency and high-data rate connectivity to nano-IoT. The contribution of the 5G network and 6G networks under development towards supplying the infrastructure for the high-speed communication backbone for nano-IoT systems is also essential because the capability of communication via nano-antennas should match the network-level capacity [14].

In this study, a systematic review is conducted for various nanodevice components, namely nano-sensors, nano-antennas, nano-processors, and nanobatteries, with emphasis on their application in scalable IoT systems for smart factories. This review addresses the following aspects: (i) nanomaterial properties essential for device functionality in the IoT context; (ii) the current state of the art of each nanodevice component type in terms of performance as described in recent experimental and simulation works; (iii) a critical comparison of nanodevice performance in contrast to that of classical electronics; (iv) an exemplary multi-

parametric Performance Index (PI) formulation and a candid assessment of the limitations thereof; and (v) remaining challenges and research priorities for practical implementation in smart factories.

2. METHODOLOGY AND LITERATURE REVIEW STRATEGY

This study represents a structured review of peer-reviewed scientific literature on the topic of IoT devices comprising nanomaterial-based components. Literature searches were performed systematically within the bibliographic databases Scopus, Web of Science, IEEE Xplore, and Google Scholar using combinations of keywords like 'nano-sensor IoT', 'nanoantenna terahertz', 'CNT field-effect transistor logic', 'nanostructured battery IoT', 'smart factory nanoelectronics', and 'Internet of Nano-Things'. Publications dated from 2017 up to 2025 were given preference to ensure inclusion of any breakthroughs made in recent years. Older but essential publications have been considered when there is a need to provide theoretical background. In total, 35 papers have been referred to, taking into account their relevance, citation rate, and methodology. No additional measurements have been conducted; all the performance values are taken from previously cited publications. All graphs and tables in the current paper are copied from cited references; see acknowledgments for details.

2.1. Nanomaterial Properties

Table 1 summarizes the key mechanical, thermal, electrical, optical, and magnetic properties of nanomaterials, highlighting their distinctive features and potential applications in IoT systems, including smart sensors, energy harvesting, and real-time monitoring.

Table 1. Key Properties of Nanomaterials and Their IoT-Relevant Applications

Property Type	Key Features	Examples / Applications
Mechanical	Increased strength & hardness due to limited dislocation motion (Hall-Petch effect); exceptional tensile strength in CNTs (~100GPa) [1,2]	Carbon nanotubes in structural composites; high-strength nanometals
Thermal	Reduced thermal conductivity via phonon scattering; altered thermal expansion coefficients	Thermoelectric generators; thermal barrier coatings for turbines
Electrical	Quantum confinement modifies band gaps; ballistic transport in nanowires/CNTs; surface scattering raises resistivity	Nanoelectronics transistors; nanosensors; supercapacitors
Optical	Surface plasmon resonance enhances absorption and scattering; quantum confinement shifts emission spectra	Biosensing; photothermal cancer therapy; SERS imaging
Magnetic	Transition to single-domain state increases coercivity; superparamagnetic due to thermal fluctuations	Magnetic data storage; MRI contrast agents; targeted drug delivery

2.2. Nanodevice Components for IoT: State of the Art and Critical Review

The scaling of silicon-based technologies under the tenets of Moore's Law has driven the improvement of semiconductor devices over five decades now. In the face of physical limitations, two-dimensional materials, CNTs, and nanowires as low-dimensional nanomaterials are being widely explored as channel materials that enable high mobility, ultra-thin channel structures, and superior resistance against short-channel effects [20-22]. Out of the new generations of transistors, nanosheet field-effect transistors have been foreseen to be the next device after FinFET at the 3-nm technology node [23]. Nevertheless, achieving manufacturability in

volume production is the major obstacle yet to be conquered**. Table 2** shows the four main types of nanodevice components addressed in this paper, including their respective challenges and limitations.

Table 2. Nanodevice Components for IoT: Functions, Materials, Applications, and Limitations

Component	Key Function	Key Nanomaterials	Typical Application	Challenges & Limitations
Nanosensors	Sensing physical, chemical, biological phenomena	Nanowires, CNTs, nanoparticles, graphene	Environmental & biomedical monitoring in smart factories	Cross-sensitivity to interferents; long-term drift; calibration complexity [8,22]
Nanoantennas	THz-band wireless signal transmission/reception	Graphene, CNTs, MXenes	Compact on-chip communications; RFID	Communication range <10 m; THz transceiver integration immature at scale [17,20]
Nanoprocessors	Ultra-low-power computation and logic operations	CNT FETs, nanowire FETs, 2D MoS_2	Edge AI; embedded IoT computing nodes	Wafer-scale yield below CMOS; circuit-level integration remains at prototype stage [23,24]
Nanobatteries	High-density energy storage and rapid charging	CNTs, LTO nanoparticles, Ge nanowires, Si anodes	Fast-charging power supply for IoT nodes and wearables	Capacity fade on cycling; electrolyte decomposition; cost of nanostructured electrode synthesis [25]

As can be seen from the critical evaluation in **Table 2**, one of the most important findings presented in this review is that although individual nanodevice types show significant improvements in performance over their respective component-level counterparts, no commercial realization of the co-integration of all four types of nanodevices into a functional nano-IoT node has yet been achieved. In particular, interfacial resistance between the CNT sensor array and nano-logic processing layer, impedance mismatch between nano-antenna and RF circuitry, and the electrolyte compatibility required for nanobatteries each impose a penalty not present in the performance of component-level devices alone.

2.3. Performance Index (PI): A Qualitative Heuristic Tool

To create an illustrative model to represent the multi-parameter benefits offered by nanoelectronics compared to its conventional counterparts, the following definition of the Performance Index (PI) is given: $PI = (S \times E \times L \times M) / (P \times C)$.
Where S = Switching Speed (GHz), E = Energy Efficiency (ratio), L = Lifetime (hrs), M = Memory Density (Gb/cm^2), P = Power Consumption (W), and C = Component Size (nm).

IMPORTANT CAVEAT: The PI formula is explicitly presented as a qualitative, illustrative heuristic, not as a physically derived or experimentally validated engineering metric. The following limitations must be acknowledged before interpreting any PI values:
Dimensional inconsistency: These six parameters have different physical units (GHz, unitless ratio, hours, Gb/cm^2, watts, nanometres), but they are multiplied together without being normalized first, hence making the resultant scalar physically dimensionally meaningless and not comparable among various applications. (ii) Equal weighting: The formula gives equal weight to the six parameters, but in reality, in a battery-less sensor node application, the power consumed and its size matter a lot more than display longevity and memory density. (iii) Representative data and no measurements: The actual numerical data given in **Table 3** have not been obtained from measurements of any particular integrated nano-IoT device; rather, representative values from diverse publications have been used. (iv) Integration penalties ignored: The values used in the formula are component-level, hence do not include integration penalties such as resistance-capacitance losses due to the integration of nano-sensors, nano-

antennas, nano-processors, and nanobatteries. (v) No comparison with international standard: Performance Index has not been validated against International Roadmap for Devices and Systems or any other international standard. **Table 4** highlights these problems and provides possible solutions.

Table 3. Representative Performance Parameters: Nanoelectronics vs. Traditional Electronics (Illustrative Values from Published Literature)

Parameter	Nanoelectronics (representative)	Traditional Electronics (representative)
Transistor Size (nm)	5	130
Switching Speed (GHz)	10	2
Display Lifetime (hrs)	50,000	10,000
Battery Charging Time (h)	0.5	2.5
Power Consumption (W)	15	65
Memory Density (Gb/cm²)	10	1

Using the representative values in Table 3, the illustrative PI calculations are:

$$PI(Nano) = (10 \times 2 \times 50{,}000 \times 10) / (15 \times 5) = 1.33 \times 10^6$$

$$PI(Traditional) = (2 \times 0.4 \times 10{,}000 \times 1) / (65 \times 130) = 0.95$$

The large disparity in values (1.4 x 10^6 fold) is purely because of the mismatch of units in the equation rather than being a true representation of a million times better efficiency. This value should be seen purely as a graphic way of saying that nanoelectronics outperforms normal electronics in all six parameters that have been selected for comparison. Future researchers who wish to compare using a similar performance index should do so by making the ratio dimensionless and giving it a suitable weightage.

Table 4. Limitations of the Proposed PI Formula and Recommended Remedies

PI Formula Limitation	Explanation	Recommended Remedy
Dimensional inconsistency	Parameters S (GHz), L (hrs), M (Gb/cm²), P (W), C (nm) are multiplied without unit normalization, making the scalar physically meaningless	Normalize each parameter to a dimensionless ratio relative to a baseline before computing PI
Arbitrary equal weighting	All six parameters are weighted equally, but application-specific priorities differ (e.g., power is critical for IoT but display lifetime may be irrelevant)	Assign application-specific weights (w_i) derived from multi-criteria decision analysis or expert surveys
No experimental validation	Parameter values are drawn from disparate literature sources, not measured on a single integrated platform under standardized conditions	Validate against IRDS benchmarks or standardized device test results from a single experimental setup
Ignores integration penalties	Co-integration of nano-sensors, nano-antennas, nano-processors, and nanobatteries introduces interfacial resistance, packaging overhead, and signal compatibility constraints not captured by component-level parameters	Extend PI to include system-level overhead terms derived from simulation or system prototyping

3. RESULTS AND DISCUSSION

3.1. Comparative Performance Analysis: Nanoelectronics vs. Traditional Electronics

Conventional electronics, based on bulk silicon with lithographic feature sizes of about 130 nm (a mature technology node), consume up to 65 W of power per processor at the transistor level for high-end uses, have memory density values of 1 Gb/cm², and operate with speeds close to 2 GHz for conventional CMOS logic [24]. Conventional LCDs have an operational lifetime of about 10,000 hours; meanwhile, lithium-ion batteries with graphite anodes require 2.0-2.5 hours for their complete charging process.

Nanoelectronics, using CNTs, graphene, quantum dots, and other nanomaterials as base materials, has made transistors with a technology node of 5 nm, where the power consumption is less than 15 W, and the memory density is as high as 10 Gb/cm² for nano-storage devices, while achieving switch speeds above 10 GHz for CNT logic circuits [20,23,24]. OLED and nanomaterial-based displays have lifetimes exceeding 50,000 hours, whereas nano-electrodes in nano-batteries (such as germanium nanowire or silicon nanoparticle anodes) enable full charging in less than 30 minutes without thermal runaway effects [25].

3.2. Crucial Comparative Analysis: Nano-sensors vs. Traditional Sensors

A careful review of the existing literature on nano-sensors indicates that although their performances at the laboratory level are commendable, there are several practical limitations that separate individual components from deployable industrial IoT sensors. **Table 5** presents a critical analysis based on experimental data.

Table 5. Critical Comparison of CNT/Graphene Nano-sensors vs. Conventional Sensors for Industrial IoT Applications

Metric	CNT/Graphene Nano-sensors	Conventional MEMS/Electrochemical Sensors	Critical Remarks
Detection Limit (NO_2)	Sub-ppb (< 1 ppb) [8]	1–10 ppm (electrochemical) [22]	Nano-sensors superior in sensitivity but lab-scale results may not reflect factory deployment conditions
Selectivity	Moderate; cross-sensitive to humidity and O_2 [8]	High with selective membranes; mature error-correction methods	Conventional sensors offer better field-deployable selectivity; nanodevices require functionalization
Power Consumption	< 1 µW (self-powered prototypes) [21]	1–100 mW (typical commercial units)	Significant power advantage for nano-sensors; critical for battery-less IoT nodes
Long-Term Stability	Hours to days without encapsulation; degrades in air/humidity [30,31]	Months to years with standard calibration protocols	Major gap: conventional sensors far more stable; encapsulation solutions are an active research priority [30–32]
Manufacturing Readiness Level	TRL 3–5 (laboratory demonstration) [24]	TRL 8–9 (commercially deployed)	Nanodevices remain largely at the research stage; commercialization timeline is 5–15 years for most types [23]

Table 5: CNT- and graphene-based nanosensors have detection limits of sub-ppb levels for target gases like NO_2 and NH_3, which are two to three orders of magnitude lower than the detection limits of commercially available electrochemical sensors [8,22]. Nevertheless, their selectivity in an industrial air atmosphere where various interfering gases and humidity changes exist

still falls behind the well-developed electrochemical sensors that have been selectively engineered for decades. The crucial issue lies in long-term stability since traditional sensors can be used for months or even years with normal calibration, whereas CNT sensors only last for hours or days without encapsulation [30,31]. This encapsulation challenge is discussed further in Section 3.4. For nano-antennas, graphene-based designs operating in the terahertz (THz) frequency band (0.1–10 THz) offer theoretical bandwidths orders of magnitude beyond conventional microstrip antennas, enabling nano-scale wireless links for in-body or on-chip IoT communications [17]. In practice, however, THz transceiver systems for industrial environments remain at the research prototype stage (TRL 3–4), with demonstrated communication ranges typically below 10 metres and significant atmospheric absorption losses at THz frequencies limiting line-of-sight coverage in factory hall geometries. While nano-processors using CNT-FETs exhibit sub-1V functionality, consuming less than 1 attojoule (aJ) of energy per logic operation, making them highly attractive in battery-free or energy-harvesting IoT devices [23], integration density and fabrication yield are still inferior compared to established CMOS technologies. As seen in the latest CNT processor (a 16-bit microprocessor developed by MIT in 2019), an elaborate methodology for dealing with defect tolerance was employed due to uneven CNT networks [23,24]. Therefore, CNT-based logic is considered an emerging technology rather than an industrial one.

3.3. Neural Interfaces and Flexible Nanoelectronics

The latest developments in neural interface technology have shown the unique features offered by flexible biocompatible nanomaterial-based interfaces. Hydrogel, conductive polymer, silicone composite, and CNT-graphene nanocomposite materials can be employed for the development of electrode arrays that fit the soft and curvilinear neural tissue architecture and minimize the occurrence of inflammation caused by mechanical mismatch in comparison with conventional metal electrodes [27-29]. The graphene-based electrodes have been able to record electrophysiological signals from several hundred recording points, achieving higher noise-to-signal ratio values than platinum-iridium microelectrode arrays with the same footprint size. Such unique abilities of the technology can be directly applied to IoT-related applications, such as implantable health monitoring devices, prosthetic limb controls, and closed-loop neuromodulation devices for generating physiological signals.

3.4. Protective Strategies for Air Sensitivity of Carbon-Based Nanomaterials

Air sensitivity represents a basic issue in terms of the reliability of carbon-based nanomaterials in IoT implementation. Exposure of materials to oxygen results in the creation of trap states and oxidation of the surface of CNTs and edges of graphene layers, causing poor charge transfer properties and elevated contact resistance [30]. Hydrogen uptake by hygroscopic materials, such as MXenes, results in swelling of the material, layer separation, and an increased level of resistance, which negatively affects both sensor signal-to-noise ratio and energy storage capacity [31].

Some of the protective techniques being actively pursued are: (i) polymer/ceramic coating films using ALD/CVD techniques; (ii) device fabrication in an atmosphere of inert gases; (iii) functionalization of surfaces using self-assembled monolayer (SAM) films which inhibit any reactivity of edge sites; (iv) use of solid electrolyte films in nanobatteries which prevent the entry of moisture into devices in their liquid phase; and (v) sealed metal can or glass frit package design, drawing on experience gained from MEMS fabrication technologies [30-32]. While all of these approaches have some advantages and disadvantages, none of them so far has been able to combine the properties of ultra-thin film coating, hermetic sealing, and substrate flexibility necessary for wearable applications of nano-IoT devices.

3.5. Applications in Smart Factory Environments

The smart factory, also termed Industry 4.0 or Industry 5.0 manufacturing environment, presents a compelling target application domain for nano-IoT systems, given its requirements for distributed sensing, wireless data aggregation, real-time process control, and energy-efficient computation at the network edge [33]. Nano-sensors deployed on production machinery can detect sub-threshold vibration anomalies, trace chemical contamination in process gases, and monitor structural integrity of tooling at sensitivities inaccessible to conventional MEMS sensors. Nano-antennas integrated on chip-scale communication modules can enable dense, low-power wireless sensor networks within factory enclosures where space and weight constraints are paramount. Critically, however, the co-integration of nano-sensors, nano-antennas, nano-processors, and nanobatteries into a single, self-

contained nano-IoT node for continuous smart factory operation has not been demonstrated experimentally. Published system demonstrations typically integrate one or two nano-components with conventional off-the-shelf electronics for the remaining functions [33–35]. Achieving the full vision of an all-nano IoT node requires advances in heterogeneous nano-integration, standardized packaging platforms, and system-level power management architectures that remain active areas of research. These integration challenges are also discussed in Section 4.

4. LIMITATIONS OF THIS REVIEW AND FUTURE RESEARCH DIRECTIONS

4.1. Limitations of the Performance Index Model

As stated above, there are several caveats to the PI index discussed in Section 2.3, as outlined in **Table 4**: dimensional inconsistency, weightlessness of parameters, the use of representative rather than real values, and absence of system-level penalties for integration costs. In further quantitative studies of IoT devices, the PI formula must be replaced by the following equation for normalized, weighted PI:

$$PI_{no'm}^{r} = \Sigma_i \left[w_i \times (x_i / x_i, \text{ref}) \right]$$

Here, x_i is the real value of parameter i, x_i, ref is the reference (i.e., baseline technology) value, and w_i are specific weights of application-dependent parameters based on multi-criteria decision analysis or expert estimation. The result is a non-dimensional measure with physical interpretation that allows for specific prioritization of application-dependent performance characteristics of the device under consideration. Validation of the modified PI using IRDS benchmarks and IoT device tests' standardized data would be an appropriate step to take.

4.2. Lack of Experimental Data of the Own

Since this is a literature review, no experimental data obtained specifically for this purpose is provided. Instead, the findings were gathered from peer-reviewed publications on nanodevices used in IoT applications. Therein lies one of the major limitations.

4.3. Outstanding Challenges and Priority Research Areas

Five challenges common among all four groups of nanodevices were identified: (i) Scalable manufacture and reproducibility: Current methods of synthesizing CNTs, graphene, and MXene produce material with considerable variation in its properties between batches. Roll-to-roll processing, ALD, and printing nanoelectronic devices appear as promising manufacturing approaches that can result in scalable production at a sufficiently low cost but need further investigation for IoT devices. (ii) Reliability under operating conditions in an industrial environment: An industrial floor is known for severe conditions such as high temperatures, humidity, vibrations, and exposure to various chemical substances. Thus, the ability of the nanodevice to operate reliably for years under these conditions needs to be established. (iii) Co-integration of the device system: All nanodevice components should be co-integrated on one platform while having adequate interfacial resistance, signal compatibility, and proper thermal characteristics. One possible solution would be to use heterogeneous integration techniques developed for CMOS. (iv) Standardization of the parameters: There is no standardization for nano-IoT devices; therefore, there is no way to evaluate and compare the devices manufactured by different companies. This issue can be solved by inviting international standardization organizations (IEEE, ISO, IEC) into the process. (v) Toxicity and environmental issues: (vi) International standardization organizations (IEEE, ISO, IEC) need to be involved to develop suitable testing procedures. (v) Health and environmental safety considerations: the toxicity characteristics of CNTs, graphene, and other nanomaterials used for engineering purposes need to be studied comprehensively and made known before their use in industrial applications.

5.CONCLUSION

This review has systematically explored the current status and prospects of power-efficient nanodevices, including nano-sensors, nano-antennas, nano-processors, and nanobatteries, and their contribution toward scalable Internet-of-Things (IoT) architectures for smart factories. Based on the critical analysis of existing literature, the following conclusions can be derived. First, the use of various nanomaterials like CNTs, graphene, MXenes, and quantum dots offers practical, experimentally proven superiority compared to traditional silicon electronics in terms of detection sensitivity, energy efficiency, switching speed, memory capacity, and display lifetime. This is due to inherent quantum mechanical and surface effects unique to nanomaterials and cannot be attributed to any speculative benefits. Second, the Performance Index (PI) proposed by this review can be seen as a useful heuristic approach to visualizing the simultaneous performance benefits, but it is not meant to be a physically validated metric. Due to its dimensional inconsistency, equal treatment of all parameters, and dependence on selected literature values, the numerical significance of the PI cannot be interpreted quantitatively. Therefore, researchers may use the PI value solely as an illustrative comparative example. Third, despite high-level performance achieved for individual components, many challenges still exist between proof-of-concept studies and an industrialized application of nanotechnology-based IoT systems. Long-term air stability, large-scale fabrication yields, integration of all four types of devices into one system, and the development of benchmarking methodologies for comparison purposes are just a few among the key challenges. To date, there have been no reports of any complete and continuous operation of the nano-based IoT node in industry-related environments. Fourth, the combination of nanotechnology technology with wireless infrastructure, AI, edge computing, and green energy sources appears to provide a promising route towards achieving Society 5.0 and Industry 5.0 goals by providing resilience and intelligence for future production systems. However, realizing such potential would require continued work in various fields, from materials science, electronics, and manufacturing to standardization and safety regulation processes.

The domain of nanoelectronics is developing at an accelerated pace, with the development of CNT, graphene, MXene, and nanowire manufacturing techniques continuously narrowing the distance between their experimental efficiency and practical applications. The immediate future goals include the creation of self-sustaining nano-sensor technologies using triboelectric or piezoelectric nanogenerators, neuromorphic computing through the use of nanomaterials in hardware, and closed-loop nano-IoT networks with AI-based signal analysis performed on the sensing nodes themselves. Long-term objectives include the development of eco-friendly nanomaterials, enhanced recyclability of nano-enhanced electronic products, and reduced toxic waste resulting from nanoparticle manufacturing. The current trend in nanotechnology for electronics is expected to enable the foundation of the next era of sustainable, autonomous, and intelligent technology platforms that will increase productivity and improve social welfare in the upcoming decades.

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