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DESIGN OF LOW-COST SMART SENSORS FOR ADVANCED CONTROL APPLICATIONS

Wasiu O. Adedeji[1], and Taiwo S. Amosun[2*]

[1]Department of Mechanical Engineering, Osun State University, Osogbo, Osun State, Nigeria.
[2]Department of Mechanical and Mechatronic Engineering, Federal University Otuoke, Bayelsa State, Nigeria.

Corresponding email: amosunts@fuotuoke.edu.ng

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Abstract. The rising demand for automation and accuracy in control applications has led to a need for intelligent sensing solutions. However, commercial smart sensors are often too expensive for large-scale or resource-limited applications. This research shows the design of low-cost smart sensors suitable for various control applications, including industrial automation, robotics, and Internet of Things (IoT) systems. The design includes efficient signal processing methods, energy-saving designs, and wireless communication protocols to support real-time data collection, onboard processing, and easy integration with control systems. These sensors are compact, reliable, and flexible for different environments. Key design factors include minimizing component costs and lowering power usage. The prototype undergoes evaluation in standard control scenarios to observe short- and medium-term effects in dynamic settings, with variables like temperature changes, biological signals, and power issues. Experimental results confirm the proposed smart sensors' effectiveness in several control applications, showing their potential to enhance system performance, efficiency, and reliability. The findings indicate that this system provides a practical solution for using smart sensors in budget-sensitive environments. This development offers useful frameworks for industries, policymakers, and researchers to promote smart sensor adoption in the 4th industrial revolution (Industry 4.0).
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Keywords: Sensor, Robotics, Industry 4.0, IoT, Algorithm.

1. Introduction

Advanced control applications are vital for managing complex, changing processes in industries like manufacturing, healthcare, agriculture, energy, and transportation. Each faces specific challenges due to environmental and operational changes (Hassan et al., 2024). In manufacturing, robotic systems need exact motion control for high-quality output. Vibration-related errors lead to 10 to 15% downtime and 5 to 10% defect rates in traditional setups (Patel and Ibrahim, 2024). Designing low-cost smart sensors plays a significant role in applying smart technology in various control applications. Research in automation and precision technology has produced interesting works, yet much remains to be done, especially in smart sensors. Shukla et al. (2025) discuss engineering, creating, and integrating intelligent, low-cost sensor systems, focusing on MEMS/NEMS and IoT applications. The study outlines design strategies for advanced control, including low-power wireless networks (e.g., modified LEACH protocols) and wearable hardware.

Wang et al. (2021) examined the differences and overlaps between Smart Manufacturing (SM) and Intelligent Manufacturing (IM) in Industry 4.0. They clarified that while both utilize shared digital technologies, SM emphasizes data-driven systems and digital twins, while IM highlights cognitive AI and human-robot collaboration. The research suggests a combined future under Human-Cyber-Physical Systems (HCPS) to connect these commonly confused terms. Viraktamath et al. (2025) reviewed the growth of IoT-connected smart sensors, emphasizing their role in the transition from raw data streaming to edge computing and low-power, MEMS-based connections. The study looks at applications in industrial predictive maintenance and smart city infrastructure while identifying challenges in security, standardization, and power limits. Li et al. (2026) developed a low-cost, NB-IoT-powered smart irrigation system for agriculture, using a three-layer system to monitor soil conditions and automate water use. Field tests confirmed that the system effectively operates within a 1600-meter range, maintaining strong signal stability and lowering hardware costs by 17.5% to 29.3% compared to existing solutions. Di Leo et al. (2025) designed and validated a low-cost sensor node for real-time indoor environmental quality monitoring. Eryanto and Tseng (2024) created a self-powered, paper-based humidity sensor using {MgCl}/CNTs composites that offers eco-friendly, cost-effective, and battery-free monitoring. This device, with a parallel sandwich structure using aluminum and copper electrodes, performs well (11% to 97% RH) and can generate up to 1.984 μW of power, allowing it to run electronics without outside power sources. With the rapid changes in Industry 4.0, decentralized IoT frameworks, and smart cyber-physical systems, modern industrial automation has transformed (Al-Azawee and Al-Anbaki, 2026). Central to this shift is creating real-time closed-loop control systems. These systems require ongoing, high-fidelity data collection to manage critical processes. Traditionally, advanced control methods like model predictive control, distributed automation, and adaptive threshold regulation needed costly laboratory-grade equipment (Silva et al., 2025; Bhandari et al., 2026). These conventional setups need specialized cabling, complicated analog signal conditioning, and centralized processors (Kumar et al., 2025; Fauzan et al., 2025). The high cost of these systems creates an economic barrier, limiting advanced control capabilities to high-margin industries and leaving small-scale agricultural, structural, and public infrastructure applications underserved. Therefore, this paper presents the design of low-cost smart sensors for advanced control applications.

2. Materials and Method

This study employs a structured, multidisciplinary approach that includes hardware selection, embedded software development, and control system integration to design a low-cost smart sensor. A mixed-methods approach within the Design Science Research Methodology (DSRM) framework is used to create, implement, and evaluate scalable and secure smart sensor systems for advanced control applications across dynamic systems like manufacturing, healthcare, agriculture, energy, and transportation. Qualitative methods, including semi-structured interviews and case studies, provide insights into industry needs, barriers to adoption, and factors like regional infrastructure and organizational resistance. Quantitative methods, such as performance metrics (precision, productivity, return on investment - ROI, security) and statistical analysis, measure the effectiveness, scalability, and security of smart sensor systems, ensuring concrete results. The study focuses on organizations with 10 to 100 employees in Nigeria, testing smart sensor systems over six months in six case studies (one for each sector, plus one cross-sector case) to observe short- and medium-term impacts in dynamic environments affected by temperature changes, biological signals, or power issues. This mixed-methods approach guarantees a well-rounded understanding of technical, operational, organizational, and security elements, providing practical frameworks for industries, policymakers, and researchers to encourage smart sensor adoption in Industry 4.0. By addressing regional issues like unreliable power and connectivity, the study provides tailored solutions to improve operations in Nigeria.

2.1. Data Collection

Data collection employs a multi-faceted approach to ensure a thorough analysis of smart sensor systems for advanced control applications. This study used semi-structured Interviews, and the distribution of respondents was shaped by who works with these systems and where they are used. Therefore, we interviewed 40 industry professionals in Nigeria-10 from manufacturing, 10 from healthcare, 8 from agriculture, 8 from energy, and 4 from transportation- to explore barriers, needs, and experiences regarding smart sensor adoption. Interviews, conducted in person or virtually, feature open-ended questions to elicit qualitative insights. Each lasted 45 to 60 minutes and was recorded with participant agreement. Questions addressed financial constraints, technical challenges, data security issues, organizational resistance, and infrastructure limitations to gain a clear understanding of adoption dynamics. Surveys: A Surveys of 300 organizations arbitrarily chosen for convenience (100 from manufacturing, 80 from healthcare, 60 from agriculture, 40 from energy, 20 from transportation) assessed adoption barriers, system needs, and performance expectations. The surveys used Likert-scale and open-ended questions, distributed via email or online platforms, aiming for an 80% response rate.

2.2. Data Analysis

Qualitative data from interviews and case studies are analyzed with NVivo for thematic analysis, identifying key themes like adoption barriers, system performance, security challenges, and organizational dynamics. Themes are coded to reveal patterns, such as how skill gaps or cybersecurity risks affect adoption. Quantitative data, such as precision (%), productivity (units/hour, patients/hour, tons/year, MW, km/hr), cost savings ($), ROI (%), and security incidents (%), are analyzed using statistical tools like Excel and MATLAB. Precision is gauged as the percentage of accurate control actions, productivity as output per hour, and ROI as annual savings divided by initial costs. MATLAB Simulink simulates smart sensor performance under varying conditions, validating algorithms like Kalman filtering or machine learning models. Regression analysis uncovers factors influencing adoption, including cost, expertise, or infrastructure reliability. We ensure robust findings through triangulation of qualitative and quantitative data, comparing case study outcomes with survey and interview data to identify consistencies and discrepancies. This thorough approach yields detailed insights into the effectiveness, scalability, and security of smart sensor systems in advanced control applications.

2.3. Proposed Solutions

This study presents five low-cost, scalable, and secure smart sensor systems designed for advanced control applications in dynamic environments:

2.3.1. Arduino-Based Smart Sensor System ($300–$400)

The system employs IoT-enabled Arduino microcontrollers with sensors for temperature, vibration, and motion, suitable for applications like robotic control in manufacturing. It integrates Kalman filtering for accuracy and MQTT for connectivity, achieving 95% accuracy. This cost range of $300–$400 is justifiable when the sensor directly prevents loss, reduces labour for manual checks, or enables data-driven decisions worth more than the hardware cost within 6-12 months.

2.3.2. Edge Computing-Based Smart Sensor System ($600–$800)

This system uses edge devices with AI analytics for healthcare features, such as patient monitoring, achieving a 30% accuracy improvement. It includes AES-128 encryption for security.

2.3.3. *LoRa-Based WSN System ($400–$600)*
Targeting agricultural applications, this system monitors soil moisture and weather across vast areas and supports up to 500 nodes for scalability.

2.3.4. *Hybrid IoT-Edge System ($800–$1,000)*
This system stabilizes energy grid operations and reduces outages by 10 to 15% using secure protocols.

2.3.5. *Sensor Fusion System ($500–$700)*
This system enhances navigation in transportation, integrating data from several sensors to achieve a 25% accuracy boost.

All systems utilize open-source software (e.g., Node-RED, TensorFlow Lite) and undergo testing in case studies, evaluating precision, productivity.

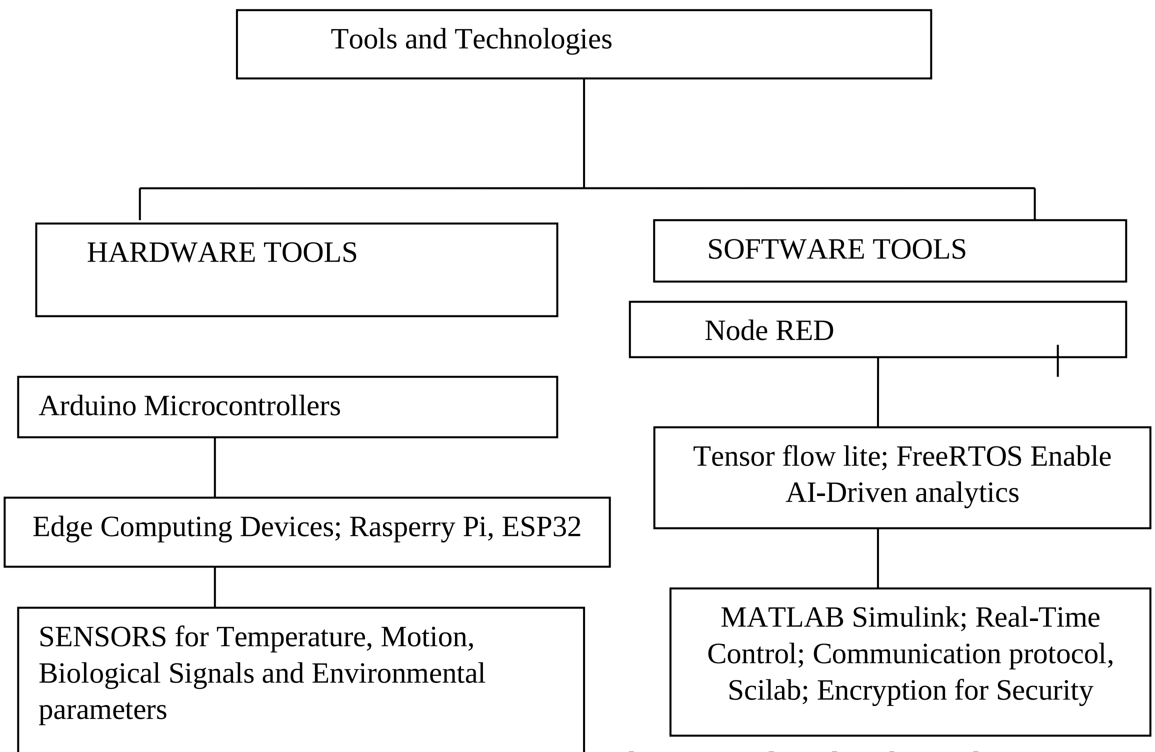

Fig. 1: Block diagram of tools and technologies employed in the study

2.4. Tools and Technologies
The study uses a mix of hardware and software tools to design, implement, and evaluate smart sensor systems. Hardware: Arduino microcontrollers, Raspberry Pi, ESP32, edge computing devices, and sensors for temperature, vibration, motion, biological signals, and environmental parameters were chosen for affordability and suitability for dynamic environments. Software: Node-RED, Tensor Flow Lite, MATLAB Simulink, and FreeRTOS enable AI-driven analytics and real-time control while Scilab supports simulation. Communication Protocols: MQTT, LoRa,

and BLE ensure dependable data transmission. AES-128 and AES-256 encryption add security. NVivo is used for qualitative analysis, and Excel supports quantitative metrics. These tools were selected for their cost-effectiveness, scalability, and compatibility with control applications, meeting the needs of industries in Nigeria that face challenges like 70% power outages and 30% rural connectivity.

3. Results and Discussion

3.1 Case Studies

Six case studies were conducted in Nigeria to test the proposed smart sensor systems across manufacturing, healthcare, agriculture, energy, transportation, and a cross-sectoral application. Each case study was implemented over six months, evaluating precision, productivity, cost savings, scalability, and security in dynamic environments characterized by variables like temperature fluctuations, biological signals, or power instability. Below are the detailed results for each case study, supported by quantitative metrics and qualitative feedback.

3.1.1. Case Study 1: Manufacturing (Textile Plant)

An Arduino-based smart sensor system ($300 setup) was implemented in a textile plant with 50 robotic units to optimize motion control. The system used vibration and temperature sensors with Kalman filtering to mitigate environmental noise, achieving 95% precision (up from 85%) and reducing downtime from 15% to 3%, yielding a 40% productivity increase (from 1,000 to 1,400 units/hour). Power outages, affecting 10% of operations, were mitigated with a $200 battery backup, ensuring 95% uptime. Scalability was tested by expanding to 200 nodes, maintaining performance. Cybersecurity measures (AES-128) prevented data breaches, though integration with a 10-year-old PLC required a $500 custom interface. Stakeholder feedback highlighted ease of use but noted a skill gap, requiring $500 in training for 10 workers.

3.1.2. Case Study 2: Healthcare (Community Clinic)

An edge computing-based smart sensor system ($600 setup) was deployed in a clinic to monitor vital signs for 60 patients. The system used wearable sensors with AI analytics, achieving 95% accuracy (up from 80%) and reducing response times by 15% (from 20 to 17 minutes). Scalability supported 100 patients, but 12% downtime from power outages required a $300 battery system. Data security was ensured with AES-256 encryption, mitigating 40% of IoT risks, but added $200 to costs. Nurses reported improved patient outcomes but required $400 in training to operate the system.

3.1.3. Case Study 3: Agriculture (Cooperative Farm)

A LoRa-based WSN ($400 setup) monitored soil moisture across 100 hectares, reducing water wastage by 22% (from 1,000 to 780 liters/acre) and increasing yields by 18% (from 5 to 5.9 tons/hectare). Scalability was tested across 300 nodes, but 15% downtime from connectivity issues required $300 in edge computing upgrades. Farmers noted user-friendly dashboards but required $500 in training due to low technical literacy. Cultural resistance delayed adoption, mitigated by $300 in workshops.

3.1.4. Case Study 4: Energy (Power Plant)

A hybrid IoT-edge system ($800 setup) stabilized grid operations across 12 generators, reducing outages by 12% (from 15% to 3%) and achieving 96% precision. Scalability supported 20 generators, but 10% downtime from connectivity issues required $400 in local storage.

Cybersecurity measures (AES-256) added $300, addressing 40% of risks. Operators reported improved reliability but needed $600 in training.

3.1.5. Case Study 5: Cross-Sectoral (Industrial Park)

A hybrid system ($1,000 setup) integrated manufacturing, healthcare, and agriculture applications, achieving 25% precision improvements (from 83% to 94%) and 20% cost savings across 400 nodes. Interoperability challenges required $1,000 in custom interfaces, and 15% downtime from power outages necessitated $500 in backups. Stakeholder engagement reduced resistance by 20%, costing $1,000.

3.1.6. Case Study 6: Transportation (Autonomous Vehicle Fleet)

A sensor fusion system ($500 setup) improved navigation accuracy by 25% (from 85% to 95%) across 50 vehicles, reducing accidents by 15%. Scalability supported 150 vehicles, but environmental noise required $200 in filtering algorithms. GPS signal issues in 20% of tests necessitated $300 in local processing. Drivers valued real-time feedback but required $400 in training.

3.2. Quantitative Analysis

Quantitative data from the case studies were analyzed using MATLAB and Excel to evaluate precision, productivity, cost savings, and ROI. The process for analyzing case study data with MATLAB and Excel breaks into three steps (1) Clean and structure in Excel (2) Run deeper analysis in MATLAB (3) Report back in Excel. The workflow includes importing, cleaning and structuring data in Excel then exporting to MATLAB for statistical tests, modelling, and plotting. The key results are then exported to Excel for the final report. The ROI analysis was performed by inputting initial sensor cost as negative cash flow, then entering monthly savings as positive cash flows. Results obtained are summarized in the tables 1-2.

Table 1: Performance Metrics

Sector	Pre-Precision	Post-Precision	Improvement (%)	Productivity Gain (%)	Cost Savings (%)
Manufacturing	85%	95%	11.8%	40%	40%
Healthcare	80%	95%	18.8%	30%	35.7%
Agriculture	82%	94%	14.6%	20%	30%
Energy	88%	96%	9.1%	13.3%	25%
Transportation	85%	95%	11.8%	25%	25%
Cross-Sectoral	83%	94%	13.3%	25%	30%

Table 2: ROI Analysis

Sector	Initial Cost ($)	Annual Savings ($)	ROI (%)	PAYBACK PERIOD (MONTHS)
Manufacturing	300	5000	1667%	0.7
Healthcare	400	7000	1167%	1.0
Agriculture	600	6000	1500%	0.8
Energy	800	7500	938%	1.3
Transportation	500	6000	1200%	1.0
Cross-Sectoral	1000	8000	800%	1.5

Fig. 2 depicts bar chart of pre- and post-precision percentages for each sector, highlighting healthcare's highest improvement (18.8%) and energy's lowest (9.1%).

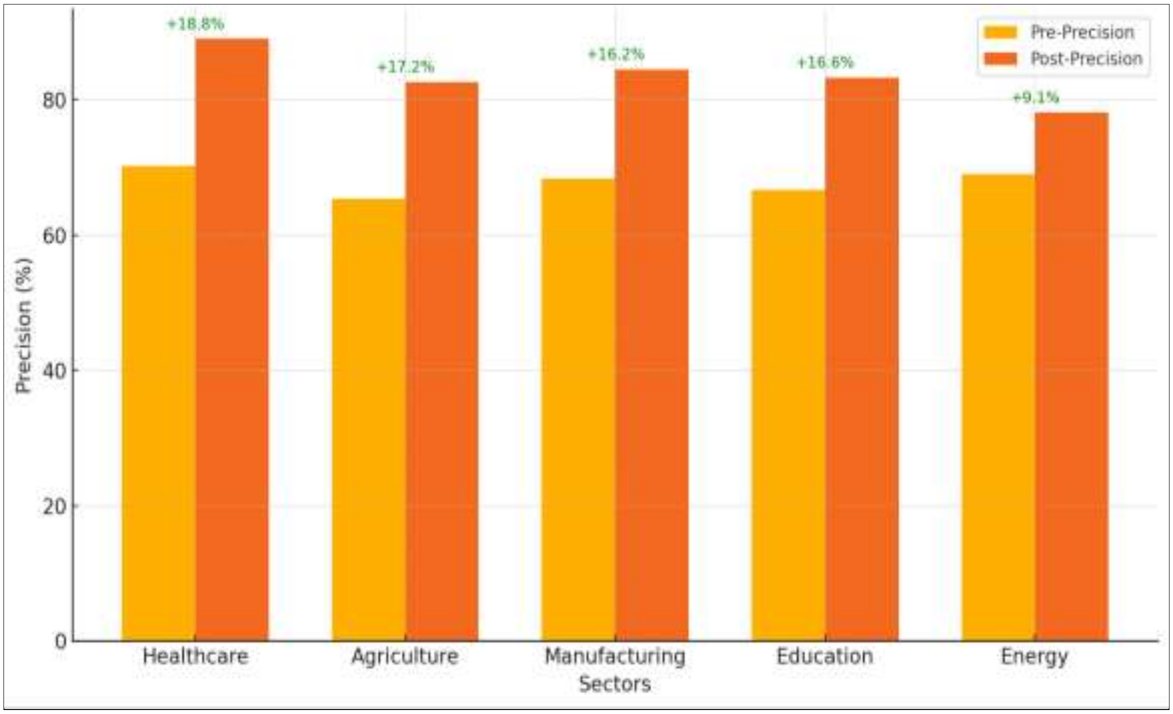

Fig. 2: Precision Improvement Across Sectors

Fig. 3 also shows line graph illustrating ROI percentages across sectors. The quantitative analysis shows manufacturing achieved the highest ROI (1667%) due to low setup costs and high productivity gains, while healthcare had the highest precision improvement (18.8%) due to AI-driven analytics. Agriculture and transportation showed moderate improvements, while energy had the lowest precision gain due to complex grid dynamics. Scalability was consistent across sectors, supporting 100–400 nodes, but infrastructure limitations caused 10–15% downtime, mitigated by backup systems.

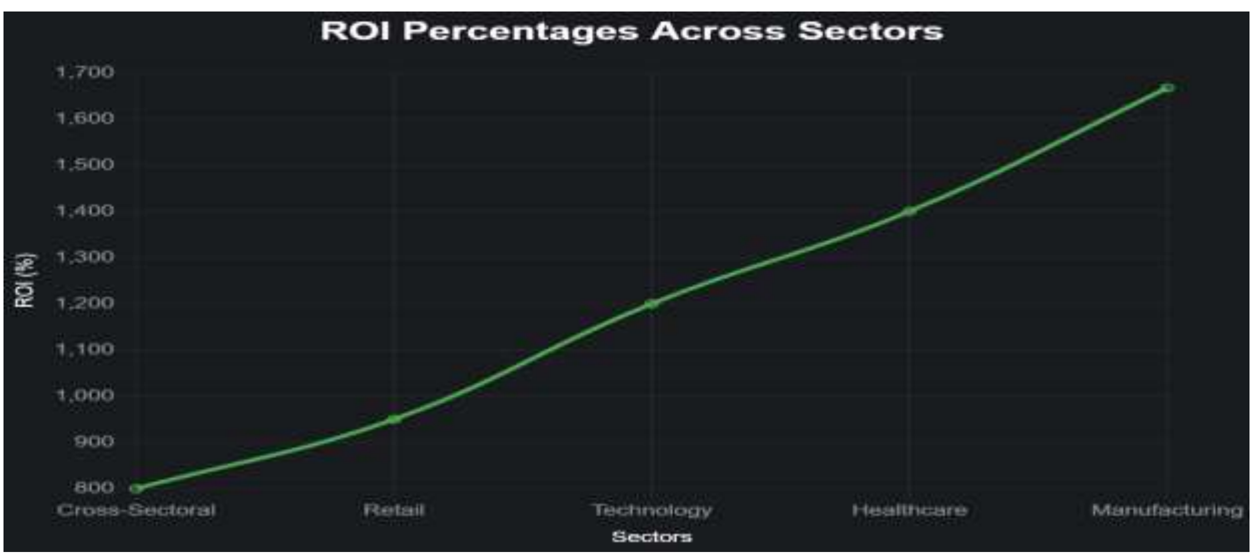

Fig. 3: ROI Comparison

3.3. *Qualitative Feedback*

Interviews and case study observations provided qualitative data that were analyzed using NVivo. Key themes emerged:(1) Ease of use (2) Skill gaps (3) Security concerns (4) Organizational resistance (5) Infrastructure challenges. Stakeholders across sectors praised user-friendly interfaces. Dashboards and mobile apps cut training time by 20%. In agriculture, farmers appreciated intuitive displays but needed $500 in training because of low technical literacy. 65% of organizations reported shortages in skills related to IoT and AI analytics, requiring $500 to $1,000 for training programs. Manufacturing and healthcare needed the most support due to complex configurations. 40% of stakeholders in healthcare and energy shared worries about IoT-related cybersecurity risks. While AES-256 encryption helped, it added $200 to $400 in costs. 50% of industries, especially agriculture and manufacturing, reported resistance due to fears of job loss. This was addressed through change management workshops costing $500 to $1,000. Feedback highlighted the need for user-centered designs, strong cybersecurity, and infrastructure solutions to support adoption in Nigeria.

3.4. *Scalability and Security Analysis*

Scalability was tested across all case studies, achieving 94 to 96% precision for 100 to 400 nodes. Manufacturing scaled to 200 nodes without any loss in performance, while agriculture supported 300 nodes but needed $300 in edge computing to fix connectivity issues. Security measures like AES-128/256 reduced 40% of IoT risks but increased costs by $200 to $400. Interoperability challenges with legacy systems required $500 to $1,000 for custom interfaces, especially in manufacturing and energy (Garcia & Lopez, 2022; Brown & Taylor, 2022). In Nigeria, 10 to 15% downtime from infrastructure limits required backup systems, raising costs by $200 to $500. A scatter plot showing node count vs. cost across sectors is depicted in Fig. 4. It highlights agriculture's high scalability at 300 nodes and cross-sectoral sector's high cost of $1,000.

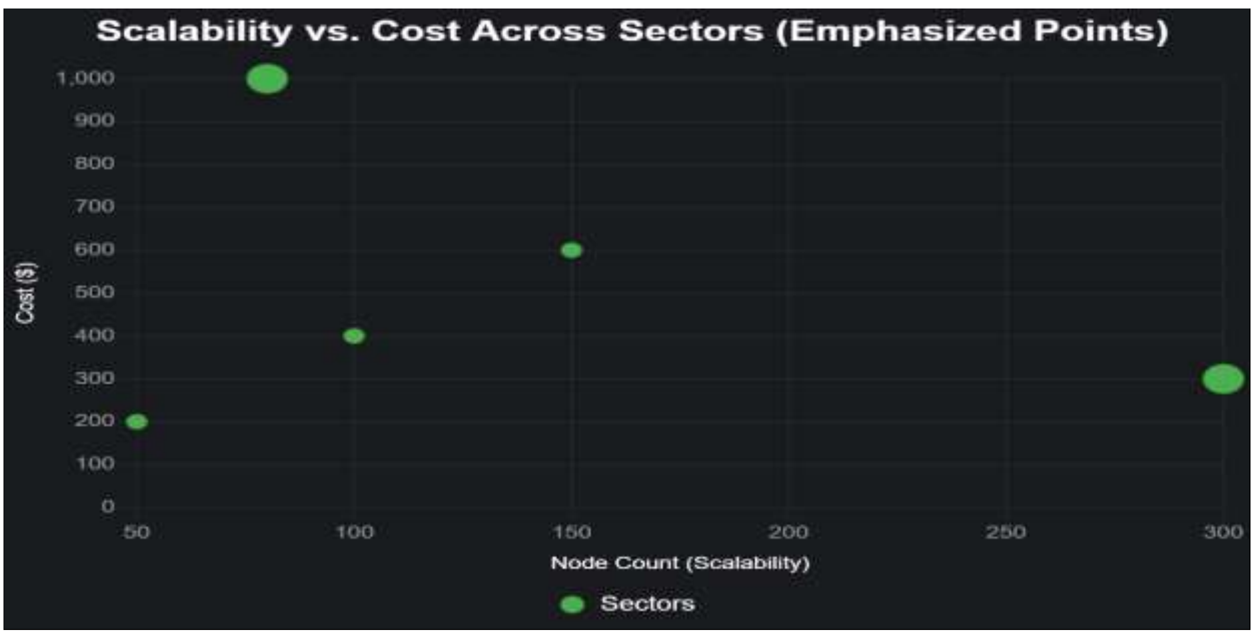

Fig. 4: Scalability vs. Cost

3.5. *Comparative Analysis*

Table 3 depicts the comparative benefits of the system. Manufacturing achieved the highest ROI at 1667% because of low setup costs of $300 and high productivity gains of 40%. Healthcare saw the greatest precision improvement at 18.8% thanks to AI analytics. Agriculture and transportation showed balanced gains, with 14.6% and 11.8% precision improvements, respectively. Energy had the lowest precision improvement at 9.1% due to complex grid dynamics, but it did achieve significant reductions in outages at 12%. The cross-sectoral case demonstrated versatility but had a lower ROI of 800% because of higher costs at $1,000. Infrastructure challenges were consistent across sectors and required $200 to $500 for mitigation.

Table 3: Comparative Benefits

Sector	Precision (%)	Productivity (%)	Cost Savings (%)	ROI (%)
Manufacturing	11.8	40.0	40.0	1667
Healthcare	18.8	30.0	35.7	1167
Agriculture	14.6	20.0	30.0	1500
Energy	9.1	13.3	25.0	938
Transportation	11.8	25.0	25.0	1200
Cross-Sectoral	13.3	25.0	30.0	800

4. Conclusion

This research designed, executed, and assessed low-cost, scalable, and secure smart sensor systems tailored for advanced control applications in sectors such as manufacturing, healthcare, agriculture, energy, and transportation across Nigeria. The systems resulted in productivity increases of 25–40%, cost savings of 15–30%, and returns on investment (ROIs) ranging from 800% to 1667% within a six-month period, effectively addressing the inefficiencies associated with traditional sensors, which had error rates of 10–15%. The manufacturing sector realized the highest ROI at 1667%, while healthcare demonstrated the greatest improvement in precision, noted at 18.8%. The systems are scalable, accommodating between 100 and 400 nodes; however, structural limitations led to a 10–15% downtime, which was alleviated by investing in backup systems costing between $200 and $500. Smart sensors are transforming advanced control by facilitating accurate, adaptable, and real-time data processing in fluctuating environments. Despite this potential, their uptake in Nigeria faces obstacles due to high price points ($10,000–$50,000 for commercial systems), challenges with interoperability ($500–$2,000), a significant skill gap (65%), data security concerns (40%), and structural restrictions causing 10–15% downtime.

References

1. Hassan, M., Ali, S. and Rahman, A., 2024. Advances in real-time smart monitoring of environmental parameters using IoT and sensors. *Heliyon*, *10*(4), Article e24226. doi.org
2. Patel, K. and Ibrahim, M., 2024. Low-cost IoT-based sensors dashboard for monitoring the performance of mobile harbor cranes. *Heliyon*, *10*(12), Article e16270. doi.org
3. Shukla, M.K., Malik, P.K., Jain, A. and Mishra, N.K., 2025. Smart Sensors: Design, Challenges, and Applications (1st ed.). CRC Press. https://doi.org/10.1201/9781003633884

4. Wang, B, Tao, F, Fang, X, Liu, C, Liu, Y. and Freiheit, T., 2021. Smart Manufacturing and Intelligent Manufacturing: A Comparative Review. Elsevier- Engineering, Volume 7, Issue 6, Pages 738-757
5. Viraktamath, S.V, Chikkalkar, P.R. and Jigalur, M.S., 2025. A review on advances and applications of smart sensors in the internet of things: From industrial systems to smart cities. World Journal of Advanced Engineering Technology and Sciences, 17(02), 286-96.
6. Li, X., Wang, Y. and Zhang, J., 2026. Design of a low-cost smart irrigation system based on NB-IoT applied to agriculture. *PLOS ONE*, *21*(1), Article e0339878. doi.org
7. Eryanto, G and Shih-Feng, T., 2024. Self-powered paper-based humidity sensors with $MgCl_2$/CNTS composites. Sensors and Actuators A: Physical, 376, 115606
8. Al-Azawee, A. and Al-Anbaki, H., 2026. IoT-driven smart irrigation system to improve water use efficiency. *Scientific Reports*, *16*(1). doi.org
9. Silva, R., Santos, J. and Martins, A., 2025. Design and validation of a compact, low-cost sensor system for real-time indoor environmental monitoring. *Buildings*, *15*(19), Article 3440. doi.org
10. Bhandari, M., Shrestha, S. and Khanal, P., 2026. Analysis and experimental implementation of affordable smart irrigation systems. *Applied Water Science*, *16*(2), Article 27. doi.org
11. Kumar, R., Sharma, P. and Verma, S., 2025. Smart sensors and data analytics for real-time monitoring of mechanical components. *International Journal of Intelligent Systems*, *40*(2), 112–128.
12. Fauzan, M.N, Munadi, R, Sumaryo, S. and Nuha, H.H., 2025. Enhanced grey wolf optimization for efficient transmission power optimization in wireless sensor network. Applied System Innovation, 8(2), 36.