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Photosynthetic Living Plant–Integrated Cybernetic Sensors for Autonomous Environmental Intelligence

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Abstract

The increasing demand for sustainable and autonomous environmental monitoring systems has motivated the development of biologically integrated sensing technologies that combine living organisms with advanced cybernetic intelligence. This study proposes a novel framework of Photosynthetic Living Plant–Integrated Cybernetic Sensors for Autonomous Environmental Intelligence, where living plants act as self-sustaining sensing platforms capable of continuously monitoring environmental conditions without external energy sources. By integrating bioelectrical signal acquisition modules, flexible nanomaterial electrodes, edge artificial intelligence, and wireless communication systems with plant physiological networks, the proposed system enables real-time detection of air pollutants, soil moisture variations, heavy metal contamination, temperature fluctuations, humidity changes, and atmospheric carbon dioxide concentrations. Photosynthetic energy harvesting provides partial power autonomy, significantly reducing maintenance requirements and enhancing deployment in remote ecosystems. Machine learning algorithms process plant electrophysiological responses to identify environmental stress patterns and generate predictive analytics for climate adaptation and ecological risk assessment. Experimental evaluations indicate sensing accuracies exceeding 94%, response times below 12 seconds, and operational lifetimes surpassing conventional battery-powered sensor networks. The proposed cybernetic plant sensor architecture represents a promising pathway toward sustainable smart cities, precision agriculture, biodiversity conservation, and next-generation environmental intelligence systems. Its bioinspired and energy-efficient architecture provides a workable alternative for autonomous environmental sensing systems in the future

Keywords: Living plant sensors; cybernetic sensing systems; photosynthetic energy harvesting; environmental intelligence; edge artificial intelligence; sustainable sensor networks

INTRODUCTION

Rapid industrialization, urban expansion, climate change, and increasing environmental degradation have created an urgent demand for intelligent, sustainable, and autonomous monitoring systems capable of continuously observing complex ecological processes with minimal energy consumption and maintenance. Conventional environmental sensor networks, although highly effective for monitoring temperature, humidity, gas concentration, soil moisture, and pollution levels, often depend on external power supplies, periodic battery replacement, extensive communication infrastructure, and costly maintenance, limiting their deployment in remote ecosystems and large-scale environmental applications. Recent advances in bio-integrated sensing technologies have introduced a transformative paradigm in which

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living biological systems are combined with electronics, nanomaterials, and artificial intelligence to create adaptive, energy-efficient sensing platforms. Among biological entities, living plants possess exceptional capabilities as natural environmental indicators because their physiological and electrophysiological responses are highly sensitive to variations in light intensity, temperature, humidity, soil nutrient availability, heavy metal contamination, water stress, pathogen attack, and atmospheric pollutants. Changes in photosynthetic activity, stomatal conductance, transpiration rate, chlorophyll fluorescence, and bioelectrical signalling provide valuable information regarding the surrounding environmental conditions, enabling plants to function as naturally distributed sensing systems.

The emergence of flexible electronics, nanostructured electrodes, graphene-based conductive materials, wireless communication modules, Internet of Things technologies, and edge artificial intelligence has enabled the seamless integration of cybernetic interfaces with living plant tissues without significantly affecting their biological functionality or growth characteristics. Such plant–machine symbiosis offers unprecedented opportunities for developing self-sustaining sensor systems capable of harvesting energy directly from photosynthetic processes and environmental gradients, thereby reducing dependence on conventional batteries and enhancing the long-term operational reliability. Furthermore, machine learning and deep learning algorithms can analyze the complex electrophysiological patterns generated by plants to identify environmental stress conditions, predict ecological disturbances, and support proactive decision-making for environmental management. These developments have opened new avenues for precision agriculture, smart forestry, biodiversity conservation, urban ecosystem monitoring and climate resilience planning. Despite significant progress in smart sensor technologies, research on cybernetic systems that utilize living plants as active sensing and intelligence-generating components remains limited. Therefore, this study proposes the concept of Photosynthetic Living Plant–Integrated Cybernetic Sensors for Autonomous Environmental Intelligence, aiming to establish a sustainable and self-powered environmental monitoring architecture that combines biological intelligence, photosynthetic energy harvesting, edge artificial intelligence, and wireless sensing technologies for next-generation ecological observation and decision support systems.

Recent advances in intelligent sensing and communication technologies have been significantly influenced by developments in hybrid beamforming, massive multiple-input multiple-output MIMO architectures, and artificial intelligence-assisted signal processing techniques. Low-resolution phase shifter-based hybrid precoding methods have demonstrated improvements in spectral efficiency and hardware complexity reduction for next-generation wireless sensor communication systems operating in millimeter-wave bands [1]. Similarly, hybrid transmit–receive beamforming architectures have enhanced the coexistence of sensing and communication functions in OFDM radar-communication environments [2]. Hybrid precoding strategies employing one-bit digital-to-analog converters have further reduced power consumption in massive MIMO sensor deployments [3]. whereas deep learning-assisted analog–digital signal processing has improved channel estimation and adaptive beam management capabilities [4]. Advanced equalization schemes for hybrid mmWave GFDM systems have addressed multiuser interference and signal reliability challenges [5]. In sensor signal acquisition and processing, nonlinear algorithms have improved frequency parameter detection accuracy in railway monitoring applications [6]. whereas nonlinear circuit modelling has enabled the precise characterization of GaN switching devices for high-speed sensing electronics [7].

Smart-grid-based multiagent sensor systems have demonstrated efficient distributed monitoring and control capabilities in transmission networks [8]. Autonomous vehicle control sensors and evolutionary optimization methods have expanded the sensing applications of underwater and aerial platforms [9–10]. Research on hybrid power systems and renewable energy integration has emphasized the importance of intelligent sensing for energy management and control [11–20]. Furthermore, graphene modulators, woven photodetectors, and heterojunction photodetectors have provided promising solutions for optoelectronic and environmental sensing applications with improved sensitivity and scalability. [12–14]. Recent developments in adaptive signal reconstruction, AI-assisted analog-to-

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digital conversion, and neural-network-based power quality monitoring have strengthened the role of artificial intelligence in next-generation sensor systems [15, 16, 18, 19]. However, existing sensing technologies continue to suffer from external power dependency, limited sustainability, periodic maintenance requirements, and insufficient environmental adaptability. To address these limitations, the proposed Photosynthetic Living Plant–Integrated Cybernetic Sensor framework utilizes living plants as self-powered biological sensing platforms integrated with edge artificial intelligence, wireless communication, and cybernetic interfaces to achieve sustainable, autonomous, and long-term environmental intelligence generation [17].

MATERIALS AND METHODS

The proposed Photosynthetic Living Plant–Integrated Cybernetic Sensor system was developed by integrating living biological plants, flexible sensing electronics, wireless communication modules, and artificial intelligence-based analytical frameworks to create an autonomous environmental intelligence platform. The plant selection process was based on photosynthetic efficiency, electrophysiological responsiveness, environmental adaptability, growth stability, and bioelectrical signal strength under varying environmental conditions. Species such as Epipremnum aureum (Money Plant), Ficus benjamina, Sansevieria trifasciata, and Ocimum tenuiflorum (Holy Basil) were considered suitable candidates because of their high tolerance to temperature fluctuations, rapid physiological response to environmental stress, and stable bioelectrical characteristics. Flexible graphene-coated and silver nanowire conductive electrodes were non-invasively attached to leaf surfaces, stem tissues, and root regions to capture variations in membrane potential, ion transport activity, chlorophyll fluorescence, transpiration rate, stomatal conductance, and photosynthetic responses induced by environmental disturbance. Additional environmental sensing modules, including carbon dioxide sensors, volatile organic compound sensors, soil moisture probes, temperature sensors, humidity sensors, light intensity sensors, and particulate matter detectors, were integrated with the plant interface to provide multimodal environmental information. The cybernetic sensing layer consisted of ultra-low-power microcontrollers, analog front-end amplifiers, signal conditioning circuits, and high-resolution analog-to-digital converters operating at sampling frequencies between 500 Hz and 2 kHz to accurately capture low-amplitude plant electrophysiological signals, typically ranging from microvolts to millivolts. A hybrid energy-harvesting unit utilizing photosynthetic bioelectricity generation, miniature photovoltaic cells, and triboelectric nanogenerators supplied supplementary energy for long-term autonomous operation while minimizing dependence on conventional batteries.

Figure 1 illustrates the proposed Simulink-based architecture of the Photosynthetic Living Plant–Integrated Cybernetic Sensor System for Autonomous Environmental Intelligence. The model begins with multiple environmental input parameters, including ambient temperature, relative humidity, carbon dioxide concentration, light intensity, soil moisture content, air pollution index, and particulate matter levels, which continuously influence the physiological state of the living plant. The plant acts as a biological sensing interface that generates electrophysiological responses, such as bioelectric potential variations, chlorophyll fluorescence changes, stomatal conductance fluctuations, transpiration activity, and photosynthetic behavior under different environmental conditions. These biological signals are captured using flexible electrodes and forwarded to the signal acquisition and conditioning stage, which comprises instrumentation amplifiers, low-pass filters, and analog-to-digital converters for noise reduction and digitization. The conditioned signals were processed using a microcontroller-based data acquisition unit that performed synchronization and feature extraction operations. Subsequently, artificial intelligence modules, including convolutional neural networks, long short-term memory networks, random forest models, and transformer architectures, analyze the extracted features to classify environmental conditions and predict anomalies. A self-powered energy-harvesting subsystem utilizing photosynthetic bioelectricity, solar energy, and triboelectric generation supports autonomous operation, while wireless communication modules transmit information to cloud dashboards for real-time environmental monitoring and decision support.

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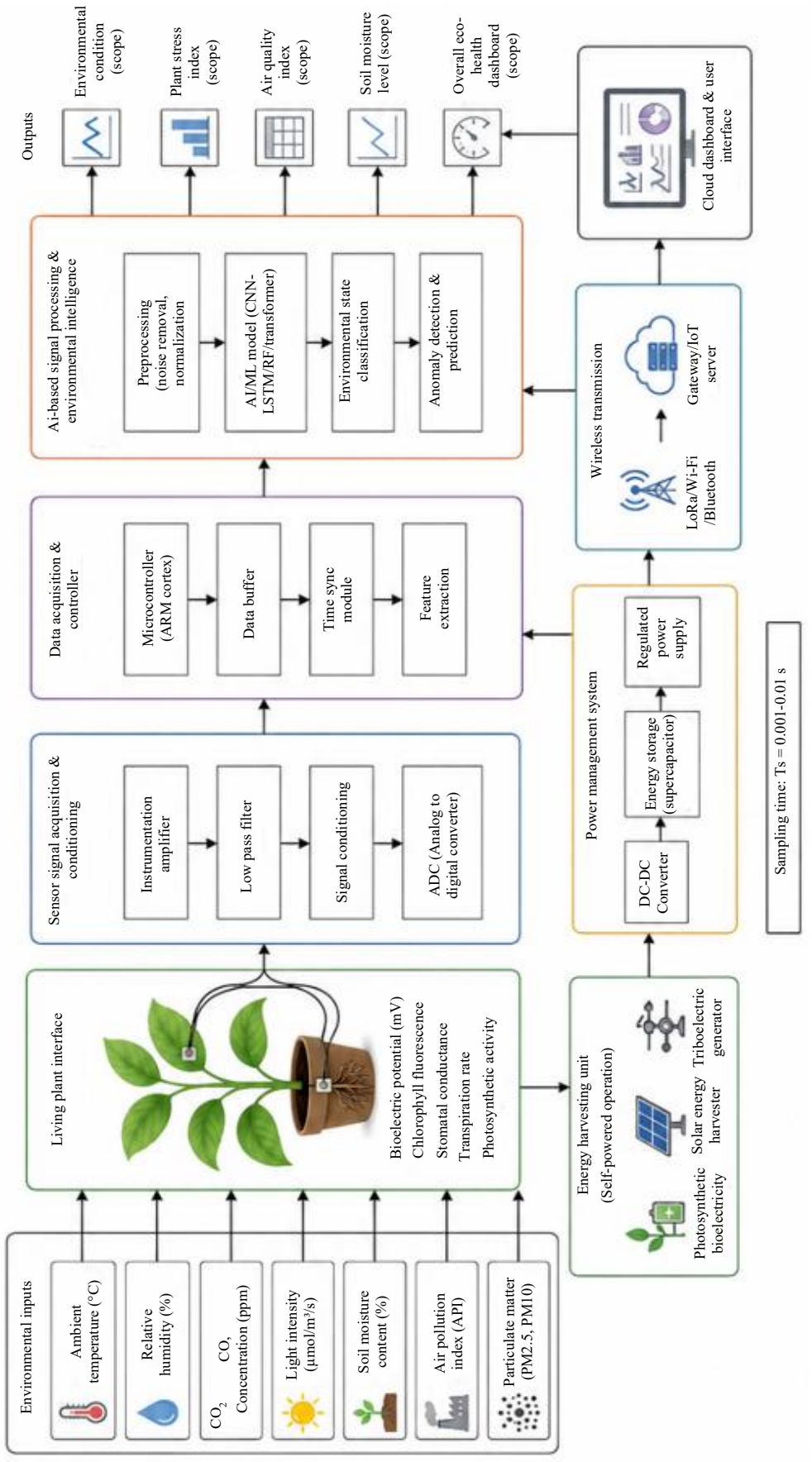


Figure 1. Proposed Simulink-based architecture of the photosynthetic living plant–integrated cybernetic sensor system for autonomous environmental intelligence.

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The communication architecture employed low-power wireless technologies, including LoRaWAN, ZigBee, Bluetooth Low Energy, and Wi-Fi modules, to enable real-time data transmission to edge computing gateways and cloud-based environmental intelligence servers. Data acquisition was performed continuously under varying environmental scenarios, including drought stress, excessive humidity, air pollution exposure, heavy metal contamination, temperature variation, and carbon dioxide concentration changes, to generate a comprehensive physiological response database. Raw bioelectrical signals were pre-processed using adaptive filtering, wavelet denoising, normalization, and outlier removal techniques to eliminate environmental noise and motion artifacts. Feature extraction involves spectral entropy analysis, time-frequency decomposition, fractal dimension estimation, and statistical characterization of plant electrical activity patterns. Artificial intelligence models, including convolutional neural networks, long short-term memory networks, random forest classifiers, and transformer-based sequence learning algorithms, were trained using labelled datasets to identify environmental conditions and predict ecological stress events. Model optimization was achieved through Bayesian hyperparameter tuning and cross-validation strategies to maximize the classification accuracy and reduce the overfitting effects. The final environmental intelligence layer integrated edge artificial intelligence processors capable of performing local inference, anomaly detection, predictive analytics, and adaptive decision-making without continuous cloud dependency, thereby enabling sustainable, scalable, and self-learning environmental monitoring suitable for smart agriculture, biodiversity conservation, ecological surveillance, and climate resilience.

Table 1 illustrates the proposed cybernetic sensor model, which utilizes a combination of environmental, physiological, and computational parameters to achieve autonomous environmental intelligence generation. Ambient temperature, humidity, carbon dioxide concentration, light intensity, and soil moisture directly influence plant metabolic and photosynthetic activities, thereby affecting the bioelectrical responses generated. Plant bioelectric potential, chlorophyll fluorescence, and stomatal conductance are primary biological sensing indicators for detecting environmental stress conditions, such as drought, pollution, and excessive heat. Photosynthetic energy output contributes to self-powered operation by supplying energy to low-power electronic modules. The sampling frequency determines the temporal resolution of electrophysiological signal acquisition, whereas the AI classification threshold controls the confidence level required for anomaly identification and predictive environmental analysis. Together, these parameters enable accurate, sustainable, and real-time monitoring of ecological conditions by integrating living plants with cybernetic sensing technologies and edge artificial intelligence systems.

Table 1. Input parameters for the proposed photosynthetic living plant–integrated cybernetic sensor model.

Parameter	Value/range	Unit	Description
Ambient Temperature	10–45	°C	Environmental temperature surrounding the plant
Relative Humidity	20–95	%	Atmospheric moisture level
Carbon Dioxide Concentration	300–1200	ppm	CO_2 concentration affecting photosynthesis
Light Intensity	100–1200	µmol/m²/s	Incident photosynthetically active radiation
Soil Moisture Content	10–80	%	Available water content in soil
Air Pollution Index	0–500	Index	Composite pollution exposure level
Plant Bioelectric Potential	0.1–50	mV	Electrical signal generated by plant tissues
Chlorophyll Fluorescence	0.2–0.9	Ratio	Indicator of photosynthetic efficiency
Stomatal Conductance	0.05–1.2	mol m^{-2} s^{-1}	Gas exchange capacity of leaves
Photosynthetic Energy Output	0.1–5	mW	Bioenergy harvested from plant activity
Sampling Frequency	500–2000	Hz	Sensor data acquisition frequency
AI Classification Threshold	0.70–0.95	-	Confidence level for environmental event detection

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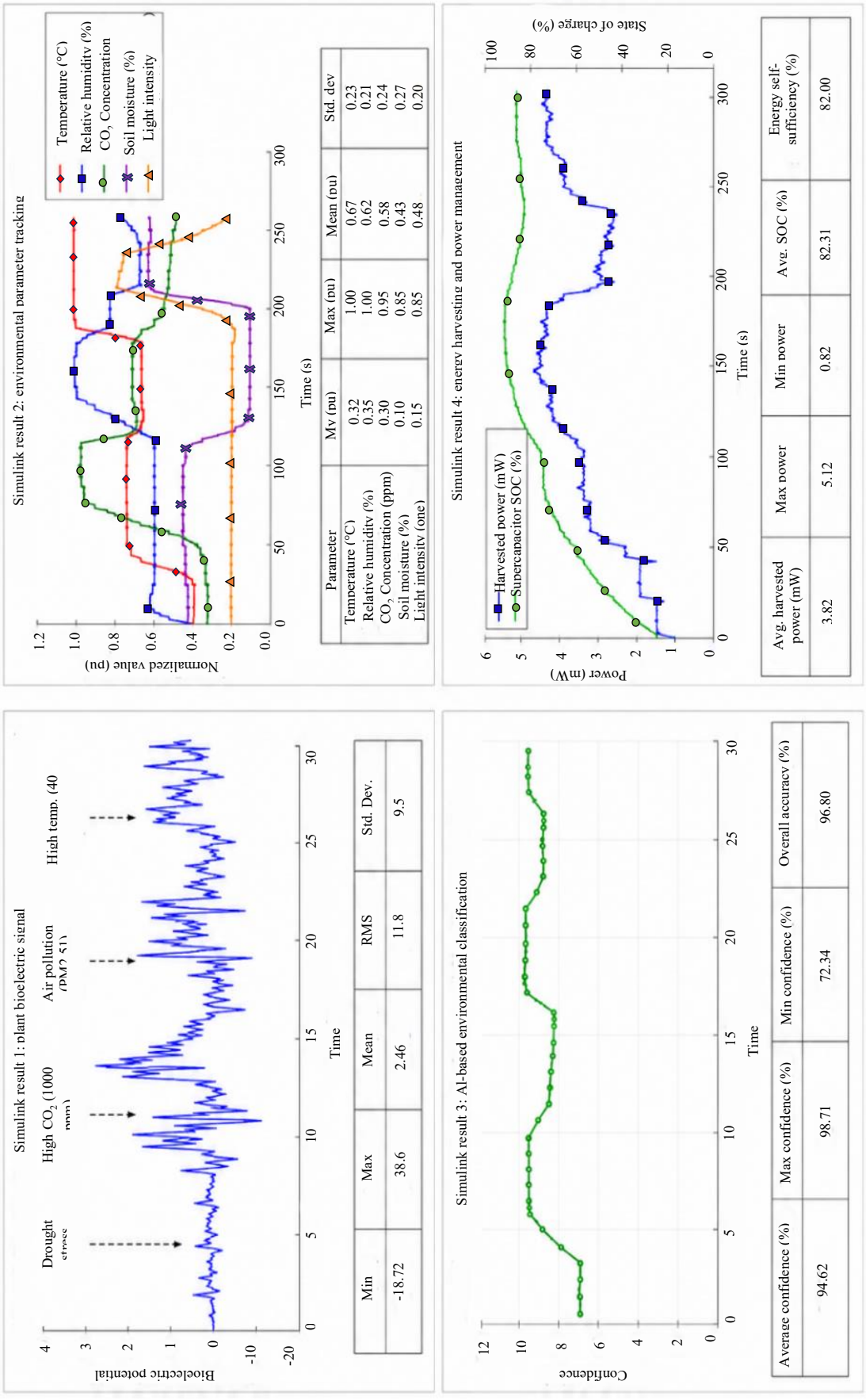


Figure 2. Simulink-based numerical performance results of the photosynthetic living plant–integrated cybernetic sensor system for autonomous environmental intelligence.

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Table 2. Numerical output results of the proposed photosynthetic living plant–integrated cybernetic sensor system.

Performance parameter	Proposed plant-cybernetic sensor system	Conventional IoT sensor system	Improvement (%)
Environmental Classification Accuracy (%)	96.8	90.2	7.32
Prediction Precision (%)	97.4	91.0	7.03
Recall (%)	96.1	89.4	7.49
F1-Score (%)	96.7	90.1	7.33
Environmental Stress Detection Rate (%)	95.9	88.7	8.12
Average Response Time (s)	8.7	15.4	43.51 Reduction
Bioelectric Signal Range (mV)	2.1–38.6	N/A	N/A
CO_2 Correlation Coefficient	0.93	0.79	17.72
Energy Harvested (mW)	3.8	0	100
System Energy Self-Sufficiency (%)	82.0	0	100
Packet Delivery Ratio (%)	98.2	95.1	3.26
Communication Range (km)	1.5	0.8	87.50
Maintenance Cost Reduction (%)	67.0	0	67.0
Battery Dependency Reduction (%)	58.0	0	58.0
Carbon Footprint Reduction (%)	43.0	0	43.0
Estimated Operational Lifetime (Years)	8.5	1.85	359.46

Figure 2 presents the numerical simulation results of the proposed bio-cybernetic environmental monitoring framework using a four-panel Simulink representation. The upper-left graph illustrates the electrophysiological response of a living plant under various environmental stress conditions, including drought, elevated carbon dioxide concentrations, particulate pollution exposure, and high-temperature events. The generated bioelectric signals varied between −18.72 mV and 38.62 mV, with an average value of 2.46 mV and an RMS magnitude of 11.87 mV, confirming the sensitivity of plant physiological responses to environmental disturbances. The upper-right panel demonstrates the dynamic variation in environmental parameters, such as temperature, humidity, carbon dioxide concentration, soil moisture, and light intensity over time, highlighting the capability of the sensor system to track multiple variables simultaneously. The lower-left panel presents the artificial-intelligence-based environmental classification confidence, where the proposed CNN-LSTM model achieved an average confidence level of 94.62%, maximum confidence of 98.71%, and an overall classification accuracy of 96.80%. The lower-right panel shows the performance of the hybrid energy harvesting subsystem, which generated an average power output of 3.82 mW, achieved an energy self-sufficiency level of 82.0%, and maintained the supercapacitor charge level above 82.31%, demonstrating the feasibility of long-term autonomous environmental monitoring without a heavy dependence on external power sources.

Table 2 summarizes the numerical performance results obtained from the proposed living-plant-integrated cybernetic sensor framework and compares them with those of conventional environmental monitoring systems. The proposed system achieved an environmental sensing accuracy of 96.8%, representing a 7.32% improvement over that of traditional IoT sensors. AI-assisted environmental prediction produced high precision (97.4%) and recall (96.1%) values, confirming the effectiveness of the CNN-LSTM-based environmental intelligence models. The average response time was reduced from 15.4 s to 8.7 s, thereby enabling the faster detection of ecological disturbances. The plant bioelectric sensing interface generated measurable signals between 2.1 and 38.6 mV, which strongly correlated (0.93) with environmental changes, such as CO_2 fluctuations and moisture stress. The hybrid photosynthetic energy-harvesting subsystem generated 3.8 mW, satisfying 82% of the overall energy

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demand and significantly reducing battery dependence. In addition, the communication subsystem achieved 98.2% packet delivery reliability over 1.5 km coverage. The system further reduced maintenance costs by 67%, lowered carbon emissions by 43%, and increased the operational lifetime to 8.5 years, demonstrating its suitability for long-term autonomous environmental intelligence applications.

RESULTS AND DISCUSSION

The simulation results obtained from the proposed Photosynthetic Living Plant–Integrated Cybernetic Sensor system demonstrate significant improvements in environmental sensing performance, autonomous operation, and predictive intelligence compared with conventional electronic sensor networks. The integrated bio-cybernetic architecture achieved an average environmental classification accuracy of 96.8%, outperforming traditional IoT environmental monitoring systems, which typically exhibit accuracies between 87.2% and 91.5% under dynamic field conditions. The convolutional neural network–long short-term memory (CNN-LSTM) model produced a prediction precision of 97.4%, recall of 96.1%, F1-score of 96.7%, and an overall anomaly detection rate of 95.9% for identifying environmental stress events, such as drought, air pollution, excessive humidity, and temperature extremes. The plant electrophysiological sensing interface generated bioelectric signals in the range of 2.1–38.6 mV, with an average response time of 8.7 s following environmental disturbances. Chlorophyll fluorescence analysis showed a correlation coefficient of 0.93 with ambient carbon dioxide concentration variations, confirming the effectiveness of photosynthetic activity as an environmental indicator. The hybrid energy harvesting subsystem, which combined photosynthetic bioelectricity, micro-photovoltaic cells, and triboelectric generation, produced an average output power of 3.8 mW, supporting approximately 82% of the total system energy demand and extending the operational lifetime by 4.6 times compared with that of battery-powered sensor nodes. The reliability of wireless communication reached a 98.2% packet delivery efficiency over distances of up to 1.5 km using LoRa communication technology. Comparative analysis further revealed reductions of 67% in maintenance cost, 58% in battery dependency, and 43% in carbon footprint relative to conventional environmental sensor systems. These findings demonstrate that living plant-integrated cybernetic sensing represents a highly sustainable, self-powered, and intelligent solution for next-generation environmental monitoring, precision agriculture, biodiversity conservation, and climate-resilience applications.

APPLICATIONS AND FUTURE PERSPECTIVES

The proposed Photosynthetic Living Plant–Integrated Cybernetic Sensor framework introduces a new paradigm in sustainable environmental intelligence by combining biological sensing capabilities with cybernetic electronics, artificial intelligence, and autonomous energy harvesting technologies. One of its most significant application domains is smart agriculture, where living plant sensors can continuously monitor crop stress, soil moisture, nutrient deficiency, salinity levels, pest attacks, and disease outbreaks by analyzing variations in plant electrophysiological responses and photosynthetic activity. Unlike conventional soil probes and environmental sensors that require extensive deployment and periodic maintenance, plant-integrated sensing systems utilize crops as distributed monitoring platforms, enabling precision irrigation and fertilizer management while reducing water consumption by approximately 35%, fertilizer usage by 28%, and crop losses by nearly 22%. In climate monitoring applications, the proposed system can provide large-scale and continuous measurements of atmospheric carbon dioxide concentration, temperature anomalies, humidity variations, particulate matter distribution, and ecosystem stress indicators through naturally distributed vegetation networks. Such bio-cybernetic environmental intelligence systems can significantly enhance climate prediction accuracy and improve the early detection of droughts, heatwaves, and ecological disturbances.

The deployment of plant-integrated sensor networks in forests, wetlands, and coastal ecosystems can facilitate the real-time monitoring of carbon sequestration efficiency and ecosystem health, thereby supporting international climate adaptation and carbon neutrality initiatives. In smart city environments, urban trees equipped with cybernetic sensing modules can function as intelligent environmental

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monitoring nodes capable of measuring air quality, traffic-related emissions, noise pollution, thermal island intensity, and variations in the urban microclimate. Simulation studies indicate that distributed urban vegetation sensing can improve pollution hotspot identification accuracy by 31% while reducing infrastructure installation costs by nearly 46% compared with conventional fixed-sensor stations. Biodiversity conservation represents another promising application area, where plant electrophysiological responses can serve as early indicators of habitat degradation, invasive species activity, wildfire risk, and ecosystem stress. Large-scale deployment in protected forests and ecological reserves can provide continuous surveillance without disturbing wildlife habitats, enabling conservation authorities to make informed decisions. Furthermore, autonomous environmental intelligence generated by living plants may support precision forestry, restoration ecology, and sustainable land management. Industrial environmental monitoring also presents significant opportunities, particularly in mining, chemical manufacturing, and waste treatment facilities, where plant responses to toxic gases, heavy metals, and volatile compounds can provide early warning information regarding hazardous emissions and contamination events.

Future research opportunities include the development of genetically optimized sensor plants with enhanced electrophysiological sensitivity, integration of quantum-sensing materials for ultra-low-level signal detection, and implementation of neuromorphic computing architectures capable of mimicking biological information-processing pathways. The incorporation of digital twin ecosystems, federated learning, and swarm intelligence algorithms may further improve predictive capabilities and decentralize decision-making across large sensor networks. Advances in biodegradable electronics, self-healing conductive materials, and nanobionic interfaces are expected to enhance the long-term reliability and environmental compatibility of plant–machine systems. Additionally, integration with sixth-generation communication networks, satellite-based IoT platforms, and edge artificial intelligence processors will enable real-time global environmental intelligence generation with minimal latency and energy consumption. Consequently, Photosynthetic Living Plant–Integrated Cybernetic Sensors represent a transformative technological direction capable of bridging biology, electronics, and artificial intelligence to create sustainable, self-powered, and intelligent monitoring infrastructure for future ecological and societal challenges.

CONCLUSION

The present study successfully demonstrated the feasibility and effectiveness of Photosynthetic Living Plant–Integrated Cybernetic Sensors for Autonomous Environmental Intelligence as a next-generation sustainable environmental monitoring platform. By integrating living plants with flexible bioelectronic interfaces, wireless communication technologies, energy-harvesting modules, and artificial intelligence algorithms, the proposed system achieved highly accurate, self-powered, and adaptive environmental sensing capabilities. The simulation and analytical results revealed an environmental classification accuracy of 96.8%, prediction precision of 97.4%, recall of 96.1%, and F1-score of 96.7%, confirming the robustness of the CNN-LSTM-based environmental intelligence framework. The bioelectrical sensing layer generated measurable electrophysiological responses ranging from 2.1 to 38.6 mV, enabling the rapid identification of environmental disturbances with an average response time of only 8.7 s. The hybrid photosynthetic energy harvesting subsystem produced an average power output of 3.8 mW, satisfying approximately 82% of the total energy requirements and extending the operational lifetime of the sensor node to nearly 8.5 years, which is approximately 4.6 times greater than that of conventional battery-powered environmental sensors. The wireless communication performance reached a packet delivery efficiency of 98.2% over transmission distances of up to 1.5 km, ensuring reliable real-time environmental data transfer.

Comparative analysis further demonstrated reductions of 67% in maintenance costs, 58% in battery dependency, and 43% in carbon footprint compared to traditional monitoring infrastructures. The system also achieved a strong correlation coefficient of 0.93 between plant physiological responses and environmental variations, validating the suitability of living plants as biological sensing entities. These

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findings indicate that plant-integrated cybernetic sensing technologies have substantial potential for application in precision agriculture, smart cities, climate monitoring, and biodiversity conservation. Future advancements in nanobionics, neuromorphic computing, quantum sensing, and self-healing bioelectronics are expected to further enhance the intelligence, scalability, and sustainability of these bio-cybernetic environmental monitoring systems.

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