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Research Article

An optimized routing protocol for energy-efficient data transmission in agricultural environments using WSN-based IoT networks

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Abstract
Wireless sensor networks (WSNs) play a critical role in numerous domains such as agriculture, healthcare, and industry, with a particular emphasis on agricultural applications, where they enhance precision farming (PF). These networks employ internet of things (IoT) technology to efficiently monitor environmental conditions, track crop health, and manage irrigation systems, ultimately boosting agricultural productivity. However, challenges such as limited processing capabilities, memory, energy, and communication bandwidth can negatively impact performance. Security concerns also persist, as agricultural IoT devices must be protected against potential cyber threats. An IoT-based WSN architecture was implemented in this study specifically designed for smart agriculture (SA), featuring two main components: an energy-efficient routing protocol and a secure clustering protocol named the optimized secure clustering-based routing protocol (OSCBRP). The OSCBRP facilitates secure data transmission between nodes by employing trusted keys and the data encryption standard (DES) algorithm, noted for its low memory and processing demands. This hierarchical system prioritizes nodes based on their residual energy, allowing more capable nodes to handle intensive tasks. Significant improvements in network performance have been recorded, with the new architecture achieving a 98% increase in throughput, a 34% packet drop rate, and a latency of 0.002 seconds, while consuming only 0.2 joules of energy and maintaining a 15% routing overhead. These enhancements are substantial when compared to other existing methods, showcasing the potential of the implemented system to revolutionize data routing in agricultural settings. The OSCBRP not only ensures energy efficiency but also guarantees secure, optimized communication from sensor nodes to base stations (BS), establishing a robust framework for intelligent agriculture. This system effectively manages energy distribution and operational load, leading to a marked improvement in packet delivery rate (PDR) and overall network efficiency in smart agricultural applications.

Keywords
Wireless sensor network, Smart agriculture, Data encryption standard, Residual energy, Optimized secure clustering-based routing protocol.

1.Introduction
Wireless Sensor Network (WSN) technology has been effectively utilized to enhance network performance across various fields [1]. A primary focus is on deploying multiple sensors in the ecological domain due to their simple configuration and ease of management [2]. Typically, sensor nodes operate independently, forming a network setup in an ad hoc manner. In this configuration, sensor nodes do not rely on a fixed network structure; instead, they connect with the nearest reliable node for data transmission based on shared features.

The sensor nodes gather information and transmit it to the base station (BS) via cluster heads (CHs) and gateways. These CHs play a crucial role in aggregating data from received data packets (DPs) and relaying it to the BS. The CHs efficiently establish either single-hop or multi-hop routes to the BS [3].

However, CHs also store the data in their memory for further processing. The central BS efficiently collects and distributes data through the internet; ensuring end-users have access to necessary information and acting as a hub for efficient data collection and distribution [4]. The deployed sensor nodes used

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during data broadcasts may be mobile or static [5]. The static sensor nodes mentioned as non-adaptive, and their built-in routing charts are secure. However, the routing concepts of moveable sensor nodes are frequent and dynamic when any modifications are defined in the network topology. Stationary routing results are defined as more confident when associated with vigorous routing [6]. In contrast, the results that depend on static methods are unreliable for vast areas and network scalability. In recent years, the integration of internet of things (IoT) technology with various domains has increased, enhancing communication in areas such as resource utilization (RU), load distribution (LD), and network throughput [7, 8].

In IoT, numerous physical objects are connected to facilitate data exchange over the internet. Additionally, WSNs provide the foundation for IoT systems, supporting the monitoring and transmission of environmental conditions [9–11]. In a smart agriculture (SA) scenario, sensors, BS, the internet, end-users, and sink nodes are involved [12].

Globally, the internet has evolved in tandem with technological advancements. The IoT has emerged as a significant area of growth, representing a vast interconnected network of devices that facilitates communication between individuals and enables data sharing across extensive networks [13]. The business and information technology (IT) perspectives on IoT highlight its potential for efficiency, cost savings, and innovation. It highlights the technical aspects of data collection and analysis. It allows a perception to create and transform IT procedures and business models according to further needs [14].

Agriculture, accounting for 17–18% of India's gross domestic product (GDP), is the primary income source for 50% of the population [15]. It significantly affects the livelihoods of millions of people. Worldwide, India holds the 5th position for its agriculture results, exports, and consumption. India's food processing area attracted USD 628.24 million in foreign direct investment (FDI) from 2018 to 2019 to increase farm income by 2022. By 2022, India’s agriculture exports are probably going to surpass the USD 60 billion mark [16]. It is anticipated that high momentum is expected in the coming years due to increased investment in cold storage, warehousing, and irrigation in the farming or agriculture sector [17]. Rajasthan is the third-biggest manufacturer of cereals and soybeans in India. The agricultural sector in Rajasthan has various challenges and limitations, including an arid environment, drought, famine, etc., and poverty among farmers [18].

IoT devices capture data from the agriculture domain, which is then transferred from machine to machine (M2M), person to person (P2P), and machine to person (M2P) [19]. Several applications, such as remote sensing (RS), automated irrigation (AI), and unnamed aerial vehicles (UAVs), are included and driven by IoT. The data generated by these IoT strategies are communicated to the farmer’s mobile devices, providing real-time notifications.

In the existing work, wireless agriculture sensors (WASs) were distributed in the farming land to remove dissimilar social composition data, like moisture levels, temperature, humidity, and water-level detectors. The existing data was securely communicated to the CHs that work as memory buffers to data communicate to the BS. After securing the data, the BS can supply users with recent data, enabling effective decision-making in less time [20]. The existing architecture provides reliable routing for automated farming innovations; however, there are still issues with high energy consumption, data losses, and minimum network lifetime when the protocol transmits data without any optimization. The research uses the optimized secure clustering-based routing protocol (OSCBRP) approach to resolve the existing issues, reducing farmers’ workload and enhancing productivity and land monitoring through secure and intelligent data routing.

Among the challenges mentioned, water scarcity [6] is the most significant. Farmers struggle with managing crop cycles due to the lack of water, necessitating organized and scheduled management through technological tools to address this issue. IoT architecture in agriculture presents a promising solution to water crises, shifting the focus of IT from statistical to quantitative methods [21]. Wireless sensors have become essential in SA, enabling a more precise, data-driven approach to agricultural IT [22]. Numerous applications in SA include communication infrastructure, user interfacing, agricultural operation automation, and intelligent decision-making [23, 24]. Several articles have surveyed this field, primarily outlining its main prospects and limitations [25, 26]. Recent research highlights several main problems, which need to be addressed to significantly enhance the field's effectiveness.

The rapid advancement and integration of IoT technologies have introduced new confidentiality and security risks within SA systems, with potential threats including network failures and hacking risks which could compromise the integrity and security of farming data [20]. Additionally, the consistency and scalability of IoT systems are crucial as they require robust data processing capabilities to support decision-making, demanding a large network of sensor nodes and scalable infrastructure to manage extensive workloads [27]. Furthermore, physical factors like climatic conditions pose significant risks that can impede the progress of SA, with some threats being persistent historical issues and others newly emerging from the swift technological advancements [12]. These challenges collectively indicate the need for improved security measures, scalable architectures, and resilience against environmental factors in SA frameworks.

This research aims to utilize an IoT-based sensor framework to collect and transmit data from various environments, ensuring effective outcomes for business services. The proposed method or protocol focuses on enhancing optimization, energy efficiency, and secure clustering-based techniques for IoT-enabled WSNs in agricultural land production and monitoring. The proposed model has implemented a protocol with CHs selected based on the optimized solution with the help of fitness or objective function. The implemented protocol provides dependable and effective methods for the improvement of huge agricultural land. It has collected data safely between agriculture sensor nodes and CHs and from CHs to BS based on optimized and trusted keys that required the smallest end-to-end delay (E2D) or time and memory. The implemented OSCBRP method is an enhanced version of an approach based on the IoT network concept. It utilizes an improved routing strategy between network nodes to achieve a higher packet delivery rate (PDR).

The research objectives of this article are as under:

(i) To study and analyze the various routing protocols used for the IoT network in the agriculture environment.

(ii)To design and implement an energy-efficient solution using an optimized routing protocol for optimal path selection, reduced delay, improved network utilization, and overall enhancement of IoT network performance.

(iii)To compare the performance with existing protocols.

The contribution of the research work includes several key phases: deployment and assignment, the routing process, implementation of the proposed secure and optimized model, evaluation of network parameters, and comparison with existing methods. The initial deployment phase involves configuring and allocating various network parameters to the nodes. Key parameters include initial energy, coverage distance, data transmission, sensing parameters, and others. With the help of these parameters, a node can sense and transmit data in the WSN. Secondly, the routing protocols step is the network that is answerable for the broadcast of sensed data from the network node. The routing protocols manage the load on the network and route the packet with limited resources to the BS with a high accuracy rate. The third phase is implementing the secure and optimization module of the proposed approach. The security-based approach, utilizing the data encryption standard (DES) along with a particle swarm optimization (PSO) algorithm, enhances the computation and selection process of the proposed routing technique. It provides optimized solutions to routing problems and helps to select the best one. The last phase calculates the performance parameters and compares them with the previous methods. It shows the productivity of the implemented algorithm and enhancements in the existing modules.

This article is organized into several sections: Section 2 presents the literature review. The proposed methods and framework are covered in Section 3. Section 4 details the experimental setup, result analysis, performance metrics, and limitations of the findings. The conclusion and future work in this area are discussed in Section 5.

2.Literature review

This section explores a summary of existing routing protocols used in IoT-based WSNs within the context of SA. WSN technology has gained significant development across various domains due to its profitability and simplicities of implementation, among other factors [28]. In a WSN, maximum sensor nodes are strategically deployed across the area to collect and transmit the necessary information. All collected information is then relayed to the BS via a multi-hop data broadcast model for further analysis. In recent years, the SA sector has played an essential role in improving the economic growth of nations. Therefore, it is essential to infuse the SF domain with innovative technologies like IoT-based WSN to optimize human efforts, save time, and maximize agricultural network throughput effectively. In the realm of SA, various metrics like moisture levels, temperature conditions, and soil characteristics are monitored and defined. Researchers have increasingly leveraged WSN technology in the SA sector to enhance network performance and alleviate the burden on farmers [29]. In their study, Haseeb et al. (2020) [30] implemented an IoT-based WSN architecture as a sensor aggregator (SeA), comprising various design phases. Initially, agricultural sensor nodes considered reliable information and selected a set of CHs using a multi-criteria decision method. The signal strength of data transmission was generally calculated using signal-to-noise ratio (SNR) to attain effective data transmission. Lastly, data broadcast from agricultural sensor nodes to the BS was secured using a linear congruential generator (LCG) for frequency hopping. Experimental results demonstrated that the implemented method improved network communication performance metrics, including a 13.5 % increase in network throughput, a 38.5 % decrease in data packet drop (DPD), a 13.5 % reduction in latency, a 16 % decrease in EC, and a 26 %reduction in routing overhead (RO) for the SA compared to other methods. Awan et al. (2020) [31], presented a well-organized routing method that combines IoT with blockchain (BC) technology for allocated nodes. This approach was designed to efficiently utilize the transmission connections. The proposed solution employed smart contracts in heterogeneous IoT systems to establish paths to BS. Each node ensures a reliable route from the IoT sensor nodes to the destination and then to the BS, enabling IoT devices to collaborate during data transfer. The suggested routing protocols effectively filtered out unnecessary data and mitigated IoT-related security threats, resulting in reduced power consumption (PC) and improved network longevity. To calculate the efficiency of this approach, the authors compared it with the current IoT-based farming method and the low-energy adaptive clustering hierarchical (LEACH) protocol in farming. The protocol's outcomes demonstrated that integrating IoT with BC technology led to a more organized system that consumed less energy, increased output, and extended the network's lifespan. Farooq et al. (2020) [32] presented a complete summary of skills encompassing the field of IoT in agriculture. This study elucidated the crucial mechanisms of IoT-based SA. It conducted a difficult examination of network technologies employed in IoT-based data storage (DS) farming, encompassing network planning, layers, and procedures. Also, it explored the integration of IoT-based farming structures with appropriate skills, including cloud computing (CC), large-scale DS, and problem-solving capabilities. Additionally, the study emphasized security problems in IoT agriculture. It provided a list of smartphone-based and sensor-based uses developed for various aspects of agricultural management. Finally, the study showcased regulations and strategies enacted by different countries to govern IoT-based farming, accompanied by success stories from the field. Kumar and Reddy (2020) [33] proposed a simulation-based task, while others provided a comprehensive explanation of the entire plan, progress, and operation of WSN. To plan and implement a cost-effective WSN for agricultural use, a deep understanding of device perspectives, sensor node design, wireless mechanisms, operating system (OS) for sensor nodes, routing protocols, DP formats, data association methods, and implementation procedures were required. The study also addressed various challenges faced by end-users during the establishment and deployment of WSNs. In a separate work, Khanna and Kaur (2020) [34], discussed various aspects of IoT, including its technology, applications, and associated issues. They conducted a thorough assessment of different articles by analysts in various application domains and frameworks, emphasizing prevalent issues. Multiple parameters were identified to evaluate how specific issues were addressed. García et al. (2020) [35], emphasized the critical importance of water resource management in nations facing water shortages, particularly its profound impact on agriculture, which consumes a significant portion of available water. The potential consequences of global warming (GW) have spurred discussions on adopting water conservation measures to ensure water availability for crop productivity and utilization. Consequently, there has been a developing body of work addressing the need to reduce water usage in irrigation practices in recent years. Navarro et al. (2020) [36] implemented the integration of SF techniques with the IoT to address contemporary food production challenges. They employed the preferred reporting items for systematic reviews (PRISMA) framework to comprehensively evaluate the current works on SF and IoT. The research explored key tools, policies, network methods, data preparation skills, and the application of SF in conjunction with IoT in agriculture. While traditional methods were mainly reactive, recent technological advancements have enabled the proactive utilization of information to mitigate food-related issues and enhance crop diagnosis accuracy. Gupta and Singh (2023) [37] described the development of precision agriculture worldwide, highlighting its role in enhancing agriculture and productivity through the use of WSN. The primary objective was to monitor and assess how multiple WSNs functioned and transferred data to an integrated server. They devised an energy-efficient solution for the WSN routing protocol and employed sensor nodes for soil identification. They aimed to enhance the performance of the implemented WSN routing protocols by evaluating various performance metrics, including latency, throughput or an optimal path, and network lifespan. To achieve this goal, they conducted comparisons among several types of routing protocols. Uppalapati (2020) [38] discussed the extensive applications of WSN, widely used for data collection, particularly in development tasks. Managing the energy-efficient operation of routing protocols in sensor nodes posed a significant challenge and was critical for sensor performance. To address this challenge, the authors introduced an energy efficiency, time-scheduling-based clustering protocol using PSO and unequal fault tolerance (FT). This protocol selected efficient CHs based on distance parameters. The routine of the implemented protocol demonstrated significant improvements compared to current techniques. Hassan et al. (2024) [39] presented a novel approach based on the Levenberg Marquardt optimization algorithm in WSN-based SA systems. The implemented model utilized range measurements and reduced error. The proposed method effectively estimates unknown sensor node positions, demonstrating robustness and scalability across various network scenarios, even with an increase in unknown node numbers. The proposed localization algorithm outperformed other algorithms by 58% in estimation accuracy, despite a slight accuracy reduction, demonstrating its practical viability and robustness. Chandrasekaran and Rajasekaran et al. (2024) [40] described sensor data processing and communication challenges with clustering. They select the appropriate CH and optimize data transmission paths to improve IoT system performance. So, the authors developed a method by using the whale optimization algorithm (WOA) and enhanced crow swarm optimization (ECSO) methods. They optimize data transmission in SA setups and outperform existing methods in terms of various parameters. The proposed agriculture system improved crop yield and profitability for farmers and simulation experiments show superior performance parameters. Roa et al. (2022) [41] described IoT systems in agriculture to provide efficiency. The authors reviewed SA techniques and their basic architecture, focusing on wireless IoT-based systems, allowing for simpler implementation in various circumstances. They discussed various techniques for wireless IoT-based agriculture systems, emphasizing the crucial role of routing protocols in WSNs. Rengarajan et al. (2023) [42] described WSNs are being utilized in agriculture, manufacturing, and smart health for efficient yield detection and automation, despite limited resources for handling large data sets. So, the authors developed a WSN structure for SA and addressed limitations in resources for handling large quantities of data collected by sensors in rural regions. They introduced an IoT-based WSN structure for SA and also focused on security. The SA model has significantly improved the performance using a direct congruential generator. Agarwal et al. (2023) [43] described precision agriculture, the IoT and WSN used for monitoring crop fields and making quick decisions, despite their limited energy usage. The authors discussed the use of IoT and WSN technologies in smart precision agriculture, emphasizing energy efficient processes, location-aware sensors, and techniques for agricultural issues. Identifying pests, water shortages, and leaf diseases can provide effective solutions by focusing on pest identification, soil and water conservation, and other problems. Arduino and sensors were integrated into IoT and WSN to automatically solve problems and achieve energy conservation through efficient programs. Shukre et al. (2024) [44] developed an energy efficient IoT-based SF approach, k-means clustering (KMC), and adaptive mud ring optimization. They deployed for cluster formation and optimal path optimization. The collected data is stored in cloud storage and accessed via a hybrid artificial neural network (HANN) using Google Net for disease prediction. Network simulator-2 software is used for performance validation, comparing results with current research. The proposed approach enhances agricultural productivity by efficiently managing resources and predicting crop diseases. The presentation of the planned model outperforms other techniques by analyzing different parameters. Huo et al. (2024) [45] described IoT-based SF that has grown rapidly. Numerous studies have provided a comprehensive introduction to the research domain. It focuses on architectures, devices, and communication technologies. The authors reviewed the scientific mapping to visualize IoT SF research. They identified citation networks and tracked interest evolution. Saha et al. (2024) [46] described the IoT revolution has revolutionized agriculture by providing advanced solutions for crop monitoring and management. They included a SA IoT system for actual moisture and temperature monitoring. The major motive of the proposed model was to develop an IoT system to monitor temperature and moisture levels in agricultural fields. They enabled smarter crop management decisions and demonstrated that an IoT-based system enhancement proposed ensured food security amid changing climatic conditions and increasing population demands due to IoT advancements.

Numerous studies have demonstrated the effectiveness of IoT-based WSNs in SA, though some challenges and limitations persist. A key issue is the energy efficiency of sensor nodes and their ability to maintain performance over extended periods. While optimization techniques have been developed to reduce energy consumption, ensuring consistent long-term operation remains challenging due to resource constraints in rural areas. Another major challenge is ensuring security and data integrity, as IoT systems collect vast amounts of agricultural data, making them susceptible to unauthorized access and data breaches. BC based routing offers a potential solution, but its adoption is limited by the complexity of integrating smart contracts across diverse networks.

Additionally, poor connectivity in remote agricultural areas often disrupts reliable data transmission, impacting the network's overall stability and performance. Our research addresses these issues through the implementation of the OSCBRP protocol. This approach minimizes unnecessary data transmissions by selecting the most efficient transmission paths. It also enhances network security through secure clustering, employing encryption and verification mechanisms to safeguard against unauthorized access and prevent attacks like man-in-the-middle. Furthermore, the protocol extends the lifespan of sensor nodes and reduces maintenance requirements, thereby improving the system's overall reliability and sustainability.

3.Methods

This section discusses the planned energy-efficient data transmission protocols for IoT-based WSNs in SA. It elaborates on the optimized and secure data transmission from farming sensor nodes to the BS, as well as the existing energy and link-efficient protocols.

3.1Optimized secure clustering–based routing protocol (OSCBRP)

The main objective is to design an optimized, energy-efficient, and secure IoT-based WSN infrastructure to improve agricultural land management. The implemented protocol facilitates secure data transmission between agricultural sensors and CHs, as well as from CHs to the BS, using trusted secret keys and the DES method.

The proposed research methodology is outlined below, highlighting the key features and components of the study:

(i) Initially, agricultural sensor nodes are deployed to collect DPs. These sensor nodes are organized hierarchically based on their residual energy levels, with hierarchical nodes having higher energy levels than regular sensor nodes. The agricultural sensor nodes are distributed across various remote fields, with each domain assigned one CH. The primary role of the CH is to collect data from the agricultural fields and efficiently communicate it to the BS. This research focuses on optimizing energy usage and managing data loads among agricultural sensor nodes, selecting reliable CHs using greedy algorithm (GA).

(ii) Next, the study addresses security measures by implementing symmetric DES encryption among sensor nodes and ensuring secure data broadcasting within the network using pseudorandom number generation. As illustrated in *Figure 1*, the proposed strategy for SA involves the CH initiating communication by distributing DPs to all agricultural sensor nodes. The BS generates a set of optimized trusted keys using the PSO method based on the DES algorithm. These optimized secret keys are then transmitted to the agricultural sensor nodes. Subsequently, an XOR operation is performed on the DPs from agricultural sensor nodes to CHs, followed by encrypted data transmission to the BS. This approach enhances network performance across various metrics.

The DES is a type of cryptographic algorithm designed for securing numerically coded information, commonly used for password-protecting computer data [47]. The complexity in correlating the mathematical properties of the ciphertext with the key value makes it difficult for cryptanalysts to deduce the relationship between the key, plaintext, and ciphertext. *Figure 2* illustrates the DES method, which begins by encrypting plaintext into 64-bit data blocks. These blocks are then divided into left and right 32-bit segments through an initial permutation process. The PSO algorithm is employed to enhance these calculations by providing optimized solutions to routing problems and assisting in the assortment of the most suitable routes for achieving maximum

network performance. In the PSO method, potential solutions are represented by particles, with their performance evaluated using a fitness function.
Based on this evaluation, global and local optimized solutions are selected to update the particle positions throughout each repetition. After, several repetitions, the particles converge toward the best solution within the search space. The flowchart of the PSO method is shown in *Figure 3* [18, 48].

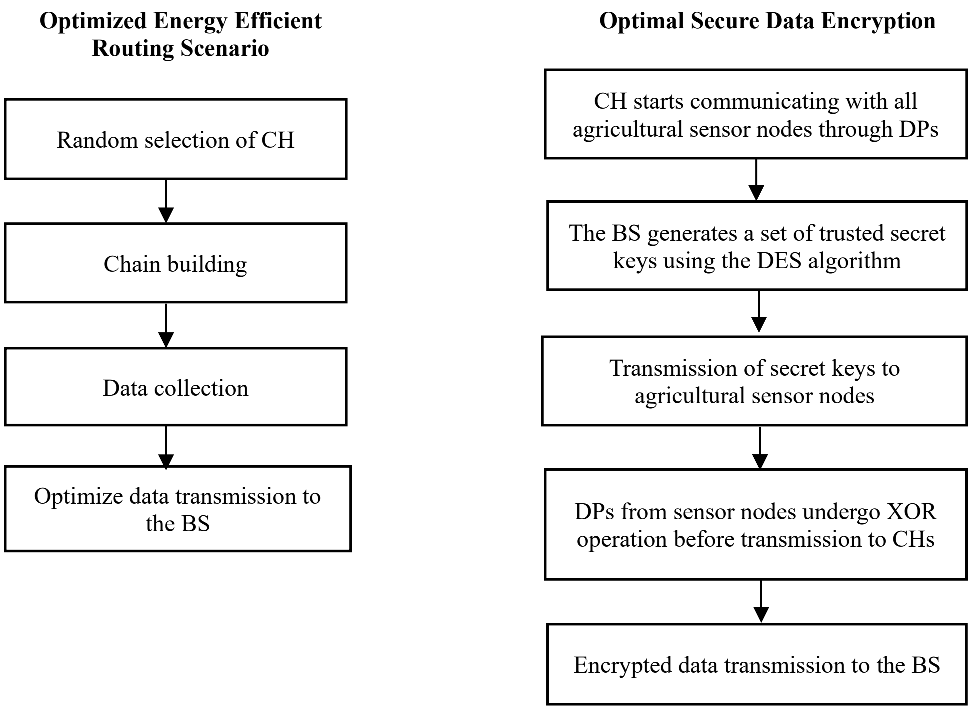

Figure 1 The design of the proposed OSCBRP IoT-based WSN framework for SA

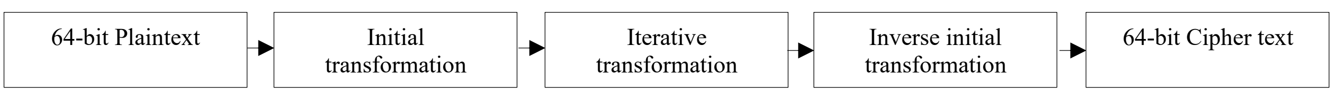

Figure 2 Structure of the DES method

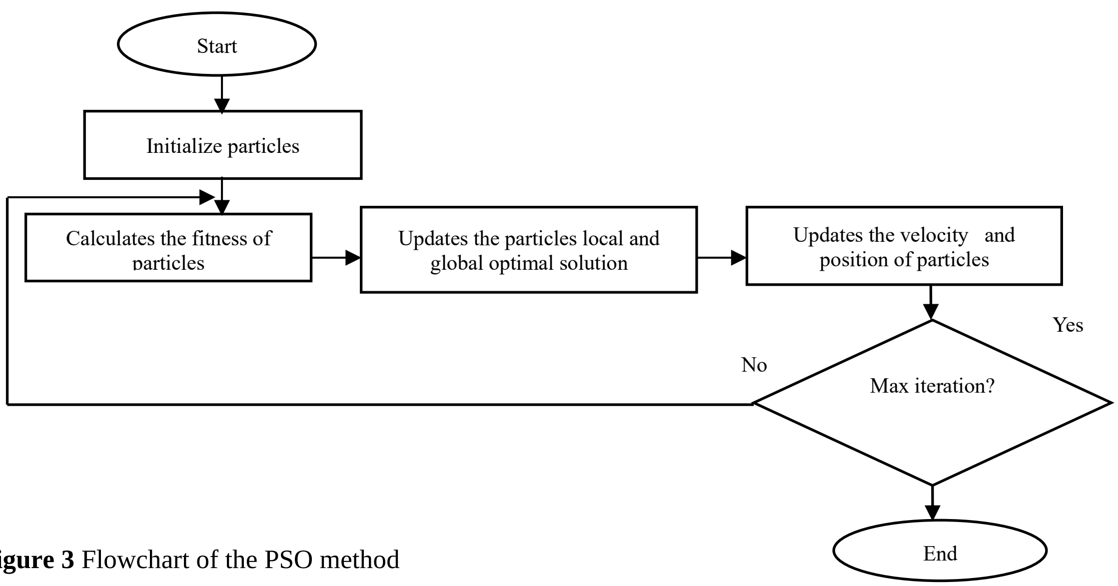

Figure 3 Flowchart of the PSO method

3.1.1OSCBRP method: network assumption

In the proposed OSCBRP for the IoT-based WSN architecture in SA, several protocol assumptions are outlined as follows:

(i) Sensor nodes are capable of efficiently managing their power consumption.
(ii) Each node in the network can transmit signals directly to the BS.
(iii) Agricultural sensor nodes have consistent energy consumption.
(iv) Data transmission connections are symmetric, secured using the DES.
(v) Agricultural sensor nodes are organized hierarchically based on their energy levels.
(vi) Improved results are obtained by applying the PSO method.

3.2Energy-efficient data transmission routing protocol for IoT-based WSN in SA

Several methods for IoT-based WSNs in SA can be categorized into hierarchical and flat-plane protocols based on network topology.

The main motive of the hierarchical approach is to cluster sensor nodes to enable CHs to perform data aggregation and energy-saving measures. A routing protocol for data transmission was implemented using PSO to establish the framework for the OSCBRP method. OSCBRP is a chain-based technique designed for hierarchical network methods based on the GA. In the OSCBRP method, farming sensor nodes completely communicate with their nearest sensor nodes' neighbors. OSCBRP efficiently assigns the responsibility of transmitting signals to the BS to only those agricultural sensor nodes that are in proximity to the BS. To initiate the chain of communication, the first member of the chain is selected from agricultural sensor nodes, with the one closest to the BS allocation as the first member. The adjacent neighbor of this initial member is then chosen as the additional agricultural sensor node in the chain. Agricultural sensor nodes generate DPs from an existing member of the chain and combine their data signals into the established DP, creating a signal DP. This development lasts until the chain extends its final member, which is the one nearest to the BS. Data collection rounds can be organized by an entity that receives inspiration from the BS. To initiate the chain of communication, the first member of the chain is selected from the agricultural sensor node, which is the end node of the chain closest to the BS, and transmits the data to the BS. If a node becomes non-operational, the chain may transform. This method represents an optimized chain-based approach, especially crucial due to limited battery power, as it is essential to prolong the network's lifetime. For data transmission, sensor nodes are only compulsory to connect with their nearest neighbors and send data to the BS. A fundamental radio protocol is employed to enhance the network's lifetime, and the formula for this radio protocol is as shown in Equation 1(*Figure 4*).

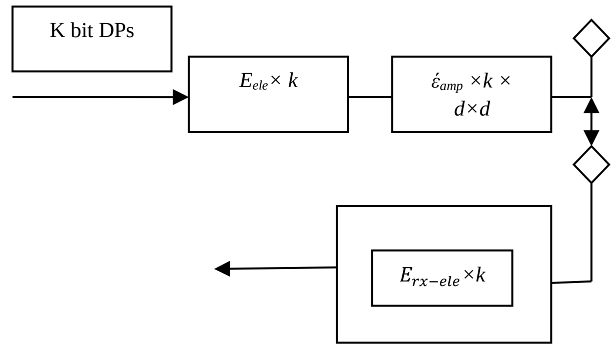

Figure 4 Radio energy model

$$E_{tx}(k,d) = E_{tx-ele}(k) + E_{tx\_amp}(k) = E_{ele}\times k + \acute{\varepsilon}_{amp}\times k\times d\times d \quad (1)$$

Here, in Equation 1 the energy consumed by transmitting electronics and amplifiers to transmit one bit of data is defined by Equation 2, where k represents a message at distance d.

$$E_{tx}(k,d) = E_{rx-ele}(k) = E_{ele}\times k \quad (2)$$

Where E_{tx-ele}= transmitted electronically,
E_{rx-ele} = receiver electronic,
$E_{tx-ele} = E_{rx-ele} = E_{ele}$; E_{tx-ele} = 50 nj per bit.

The transmission of energy is utilized by the function of the amplifier of both the number of bits and distance d.

$$E_{tx\text{-}amp} = \begin{cases} E_{fs} * k * d * d, if d < do \\ E_{amp} * k * d * d, if d > do \end{cases} \quad (3)$$

In Equation 3, do = *threshold* utilized to determine that the fading model is utilized and is defined by Equation 4:

$$do = \sqrt{\frac{Efs}{Eamp}} \quad (4)$$

In Equations (3) and (4) E_{fs} *and* E_{amp} are constants that are utilized in free-space and multiple-path models respectively.

$$\begin{cases} E_{ele}\times k\times E_{fs}\times k\times d\times d, if d < do \\ E_{ele}\times k\times E_{amp}\times d\times d, if d > do \end{cases} \quad (5)$$

Equation 5 illustrates that the energy required for reception consists solely of the energy needed to operate the circuit. Equation 6 represents the energy consumed by the receivers.

$E_{rx\text{-}ele} = E_{ele} \times l$ (6)

The cost of energy for data aggregation is shown in Equation 7:

$E_{da\text{-}to} = s \times k \times E_{da}$ (7)

Where E_{da} = Energy expended per bit in aggregation, representing the number of signals being aggregated.

3.3Optimized and secure transmission from agriculture sensor nodes to BS

Figure 5 shows the flowchart of the optimization algorithm using PSO to enhance the calculations and selection of the proposed routing technique. It provides optimized solutions to routing problems and helps to select the best one to achieve a high accuracy rate. The DP from the agricultural sensor nodes is transmitted while utilizing an optimized, secure network to the CHs and further to the BS. The implemented method evaluates the energy consumption of the network utilizing the optimized best route and security provided by the DES method without measuring the latency, overhead, or DPs in the WSN.

The main advantage of the optimized DES method is its low complexity, minimum energy consumption, and small key size.

The proposed protocol defines two steps.

(i) Key management

(ii)Optimization with encryption.

The BS creates secret keys using the optimized DES equation that is defined by Equation 8;

$x_{m+1} = (\alpha \times x_m + \beta) \times |p|$ (8)

Here x_j are defined random values for agricultural sensor node m_j, p is the reminder metric that must be higher than zero, α is the different metric and it must be higher than 0 and minimum than the reminder p, β is the increment metric and higher than equal to 0 and less than the reminder p, and x_0 is the seed value. It must be also higher than or equal to 0, less than the reminder p. Here, x_j represents defined random values for agricultural sensor node m_j, p is the modulus value, which must be greater than zero. α is the difference metric, which must be greater than 0 and less than p, while β is the increment metric, which must be greater than or equal to 0 and less than p. x_0 is the seed value, which must also be greater than or equal to 0 and less than p. All the agricultural sensor nodes are given trusted keys utilizing Equation 8. After that when the agricultural sensor nodes m_j transmits the data p_i to the CHj. It is encoded as shown in Equation 9.

$Ec_j(p_j) = p_j \oplus Ec_j(p_j) = p_j \oplus y_j$ (9)

Here, ⊕ is the XOR operator among the data p_j from the agricultural sensor nodes m_i towards CH_j. The encoded data $Ec_j(p_i)$ is the future communicated to the BS that can decode it by the XOR operator with the key y_i as defined in Equation 10.

$Dc_j(p_j) = EC_j(p_i)y_j$ (10)

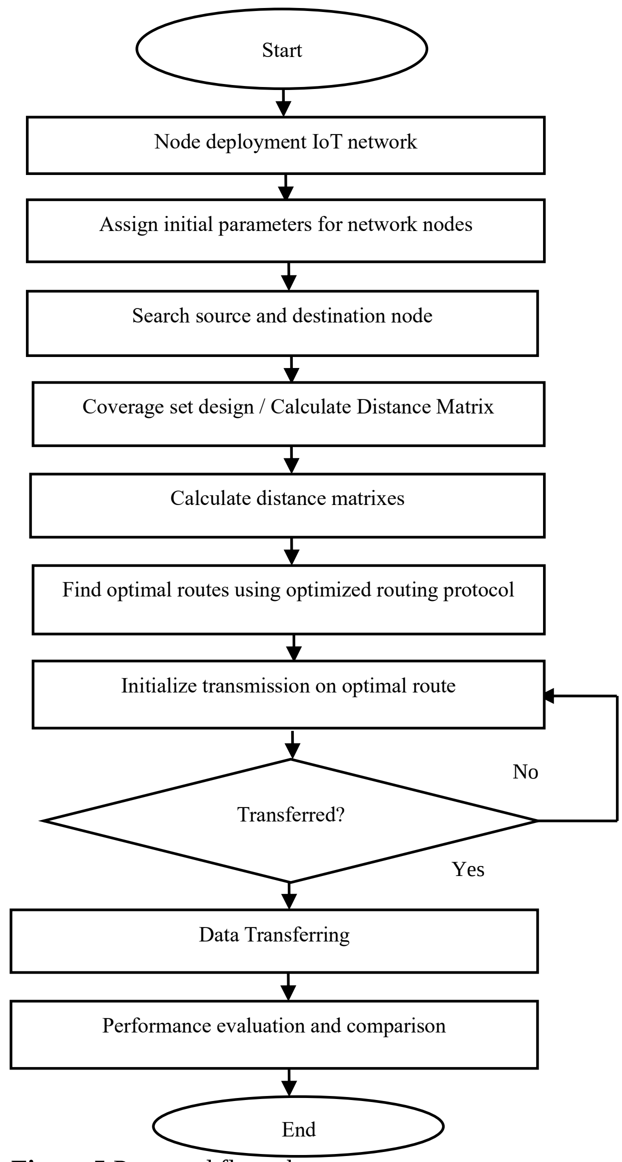

Figure 5 Proposed flow chart

The proposed model introduces an energy-efficient and link-efficient routing protocol, emphasizing a multi-criteria decision method for selecting optimal clusters with a minimum number of energy-consumption nodes. In the first phase, a multi-criteria decision method is employed to select optimal CHs, aiming to form clusters with the fewest energy consumption nodes. The second phase focused on developing an energy- and link-efficient routing protocol that ensures the long-term reliability of the routing channel. This reliability prevents wireless connections from becoming vulnerable to malicious events between the CHs and the BS.

While the main motive of the existing methods is to improve data delivery performance, certain challenges remain. These include addressing the energy hole issue, reducing the PDR, and mitigating uncertainties within the network coverage area.

The comparison protocols used in the result section are as under.

3.4Energy and link efficient protocol (EALP)

EALP is a data-centric protocol that optimizes network lifetime by measuring distance and energy, utilizing a probabilistic approach to select routes based on their energy levels [30]. Agricultural sensor nodes collect essential DPs and forward them to their respective CHs. The CHs then use a single-hop mechanism to transmit the data to the BS, which connects to the internet, allowing end users to access agricultural data for future analysis.

3.5Energy-efficient centroid-based routing protocol (EECRP)

EECRP aims to facilitate effective data transmission with WSNs. In this protocol, the BS initiates the procedure by calculating the center location and dividing the network area into multiple clusters. Initially, the node closest to the centroid is designated as the starting CH. The role of the CH is periodically reassigned by determining a new centroid location. This dynamic clustering approach reduces energy consumption, especially for long-distance data communication [49].

3.6PSO-energy-efficient CH selection (PSO-ECHS) Protocol

PSO-ECHS routing protocol aims to enhance network stability and extend the network's lifetime. In this protocol, CHs are selected using FFn that considers factors such as residual energy, the distance from sensor nodes to nearby nodes, and the distance from sensor nodes to the BS. CHs are designated based on the lowest fitness value, after which the cluster creation process begins. Each selected CH broadcasts an advertisement message, and the regular sensor nodes connect to these CHs to form clusters [50].

4.Results

The experimental results are analyzed using the MATLAB 2018a tool for evaluating WSN communication and routing. *Table 1* lists the experimental metrics along with their corresponding estimated values. The outcomes and discussions depend on different numbers of agricultural sensor nodes, which include light, soil moisture, position, airflow, temperature sensors, and additional unnamed sensors that are randomly distributed. The residual energy of the agricultural sensor nodes varies non-uniformly, ranging from 2 to 4 joules. The broadcasting range of these sensor nodes is fixed at 20 meters.

Table 1 Experimental Metrics

Metrics	Values
Network size	1000×1000 meters
Network node deployment	Randomly
Agricultural SNs/No. of Nodes	30-100
Data packet size	64 bits
Level of energy	2-4joules
Message control	25 bits
Range of data transmission	20 m
Simulation tool	MATLAB 2018a
Parameters	Throughput, energy consumption, overhead
Proposed protocol	OSCBRP
Comparison protocols	EALP [30], EECRP [49], PSO-ECHS [50]

This section delineates the analysis of simulation results, comparing the research work with previous methods, and evaluating the research protocol against other results. These evaluations are based on various network performance metrics, including network throughput, energy consumption, overhead, and latency, among others.

4.1Result analysis

4.1.1Network throughput

In *Figure 6*, the proposed research method is compared to existing routing protocols, including EALP [30], EECRP [49], and PSO-ECHS [50], in terms of network throughput while varying the number of sensor nodes. The results indicate that the proposed protocol enhances performance, achieving improvements of 5%, 10%, and 17% compared to the EALP [30], PSO-ECHS [50], and EECRP [49] protocols, respectively. This improvement in network throughput can be attributed to the use of optimized, secure, clustering-based routing protocols. The implemented routing protocol takes into account not only signal metrics between sensor nodes but also incorporates a success ratio metric in the decision-making process for selecting CHs. This enhances the PDR in secure areas due to its robust design. Additionally, the improvement in network throughput for the OSCBRP, compared to current results, is due to the secure allocation of encrypted data with trusted keys and the optimization of secure information through the PSO optimization approach.

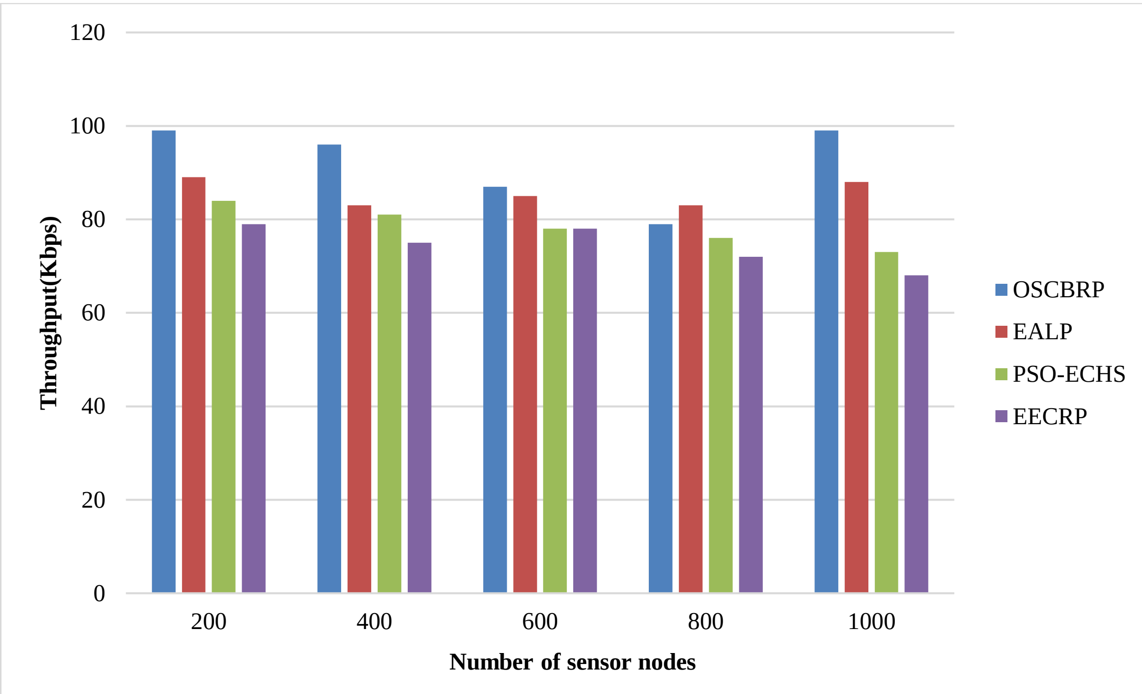

Figure 6 Network throughput comparison across different protocols for changing numbers of sensor nodes

The mathematical formula for network throughput is presented in Equation 11.

$$Throughput = \frac{DPS_{size}}{Trans_{time}} \quad (11)$$

Where, DPS_{size} represents the size of the data packet (in bits), and $trans_{time}$ refers to the transmission time.

The research work findings indicate improved network throughput and reliable connectivity. The OSCBRP method calculates the fitness value based on the number of active sensor nodes involved in specific data transfer operations. This significantly enhances the efficiency of data transmission from agricultural sensors to the BS.

4.1.2Analysis of latency

The mathematical formulas for latency are provided in Equation 12, where latency is determined by the transmission delay.

$$Latency = \frac{DPS_{size}}{Data_{rate}} \quad (12)$$

Where, DPS_{size} represents the size of the data packet being communicated and data rate has been represented by $Data_{rate}$ of the transmission channel. It directly influences the efficiency of the transmission process.

Figure 7 illustrates the results of network latency. Attacker nodes in the network can increase the risk of network disconnection, leading to higher network latency ratios. Simulation results demonstrate that the implemented protocol reduces latency by 10%, 11%, and 17% compared to the EALP [30], PSO-ECHS [50], and EECRP [49] protocols, respectively. This improvement is achieved by selecting the most energy-efficient CHs for data routing to the BS.

The protocol integrates optimization and security mechanisms to detect and prevent malicious node activity, thereby reducing the risk of selecting vulnerable nodes for data forwarding. By utilizing direct communication paths and minimizing intermediate hops, the proposed protocol significantly lowers network latency through its "forward and save" mechanism. In contrast, existing protocols lack robust data security measures, resulting in increased packet loss due to attacker nodes. The implemented protocol ensures optimized and secure data transmission, which reduces the need for retransmissions and minimizes latency between SA sensor nodes and the BS.

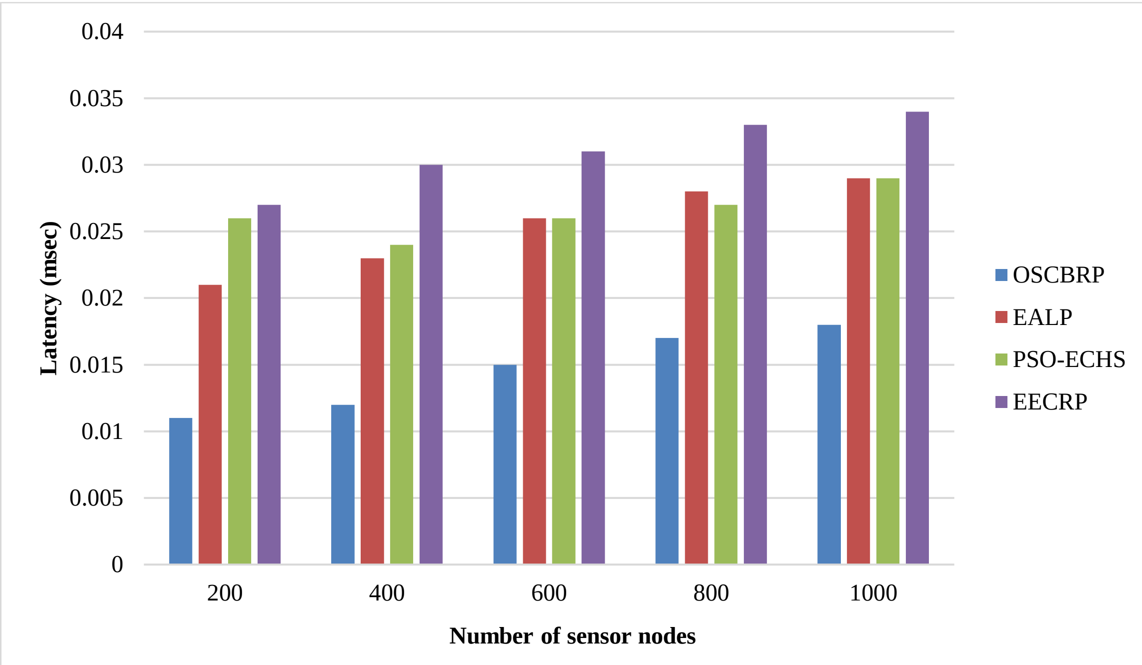

Figure 7 Network latency comparison across different protocols for varying numbers of sensor nodes

4.1.3Analysis of energy consumption

Energy consumption is determined by various factors such as transmission distance, data rate, and communication routing methods. The formula for calculating energy consumption is provided in Equation 13.

$$Energy = P_{trans} \times T_{trans} \times P_r \times T_{\mathfrak{R}} \quad (13)$$

Where P_{trans}= PC during transmission, P_r = PC during reception, T_{trans} = transmission time, and $T_{\mathfrak{R}}$= reception time.

In *Figure 8*, the analysis of the proposed research protocol is compared to other methods in terms of energy consumption. Generally, sensor nodes consume energy while communicating and collecting data from nearby nodes or the sink node.

The experimental outcome analysis shows that OSCBRP improves energy efficiency by 9%, 11%, and 21% compared to other protocols. The proposed protocol effectively distributes energy and load among sensor nodes. In this research approach, optimized sensor nodes for cluster locations in SA fields are selected. The re-routing process is eliminated in the current method due to its use of a multi-hop approach. This implemented protocol significantly reduces energy consumption in the SA field, effectively optimizing energy by selecting more suitable CHs based on optimized, secure, and energy-efficient protocols, while also considering the distance to the BS.

4.1.4Analysis of routing overhead

In *Figure 9*, the routing overhead analysis of the proposed research protocol demonstrates its objective of optimizing and securing the selection of CHs while minimizing the routing overhead on agricultural sensor nodes. The protocol achieves optimized data transmission by considering the distance to the BS along with other key parameters. It enhances data transmission performance in the agricultural domain by maintaining a stable global data rate and updating routing tables only when necessary, thereby reducing the routing overhead ratio. The implemented protocol also decreases routing overhead among nodes by minimizing the likelihood of data rerouting. Additionally, it incorporates a data encryption (DE) method utilizing the optimized DES algorithm, further enhancing network security.

It involves the transmission of control messages such as route requests, replies, and error messages. These messages are used by routing protocols to establish, update, and maintain routes in the WSN. The mathematical formula for calculating routing overhead in WSNs can vary depending on the specific protocols and parameters involved. The relevant formulas are provided in Equation 14.

Routing overhead = Control message overhead + routing table update+ route discovery + route maintenance (14)

The primary objective of effective routing protocols is to minimize this overhead while maintaining optimal route quality and ensuring reliable network performance.

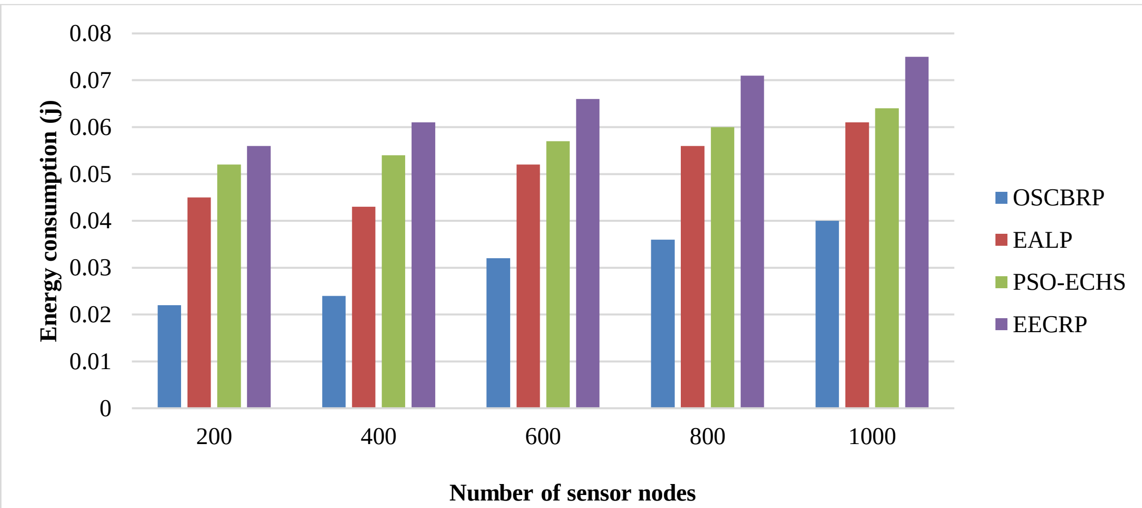

Figure 8 Energy consumption comparison across different protocols for varying numbers of sensor nodes

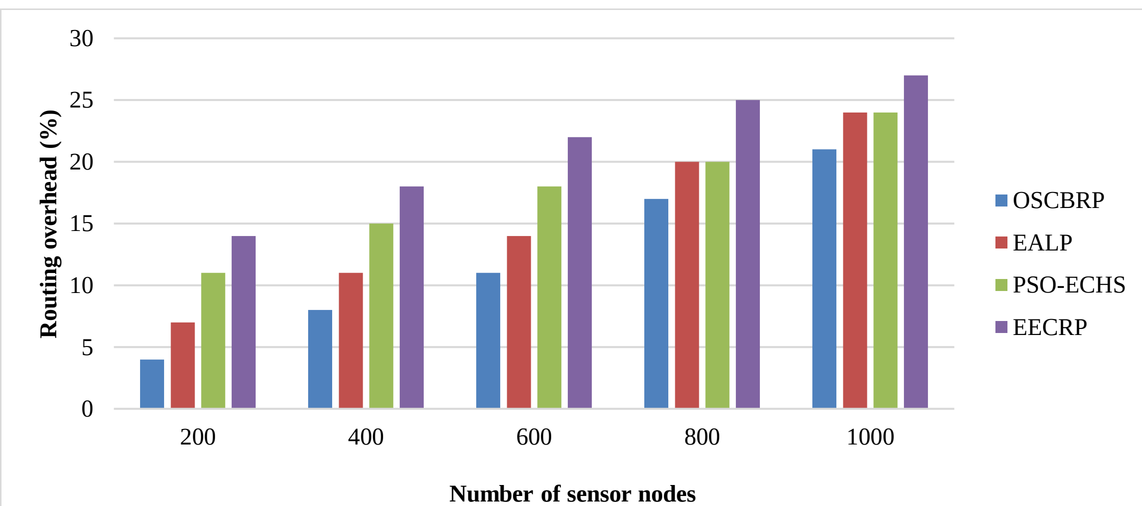

Figure 9 Comparison of different protocols: number of sensor nodes vs. routing overhead (%)

4.2Discussions and limitations

This research demonstrates that the OSCBRP protocol enhances energy efficiency, reduces delays, and extends network lifetime in SA. The integration of the PSO algorithm significantly improves calculations and optimizes the selection of routing paths. This ensures efficient data transmission, minimizes latency, and supports real-time monitoring and decision-making for agricultural operations.

The optimized throughput achieved by this method allows large volumes of data—such as information from soil and crop monitoring sensors—to be quickly transmitted to a central processing unit for analysis. The reduction in transmission delays ensures timely data collection and analysis, enabling farmers and agricultural managers to receive real-time insights and alerts, allowing them to respond promptly to changing conditions.

Overall, the proposed model enhances efficiency, reduces data losses and risks, and contributes to improved agricultural sustainability and productivity.

The research findings also highlight that the implemented protocol enables secure and optimized data transmission, reducing the need for retransmissions and lowering latency between sensor nodes and the BS. By minimizing energy consumption and avoiding frequent re-routing through multi-scenario routing strategies, the model extends the network lifetime.

The protocol improves energy optimization by selecting optimal CHs based on secure and energy-efficient parameters, factoring in their distance from the BS. Additionally, it reduces routing overhead by minimizing unnecessary data rerouting, thus streamlining data communication.

Some of the limitations of this paper are as under:

- Developing optimized routing protocols requires advanced techniques and specialized hardware, which increases the complexity of both deployment and maintenance, resulting in higher costs and greater effort.
- As the agricultural environment grows, managing a huge number of sensor nodes while maintaining energy efficient and reliable data transmission becomes increasingly difficult. Ensuring scalability without compromising network performance remains a significant challenge.

A complete list of abbreviations is listed in *Appendix I*.

5.Conclusion and future work

WSN technology has significantly contributed to advancements in the agricultural sector. This study introduced the OSCBRP protocol, which utilizes an energy-efficient and optimized secure approach within an IoT-based WSN framework for SA applications. The primary objective of this research is to select more reliable CHs using a multi-scenario approach and an objective function that considers factors such as residual energy, distance to the BS, and initial timing. The proposed protocol employs a chain formation technique using a GA for data transmission, aiming to minimize energy consumption while enhancing PDR performance in the SA domain. This mechanism defines an intelligent data routing strategy that effectively reduces energy usage and improves PDR in agricultural contexts. Compared to existing routing protocols, OSCBRP demonstrates efficient, optimized, and secure data communication from agricultural sensor nodes to the BS by leveraging trusted keys and the DES algorithm. The study shows that the proposed protocol improves throughput by 5%, 10%, and 17% compared to EALP, PSO-ECHS, and EECRP, respectively. Simulation results indicate that the implemented protocol reduces latency by 10%, 11%, and 17% relative to these protocols. Additionally, experimental analysis reveals that OSCBRP reduces energy consumption by 9%, 11%, and 21% compared to other protocols.

In future work, network performance will be investigated within the context of intelligent transportation systems and mobile-based IoT networks.

Acknowledgment
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Conflicts of interest
The authors have no conflicts of interest to declare.

Data availability
None.

Author's contribution statement
Ashutosh Kumar Rao: Study conception and design, draft writing, paper framework concept, conduct the study and result analysis. **Bhupesh Kumar Singh:** Study conceptualization, supervision and results investigation. **Kapil Kumar Nagwanshi:** Study conceptualization, supervision and results investigation.

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Appendix I

S. No.	Abbreviations	Description
1	AI	Automated Irrigation
2	ANN	Artificial Neural Network
3	BC	Blockchain
4	BS	Base Station
5	CC	Cloud Computing
6	CHs	Cluster Heads
7	DE	Data Encryption
8	DES	Data Encryption Standard
9	DPD	Data Packet Drop
10	DPs	Data Packets
11	DS	Data Storage
12	E2D	End-to-end delay
13	EALP	Energy and Link Efficient Protocol
14	ECHS	Energy-Efficient CH Selection
15	EECRP	Energy-Efficient Centroid Based Routing Protocol
16	FDI	Foreign Direct Investment
17	FT	Fault Tolerance
18	GA	Greedy Algorithm
19	GDP	Gross Domestic Product
20	GW	Global Warming
21	HANN	Hybrid Artificial Neural Network
22	IT	Information Technology
23	IoT	Internet of Things
24	KMC	K-Means Clustering
25	LCG	Linear Congruential Generator
26	LD	Load Distribution
27	LEACH	Low-Energy Adaptive Clustering Hierarchical
28	M2M	Machine to Machine
29	M2P	Machine to Person
30	OS	Operating System
31	OSCBRP	Optimized Secure Clustering-Based Routing Protocol
32	P2P	Person to Person
33	PC	Power Consumption
34	PDR	Packet Delivery Rate
35	PF	Precision Farming
36	PRISMA	Preferred Reporting Items for Systematic Reviews
37	PSO	Particle Swarm Optimization
38	RS	Remote Sensing
39	RU	Resource Utilization
40	SA	Smart Agriculture
41	SF	Smart Farming
42	SeA	Sensor Aggregator
43	UAVs	Unnamed Aerial Vehicles
44	WASs	Wireless Agriculture Sensors
45	WOA	Whale Optimization Algorithm
46	WSN	Wireless Sensor Network