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Wireless Sensor Networks for Precision Agriculture: A Review of NPK Sensor Implementations

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Abstract: The integration of Wireless Sensor Networks (WSNs) into agricultural areas has had a significant impact and has provided new, more complex, efficient, and structured solutions for enhancing crop production. This research reviews the role of Wireless Sensor Networks (WSNs) in monitoring the macro-nutrient content of plants. The review study focuses on identifying the types of sensors used to measure macro-nutrients, determining sensor placement within agricultural areas, implementing wireless technology for sensor communication, and selecting device transmission intervals and ratings. The study of NPK (Nitrogen, Phosphorus, Potassium) monitoring using sensor technology in precision agriculture is of high significance in efforts to improve agricultural productivity and efficiency. In addition to fostering technological innovations and precision farming solutions, in future this research aims to increase agricultural yields, particularly by enabling the cultivation of certain crops in locations different from their original ones.

Keywords: macro-Micro nutritients; NPK sensor; WSN; Nitrogen; Phosphorus; Potassium; soil nutrient assessment; precision agriculture; crop

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1. Introduction

As the global population continues to grow, the demand for food is also on the rise. According to the United Nations' World Population Prospects report in 2017, the population is projected to reach 9.8 billion by 2050 [1]. The Food and Agriculture Organization (FAO) of the United Nations estimates that there are approximately 30,000 edible plant species available, yet humans cultivate only 4% of these species [2]. Agricultural land has significantly decreased due to factors such as urbanization and industrialization. Consequently, addressing this issue with modern technological solutions has become imperative. Furthermore, challenges such as water scarcity, increased fertilization, and dynamic climate changes compel us to integrate technology to achieve the necessary agricultural production with minimal resource wastage.

Wireless Sensor Networks (WSN) stand out as one of the leading technologies that have evolved in the field of agriculture. WSN is primarily employed to achieve a concept known as Precision Agriculture (PA) [3]. Precision agriculture represents a new paradigm in modern farming that combines information technology and communication to enhance land and resource management. It operates by observing phenomena using sensors and responding through actuators, thereby achieving the necessary parametric values and conditions for optimal crop health and yield production, even in the face of limited resources. In this study, the authors link the emergence of Wireless Sensor Networks (WSNs) technology as a potential solution for remote and real-time data monitoring and collection across agricultural fields.

The availability of nutrients holds significant importance in supporting plant growth and production. In the context of plant nutritional requirements, nutrients can be categorized into two primary groups, namely macronutrients and micronutrients. Among these macronutrients, Nitrogen (N), Phosphorus (P), and Potassium (K), collectively referred to as NPK, play a pivotal role in providing essential nutritional support to plants. One crucial aspect of precision agriculture involves monitoring

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soil conditions, including the levels of nitrogen (N), phosphorus (P), and potassium (K), which are essential nutrients for plant growth. Effective nutrient management, particularly NPK, is of paramount importance in improving crop yields while minimizing environmental impact. Insufficient presence of these nutrients can lead to adverse effects on plants, such as reduced productivity, yellowing of leaves, and a decline in fruit quality, ultimately resulting in crop failure.
The research by [4], focuses on the development and application of Internet of Things (IoT)-based systems to assess soil nutrient content in the context of horticultural agriculture. They have developed the use of IoT sensors to measure the levels of nitrogen (N), phosphorus (P), potassium (K), and other nutrients in the soil with the aim of enhancing fertilizer management and crop yields in horticultural farming. The requirement to monitor soil nutrient levels is essential for the effective utilization of fertilizers and the mitigation of the ecological footprint resulting from fertilization techniques. Nevertheless, traditional soil assessment procedures, involving field soil sampling coupled with subsequent chemical analysis in a laboratory setting, are associated with significant expenditures and prolonged timelines [5]. The investigation conducted by [6] aimed to evaluate the potential correlation between the chemical constituents found in potato petioles and the spectral characteristics of the leaves. Additionally, the study sought to determine whether there exists a variance in correlation values when considering the spectral data of freshly harvested leaves as opposed to those that have been dried.

This research employed a systematic literature review approach with the objective of collecting and analyzing literature pertaining to the incorporation of NPK sensors within Wireless Sensor Networks (WSNs) for precision agriculture. Additionally, various other sensors, including those monitoring parameters like temperature, humidity, wind speed, solar radiation, and rainfall, play a supporting role in precision agriculture practices. The anticipated outcome of this study is to introduce innovations in the implementation of NPK sensors within WSNs, thereby opening new avenues for optimizing fertilizer utilization, averting nutrient imbalances in crops, and ultimately boosting crop yields.

2. Layout

The arrangement of sensor placements refers to how the location of a sensor is organized. When determining sensor placement, it should not be equated based on topology. Placement is sometimes also referred to as physical topology. Topology refers to the positioning of nodes to represent the direction of information flow, while placement is the physical positioning of sensor nodes. Proper attention to sensor placement is of utmost importance. The agricultural environment is highly dynamic, where parameters change both spatially and temporally. Plants will grow over time and eventually influence sensor performance. For instance, a large greenhouse may have multiple micro-nutrient zones within, exhibiting heterogeneous zones with parameters and an overall environment different from its surrounding zones. Monitoring changes in nutrients requires non-uniform sensor deployment. Irrigation and fertilization patterns can also aid in determining sensor placement locations. In this study, sensor placement is categorized into horizontal and vertical layouts.

2.1. Horizontal Layout

The layout of conventional system sensors takes on a random or grid pattern [7]. Grid patterns typically require a minimum of 6 rows and 6 columns of intersecting nodes. The resulting grid can cover an area ranging from 20 to 50 meters of farmland. Bridge nodes are placed along the outer edges of the agricultural area. This topology model can be used to cover larger areas, such as 30 $\times$ 30, using 900 sensor nodes placed at each intersection [8]. This allows for the design of a sensor layout to monitor the nutrition of a 6 $\times$ 9-meter agricultural plot.

In another scenario, instead of placing sensor nodes in a grid layout, the authors propose dividing the geographical field area into grids and siting 2-3 nodes in each grid. Nodes on the grid's edges are shared with neighboring grids. Base stations are positioned at one end of the greenhouse [9]. Nodes within the grid offer more flexibility and better coverage of empty space compared to layouts

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with nodes at grid intersections. Another variant of the grid is tessellation [10]. Grids are usually visualized as repeating square or rectangular patterns. Tessellation consists of tiles formed by regular polygons. These polygons can be triangles, squares, hexagons, and so on. Tessellation inherits the simplicity of grids and has the additional advantage of covering empty spaces. It avoids overlap and maintains consistency in communication. For example, nodes placed on the edges of the tessellation are equidistant [11]. The authors further enhance the concept by introducing tessellation layers. Figure 1 shows examples of tessellations, and Figure 2 represents tessellation layers. Nodes in different layers are represented with different notations. Layers surround the center point of the tessellation. The relationship between the number of nodes (N) and the number of layers (C) is given in Equation 1.

$$N = (2C + 1)^2, \tag{1}$$

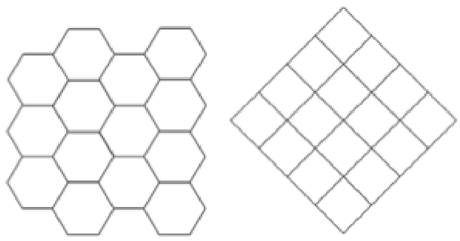

Figure 1. Tessellations

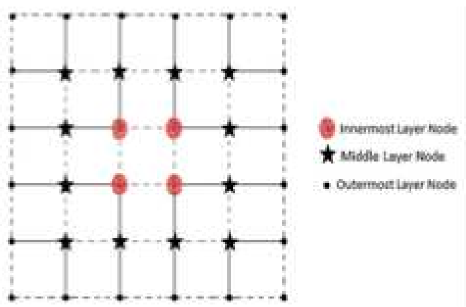

Figure 2. Layers of tessellations

In the grid, a hierarchical cluster topology is presented, that parent nodes have redundant nodes to enhance network lifetime through uniform positioning. This algorithm is referred to as the Redundant Node Deployment Algorithm (RNDA). RNDA employs the concept of load balancing to improve network longevity. With a small number of redundant nodes, the network's lifespan can be extended to thousands of rounds. In addition to the grid, random layouts are also straightforward. While the grid layout is the most commonly used [12], preferring to use directional antennas to construct a row layout. Transmitters are placed in front of each row to develop a path loss model.

During the appropriate layout phase, sensors should be placed within the agricultural field to measure external environmental parameters such as temperature, humidity, rainfall, etc. External sensors can form their own topology that is isolated from internal sensor nodes, or if sensors need to communicate, it should be within their scope. The 200 nodes are divided into 'Type A' and 'Type B.' 'Type A' represents external climate monitoring sensor nodes, while 'Type B' denotes sensors for internal climate monitoring [13]. Many other authors have also further enhanced accuracy by adding weather stations [14–16].

In order to investigate the influence of various factors on leaf growth, that examined four specific environmental conditions: well-ventilated, hot and low-humidity, humid, and warm areas [17]. Despite the uniform deployment of wireless sensors and cameras in our study, we took into consideration the diversity and dynamics of these regions when determining the density of sensor nodes in each area. To ensure a robust monitoring system within the greenhouse, in addition to stationary sensors, we also employed mobile sensors. A total of 120 sensor nodes and 4 gateway nodes were strategically positioned throughout the orchid greenhouse for monitoring purposes. Among these 120 sensor nodes, 52 remained stationary, while the remaining 68 moved at a speed of 0.15 m/s. We used the Dynamic Convergecast Tree Algorithm (DCTA) to reconfigure the network topology every 30 minutes. The furthest measured distance between sensor nodes was found to be 75.6 meters [18].

In tomato plants, sensors are evenly distributed in a tree-cluster configuration, with routing nodes forming a triangular grid. The sensor network and the routing node network are mutually dependent [19]. Distinct networks can also be formed for various sensor types. Riquelme et al. (2009) suggested the utilization of separate networks for soil sensor nodes and environmental sensor nodes [20]. To monitor the water quality used for irrigation, a separate isolated network is installed. The idea of distinct isolated networks for soil and environmental sensors could offer a fresh perspective on precision agriculture monitoring.

The sensors deployment within the layout, along with the number of sensors, spacing, and measured parameters are crucial factors. Although the grid topology appears straightforward to implement, its deployment might be excessive, leading to node wastage at times in agricultural field environments. The horizontal layout is summarized in Table 1.

Table 1. Horizontal Layout

Layout	Crop and of References	Number of Nodes	Area	Measurred Parameters
Grid	Tomato[7]	7 (including one gateway)	20m×50m	Air Temperature, Humidity and Soil
	- [13]	200	35m×200m	Temperature, Humidity, CO2 concentration and Illumination
Inside and outside	Basil [14]	-	374m×211m ×195m	Temperature, Humidity, CO2 concentration and Illumination
	Chilli [15]	7	30m×48m	Temperature, Humidity, and VPD
Tessellations	Cassava [10]	Depending on number of layers	10026m2	Temperature and Soil Moisture
Divided in regions	Orchid [17]	24 nodes and 2 gateways	130cm×140cm ×150cm	Temperature, Humidity and Illumination
Rows only	Mango [12]	273 (7 on each tree, 3 lanes of 13 trees in each row)	50m×10m x5m	Temperature, Humidity, Illumination and Soil Moisture
Fixed and moving nodes	Orchid [18]	120 (52 fixed, 68 moving)	72m×36m ×10m	Chlorophyll content
Separate topology for sensors and routers	Tomato [19]	30 (20 sensors, 9 routers, 1gateway)	50m×50m	Temperature, Sap flow, Humidity, Stem diameter, leaf thickness, leaf wetness

The range of parameter variability extends over distances of a few meters, such as soil temperature, soil moisture, soil pH, etc. While a grid layout is suitable, it requires more sensors and therefore becomes costlier. For instance, if the range of soil moisture variability in a particular field is 15 meters, then the distance between nodes should be less than 15 meters for efficient monitoring. By optimizing several layers, node density can be optimized. Including the idea of external sensors can assist in considering the often-overlooked external environmental factors. Analysis of external parameters such as illumination and wind speed can provide an additional perspective on greenhouse monitoring. For plants grown inside a greenhouse, Vapor Pressure Deficit (VPD) is a more enlightening parameter than relative humidity. VPD represents the difference between the actual humidity level in the air and the humidity level at full saturation. As the difference between them increases, VPD increases. Therefore, plants attempt to draw more water from their roots, and the rate of transpiration increases. If VPD is low, water condenses from the air on plant leaves. Hence, PD3I provides assistance in disease prediction. For analytical purposes, such as in applications where a control group needs to be compared with an experimental group, dividing the field into the most suitable regions is beneficial. The concept of mobile nodes seems intriguing, but it comes with limitations related to plant environment obstacles. Monitoring in precision agriculture covers several hectares, so the use of mobile nodes can provide additional assistance in monitoring. For parameters with a narrow range of variability, mobile nodes can be practical to avoid network congestion costs. For touch-based sensors like chlorophyll content meters, mobile robotic nodes can facilitate the monitoring process. Isolating sensor and router network topologies extends network life and manages risk. A triangular mesh topology used for routing nodes helps reduce overlap. Network isolation for sensitive sensors such as CO2 concentration sensors with compatibility issues can also extend their lifespan. Concerning additional light sources, sensors should be positioned correctly to capture the true values of illumination or radiation reaching the plants.

2.2. Vertical Layout

In the early years of the sensor era, when sensors were relatively expensive for greenhouse monitoring, sensor placement typically involved a single sensor node placed in the middle of the top section. As predicted by Moore's Law, integration levels increased, helping to reduce prices. This enabled the deployment of multiple sensors to enhance monitoring system accuracy and reliability. Some proposed having all sensor nodes at a single height [21,22]. The growth and leafage of plants significantly affect the sensor communication range [19], making the vertical layout appear to be a prominent solution.

The sensors are installed in a vertical layout because they monitor all plants' growth in the vertical direction, either upwards or downwards. The farming model in paddy fields or open fields is referred to as terracing. Meanwhile, the vertical layout model has specific characteristics for climate control and monitoring in greenhouses. On the other hand, other authors suggested placing sensors at separate height levels [12,15,23–25]. Pahuja and colleagues used this model to monitor parameters at the canopy level and above the crop canopy [15]. Research by Harris and colleagues used the monitoring of several parameters for precision agriculture calibration. In other research findings, in a different variant of the vertical layout model, sensors were positioned in the soil, with only the coordinator placed at a higher level or in the middle in the case of a single coordinator [7,23,26].

Previous research proposed monitoring soil parameters, where sensors needed to be placed vertically below the ground [27]. Yu and colleagues suggested placing only the antenna at separate heights to enhance communication range, while the sensors remained at ground level [28]. The communication distance increased with antenna height but only up to 1 meter because, beyond that height, tomato plants did not interfere. Thus, the sensor's height level depends on the plant's height. The vertical layout can support the acquisition of plant growth-related parameters such as NDVI (Normalized Difference Vegetation Index). NDVI relies on spectral data reflected from the crop canopy. Mathematically, NDVI can be represented as in the Equation 2.

$$NDVI = \frac{R_{ni} - R_v}{R_{ni} + R_v} \tag{2}$$

In which R_{ni} represents the near-infrared spectral reflectance of plants, and R_v represents the spectral reflectance of visible light from plants.

Similar to the horizontal layout, the vertical layout also depends on the measured parameters. For soil chloride concentration or soil pH, sensors need to be placed vertically downward. For wind speed, sensors need to be placed outside and at a minimum height. Because CO2 is heavier than air, CO2 sensors are more effective below the plant canopy level. Similarly, when monitoring illumination or light reaching the plant leaves, light sensors should be positioned above the leaf surface to avoid shadow zones. Another important parameter to observe is the height level. When placing sensors at different height zones, the plant canopy level must be considered to avoid interference. For example, if the monitored plants are tomatoes, then the placement of node antennas should be above 1 meter to maintain connectivity. If the plants change height significantly during the growth cycle, such as pepper plants, then the node height should be adjusted as the plants grow, or other solutions such as long-distance routing nodes should be implemented [19]. Table 2 are summarizes papers that employ a vertical layout.

Table 2. Verticals layout

Layout Sensor	Crop and References	Number of Nodes	Area	Measurred Parameters
Sensors at separate heights	Tomato [29]	4	120cm, 176cm, 295cm, and 310cm	Temperature, Humidity, CO2 and irradiance
	Mango [12]	7	0.5m, 1m, 1.5m, 2m, 2.5m, 3m, and 3.5m	Temperature, Relative humidity and weather
	Chill [15]	30	50 m × 50 m	Temperature, Humidity, VPD
	Tomato[25]	2	0.5m and 3m	Temperature, Humidity, Luminosity & Wind speed
	Pepper, Vegetable [24]	3 until 5	Final height was 2.5 m	Temperature, Humidity and Soil pH
Sensors at one height level	- [21]	4	1m	Temperature, Humidity, Luminosity and Pressure NDVI
	Strawberry [22]	7	Coordinator at height of 65cm	Air Temperature, Humidity and Soil temperature
Sensors and coordinator at separate level	Tomato [7]	7	Coordinator at height of 65 cm	Air Temperature, Humidity and Soil temperature
	- [26]	4	Coordinator at height of 3.5m in middle	Temperature and Humidity

2.3. Hybrid Layout

In addition to horizontal and vertical layouts, a hybrid sensor layout has also been proposed. In the experiment [18], as shown in Figure 3, nodes can also be placed in a 3D row-column-height grid structure [16], and both layouts have proven to be quite optimal for plant monitoring, whether inside or outside greenhouses. Aiello and colleagues suggested deploying 20 sensor nodes at 5 different locations and 4 different heights ranging from 0.7 m to 3.8 m [30].

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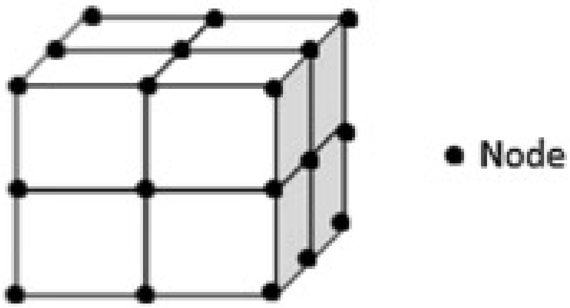

Figure 3. 3D grid layout

Changes in one parameter can influence other parameters. The illumination or radiation intensity can affect temperature and humidity measurements. Ferentinos and colleagues examined the impact of various levels of radiation intensity on temperature and relative humidity measurement errors [31]. Therefore, it is suggested to keep nodes exposed or partially boxed, as exposed sensor nodes perform better than fully boxed ones. Kuroda and colleagues also proposed placing nodes inside boxes [32]. Nodes can also be used in hierarchical or master-slave architectures. In a tier-based layout, some sensor nodes only sense data, while others with additional capabilities can collect and process data. The lowest-level nodes transmit measured data to the upper level. Upper-level sensor nodes can process data if necessary or can directly transmit it to the top level. Nodes at the highest level are connected to a gateway or central repository [33,34].

Provides an overview of studies that have applied a hybrid layout of the agricultural model combines both vertical and horizontal layouts and is a commonly employed arrangement for verification and testing [35,36]. Consequently, a single sensor node is adequate for monitoring, and the information is directly transmitted to the server without the use of any intermediary bridge or gateway (Table 3).

Table 3. Hybrid layout

Crop and References	Number of Nodes	Area	Focused
Horticulture [30]	100 (20 motes at 5 points)	24m × 30m	Disease forecasting
Lettuce [18]	37 (9 on each of the four shelves, one gateway)	255cm × 560cm, each shelf of 120cm × 60cm	Monitoring and disease forecasting
Tomato [16]	38 (12 sensors at 3 heights, one gateway, one outdoor weather station)	32m × 32m	Monitoring

3. Monitoring the nutrition with sensor NPK

According to [37], the nutritional requirements of a plant depend on the plant's type, and the quantity of fertilizer to be used also relies on the existing NPK nutrient content in the soil. [38] also report that the additional fertilizer required is influenced by the values of NPK present in the soil. Determining the range of NPK content in the soil becomes a crucial factor in optimizing fertilizer application (Table 4).

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Table 4. NPK Level and Range

Level	Range (kg/ha)		
	Nitrogen	Fosfor	Kalium
Low	0 - 280	0 - 11	0 - 118
Medium	280 - 450	11 - 22	118 - 280
High	>450	>22	>280

Source: [3]

Fertilization that is effective must involve the precise selection of suitable fertilizer types, determination of the correct dosage, adherence to appropriate timing, and the implementation of the correct method of application. The excessive or inadequate application of fertilizers can lead to reduced production yields and relatively lower quality. Table 5 presented below are fertilization recommendations that can be applied to various types of horticultural crops:

Table 5. The optimal NPK application rate for horticultural crops

Crops	Recommended dose of NPK (kg/ha)		
	Nitrogen (N)	Phosphorus (P_2O_5)	Potassium (K_2O)
Fruit Crops			
Banana	620	310	620
Mango	75	20	70
Citrus	110	35	55
Papaya	925	925	925
Guava	250	175	175
Apple	320	320	320
Pineapple	275	70	200
Sapota	100	50	50
Grapes	300	300	600
Pomegranate	500	425	975
Litchi	50	50	25
Vegetable Crops			
Potato	60	100	120
Tomato	180	120	150
Onion	125	75	125
Brinjal	180	150	120
Tapioca	45	90	120
Cabbage	150	125	100
Cauilflower	150	100	100
Okra	100	50	50
Peas	25	75	60
Sweet Potato	20	40	60
Chilli	150	75	75
Plantation Crops			
Coconut	100	55	210
Cashewnut	100	40	60
Arecanut	140	55	200
Cocoa	70	30	100

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Table 5. *Cont.*

Crops	Recommended dose of NPK (kg/ha) Nitrogen (N)	Phosphorus (P_2O_5)	Potassium (K_2O)
Spice Crops			
Garlic	40	75	75
Turmeric	150	60	108
Ginger	37.5	50	37.5
Cumin	30	20	20
Coriander	10	40	20
Tamarind	20	15	25
Fenugreek	30	25	40
Fennel	50	10	10
Pepper	110	50	155
Cardamom	75	75	150
Ajwan	40	20	20
Nutmeg	187.5	187.5	600

Source: [39]

4. Data Transmission Methods

Sensors need a method for transmitting data to the control center or users in need of information, as this is the fundamental function of sensors in WSNs. Sensor node communication can be wireless or a combination of wireless and wired. Various technologies can be utilized, as demonstrated in Table 6, where we provide a comparison of communication technologies based on parameters including range, frequency, network size, cost, data transfer rate, power consumption, and communication mode:

Table 6. Data transmission technology on WSN

Transmission Modules and Range	Frequency & Data Rate	Node	Cost & Energy	Communication Type
Zigbee (10 - 20 m)	2.4 GHz (20 - 250 Kbps)	65000 nodes per network	L and L	Peer to Peer
GPRS (35 Km)	900 - 1800 MHz (56 - 114 Kbps)	1000 nodes per network	H and H	Base station to device
LoRa (>10 Km)	169 MHz, 868 MHz, and 433 MHz (0.3 - 50 Kbps)	10000 nodes per gatewar	M and L	Peer to Peer
Bluetooth (1 - 100 m)	2.4 - 2.485 GHz (1 - 3 Mbps)	8 nodes per piconet	L and M	Master slave and Peer to Peer
WiFi (20 - 100 m)	2.4 GHz (2 - 54 Gbps)	32 nodes per network	H and H	Access point to device
Xstream (5 - 16 Km)	2.4 GHz (10 - 20 Kbps)	7 channels, 65000/channels	L and L	Peer to Peer

Note: L (Low), M (Medium), and H (High)

In Table 6, it is evident that each technology exhibits the capability to convey sampled data from sensors to the central control unit for subsequent analysis. Communication technologies characterized by high data transmission rates, such as WiFi and Bluetooth devices, are associated with elevated power consumption when compared to Zigbee. Another noteworthy observation pertains to the inherent trade-off between power consumption and device lifespan; devices with higher power consumption are naturally associated with shorter operational lifespans. Therefore, Zigbee emerges as a pragmatic choice for communication. Zigbee, Xstream, and LoRa all share the common attributes of offering extensive coverage with low data transmission rates within the peer-to-peer network framework. However, additional considerations encompass the prohibitively high cost associated with LoRa. Moreover, the LoRa platform is associated with significant latency due to the proliferation of LoRa

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devices. Conversely, while Xstream presents an economical option, its operational intricacies stem from the presence of numerous channels.

5. Results

5.1. Wireless Sensor Networks in Precision Agriculture

WSNs consist of spatially distributed sensor nodes that autonomously collect and transmit data to a central node. This network provides real-time monitoring capabilities, enabling farmers to make decisions based on current field conditions. In precision agriculture, WSNs are employed for various purposes, such as climate monitoring, soil moisture assessment, pest detection, and nutrient management.

5.2. Nutrient Management and NPK Sensor Monitoring

Optimal nutrient management is crucial for plant growth and health. Nitrogen, phosphorus, and potassium are primary nutrients that significantly impact plant development and crop yields. The integration of NPK sensors into WSNs allows continuous monitoring of nutrient levels in the soil, providing insights into plant nutrient requirements.

5.3. Implementation of NPK Sensors in WSNs

Several technologies are utilized for NPK detection, including electrochemical, optical, and spectroscopic methods. These sensors measure various parameters such as electrical conductivity, pH, and nutrient concentrations in the soil. Integrating NPK sensors into WSNs involves addressing challenges like power consumption, data accuracy, and communication protocols.

5.4. Benefits and Challenges

Integrating NPK sensors into WSNs offers several benefits, including efficient resource utilization, reduced labor costs, and improved decision-making. However, challenges such as sensor calibration, data synchronization, and network maintenance need to be addressed for successful implementation.

6. Discussion

Several implementations of NPK sensors within wireless sensor networks for precision agriculture have been documented. Typically, these sensors are integrated into a system that continuously measures soil nutrient content in real-time and transmits this measurement data to data collection stations through wireless networks. Commonly used NPK sensors in this context include ion-selective sensors, near-infrared spectroscopy (NIR) sensors, and soil impedance sensors. The success of these implementations depends on factors such as sensor accuracy, transmission range, energy efficiency, and data integration.
However, challenges such as sensor reliability, low power consumption, and interoperability need to be addressed to ensure the sustainability and effectiveness of the system.

7. Conclusions

Integrated NPK sensors within Wireless Sensor Networks (WSNs) play a pivotal role in optimizing nutrient management to enhance crop productivity and sustainability. This review underscores the significance of sustained research and development efforts to address various challenges and unlock the full potential of NPK sensor implementations in precision agriculture.

Our research findings shed light on the importance of deploying wireless sensor networks in precision agriculture, with a specific focus on NPK sensor monitoring. The utilization of NPK sensors within WSNs has the potential to bring about a transformative impact on crop nutrient management.

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This impact, in turn, has the potential to enhance agricultural productivity and support endeavors toward more sustainable agriculture.

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