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A review of innovative fertilization strategies in precision agriculture

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Abstract

The increasing global population, expected to reach over 10.3 billion in the mid-2080s, is putting huge pressure on the demand for food, making innovative techniques essential. Conventional methods have relied much on heavy chemical fertilizers, which have devastating environmental consequences, such as pollution and inefficiency of nutrient use. Precision farming deploys specific fertilization methods in response to these challenges, made possible by the latest technologies: remote sensing technology, global positioning system, wireless sensor network, internet of things, blockchain system, and data analytics. These technologies provide data from current situations at both spatial and temporal scales; hence, the application of fertilizers is well-applied to the needs of the crops in tune with the prevailing conditions of the soil. This method lowers fertilizer waste, mitigates environmental contamination, and enhances crop yields by providing nutrients precisely when and where required. Different types of fertilizers, such as nano-fertilizers, fertilizers with external coatings, and lower-solubilize fertilizers, improve nutrient absorption by crops due to retention in root zones for a longer period. Advanced fertilization methods, including variable rate technology and fertigation, improve fertilizer use efficiency by optimizing nutrient distribution. Variable Rate Technology modifies fertilizer application according to soil nutrient composition and crop development phases, while fertigation incorporates fertilizer distribution via irrigation systems, guaranteeing accurate nutrient provision. Advancements in precision agriculture promote sustainable agricultural practices, increase production, lower costs, and diminish the environmental implications of conventional fertilization methods, hence helping long-term food security and environmental preservation.

Keywords: Precision agriculture; Nano fertilizers; Coated fertilizers; Lower solubilized fertilizers; Innovative fertilization

1. Introduction

The world's population has increased over the last millennium, leading to an increasing demand for food. It is predicted to be around 10.3 billion in the mid-2080s [1] making the fulfillment of world food demand even more challenging. Hunger and malnutrition are becoming the main problems all over the world, which need prompt action. Though the Green Revolution addressed this issue, its sustainability is questionable due to the excessive use of chemical fertilizers, pesticides, etc. In commercial agriculture, fertilization is a must practice, and it plays a major part in the cost of production. To maximize output from limited land resources, farmers apply unnecessarily more and more chemical fertilizers to their fields. Since 1961, the use rate of N and P fertilizers increased by 8 times and 3 times, respectively, which leads to environmental pollution and health problems [2]. Heavy metal accumulation and nutrient imbalance in soil and crops, pollute groundwater and water bodies through drainage, leaching, runoff, and evaporation into the atmosphere, act as greenhouse gases, and finally enter the human body through contamination of the human food chain are the main problems associated with the improper fertilization [3-5]. It is estimated that N pollution levels will be 150% higher by 2050 compared to 2010, and the agricultural sector alone will be responsible for 60% of that [6].

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Moreover, improper application of chemical fertilizer leads to higher wastage of the fertilizers. As an example, plants use 30%–50% of the nitrogenous fertilizers even in ideal conditions, while others waste 50%–70% of the environment [7].

Fertilizer recommendations come to the field to avoid the negative impacts of this blanket application of chemical fertilizers. Nonetheless, different recommendation procedures were available. Phosphorus fertilizer recommendation strategies included three steps, including determining available soil P for crops, its calibration, and finally, derivation of P fertilizer recommendations [8]. Nitrogen fertilizer recommendations were done by soil-based methods such as assessing soil mineral nitrogen and assessing soil nitrogen mineralization and plant-based methods such as total nitrogen concentration, plant sap nitrogen concentration, and chlorophyll content [9]. However, these fertilizer recommendation methods still couldn't achieve maximum fertilizer use efficiency due to the demand for fertilizer depending on several factors like crop species, growth phase, soil condition, weather conditions, etc. Moreover, there is high variability in fertilizer recommendations for the same crop and the same ecology. As an example, nitrogen fertilizer recommendations for rice in Burkina varied from 90 to 130 kg ha^{-1} even in the same ecology [10]. Hence, it is mandatory to search for new advanced technologies and methods for fertilizing agricultural crops.

Precision agriculture introduces novel fertilization strategies, including the determination of actual fertilizer requirements, new types of fertilizers, and methods of application. Therefore, precision agricultural practices can tackle the issue successively to fulfill the world's food demand. It is an advanced agricultural management concept that uses data and novel technologies like sensors, global positioning systems (GPS), drones, and satellite imagery to boost crop production. It determines the precise amount of agricultural inputs like chemical fertilizer, pesticides, and water that are demanded by the crop and fulfills that demand. Hence no wastage, reduce the cost of limited agricultural inputs, minimize environmental pollution, and enhance the quality of agricultural production.

2. Determination of fertilizer requirements

The available nutrient level for crops in the soil differs from place to place. In the same land, variations are available, and analyzing soil samples for different nutrient levels is more complex. Moreover, the demand for fertilizer depends on the growth stage of the crop. Hence, in precision farming, different field information is collected by using various advanced technologies, analyzed, and decisions taken on fertilizer applications to avoid wastage of fertilizer, increase fertilizer use efficiency and production, and reduce the cost of production.

2.1. Techniques to Collect Field Information

Different techniques are available to collect information about soil, crop, and atmospheric conditions even before the crop cultivation or middle of the cropping seasons. These details support farmers in making precise decisions about fertilizer applications.

2.1.1. Remote Sensing Technology

Remote sensing is the art and science of gathering information about the objects or areas to be investigated from a distance [11]. It allowed the real-time monitoring of crop status, soil physical and chemical parameters, and farming environment. The real-time special and temporal data were sensed using sensors mounted on either satellite, aerial, or ground-based platforms. There are two types of satellite platforms, such as polar-orbiting satellites and geostationary satellites. Given that satellite images cover bigger areas; they are ideal for checking on massive farmlands. Aerial platforms, which include both aircraft and unmanned aerial vehicles (UAVs). Aerial platforms Drones and other UAVs are being increasingly used in agriculture to take high-resolution images. Three types of ground-based platforms include hand-held, free-standing in the field, and mounted on tractors or farm machinery [12]. Moreover, different kinds of sensors are used, such as visible, multispectral, hyperspectral, thermal, and microwave systems [13]. The sensor captures electromagnetic radiation reflected or emitted by plants, which is subsequently processed to generate useful information [14 - 15]. Though this technology provides a lot of advantages for making agricultural activities more efficient and productive, it is mostly used in developed countries, mainly Europe, the United States, and China, instead of developing countries.

2.1.2. Global Positioning System (GPS)

In precision agriculture, fertilization practices have greatly changed with the introduction of GPS technology allowing for precise site-specific management of nutrients. By integrating GPS with the system, farmers are able to apply fertilizer at just the right places they need them without overusing and misallocating it across their land. It enables the incorporation of real-time geospatial data, which is useful for growers in mapping field variability and creating location-based fertilizer applications that will maximize yield and revitalize food production with minimal environmental pollution [16]. Now, for example, the integration of GPS with variable rate technology (VRT) can lead to fertilization performed automatically in real-time from geo-referenced information applied, which improves productivity and sustainability [17]. GPS technology is also useful to generate detailed soil maps that help detect the nutrient needs of different areas within a field. Geospatial technology provides accurate fertilizer application; it will help to the right amount of fertilization without over-fertilizing and prevent eutrophication [18]. GPS-based fertilizer management also supports other precision agriculture tools (like GIS, and remote sensing), which represent an integrated system for sustainable soil health development and crop yield optimization [19].

2.1.3. Wireless Senor Networks (WSNs)

Wireless Sensor Networks (WSNs) are essential in enhancing precision agriculture through real-time monitoring and management of agricultural surroundings. These networks have spatially distributed sensor nodes that gather essential environmental data, including soil moisture, temperature, humidity, and light intensity, which are transmitted wirelessly to a central system for analysis and decision-making. WSNs allow farmers to continuously monitor their fields and modify agricultural inputs, including water, fertilizers, and pesticides, based on accurate, real-time data, resulting in enhanced resource efficiency [20]. WSNs provide ongoing surveillance of soil parameters, including moisture content, nutrient levels, and temperature, thereby enabling farmers to administer fertilizers accurately in both timing and location [21]. It can enhance fertilization use efficiency by preventing both over-fertilization and under-fertilization which lead to soil degradation and lower crop production. For instance, a WSN can detect nitrogen, phosphorus, and potassium (NPK) levels in crops, supplying critical data for optimizing fertilizer application rates [22]

2.1.4. Internet of Things (IoT)

In precision agriculture, the integration of the Internet of Things (IoT) has revolutionized fertilization by giving rise to a method with real-time data collection and resource management. This technology-based soil monitoring system works through the sensors and, based on determining factors like soil moisture and nutrient levels, automates the precise application of fertilizers based on this data [23]. This technique enables fertilizers to be applied right where they are needed, saving wastage and limiting environmental damage from excessive application of chemical fertilizer [24]. Using variable-rate fertilization with IoT provides fertilizer application according to what each region needs [25]. This strategy leads to having productive plants that consume less input. In addition to that, the IoT-driven fertigation system performs and combines both irrigation as well as fertilization so that these resources can be used efficiently, deploying real-time data, thereby promoting sustainable farming practices [26]. On the other hand, IoT integrated with smart farming gives farmers better tools for decision-making as well as scale data analytics and connected devices to monitor their farms at a distance. These systems provide solutions at a massive level and in places where human resources are limited and inaccessible [27].

2.1.5. Blockchain System

Precision agriculture is increasingly integrating blockchain systems to advance fertilization processes and efficiently use the available resources. Security and transparency in data management characterize blockchain technology, which is considered an important feature of precision farming since information has to be accurate to facilitate decision-making. For instance, when it involves fertilization, it would track the variety and amount of each kind of fertilizer applied to any one crop to ensure that it gets what it needs [28]. One of the major benefits of blockchain in agriculture involves providing a line that is more clear and verifiable in the supply chain from manufacturing to application in the field [29]. This therefore allows for the traceable record of the inputs in farming, including fertilizers, toward environmental compliance and enhancement of sustainability. Integration with IoT further supports monitoring of the soil conditions in real-time, hence allowing for better use of fertilizers through automation of applications based on sensor data [30]. Additionally, it increases the cooperation of farmers suppliers, and distributors within the agricultural value chains. With the shared data between them, farmers and retailers will be more knowledgeable about buying fertilizers and applying them exactly where they should [31]. The systems will still go ahead to improve in the use of smart contracts that automatically buy fertilizers and apply them, hence reducing human errors and delays in supply chains.

These techniques, when integrated, facilitate an improved collection of real-time temporal and spatial data to enable precise fertilization in precision agriculture. Precise fertilization, therefore, minimizes waste and its impact on the environment while maximizing crops with the right quantity, in the right place, and at the right time. It enhances productivity and sustainability in farming.

2.2. Information Management and Decision Making

Information collected from these above advanced techniques should be used to analyze data and make accurate decisions about fertilizer applications. It will help to determine what type of nutrient, how much, and when they are used. Precision decision-making technology is driven by data that is processed and analyzed to maximize crop management decisions. Farmers' decision-making in agriculture depends on precision fertilization and irrigation. In agriculture, the most popular applications for making decisions are decision support systems (DSS) along with expert systems. These systems manage and analyze huge quantities of crop production data using computers, which helps in saving manpower as well as preventing human error. Despite the risk of overfitting to a single system and climate, simulation functions in software can significantly enhance prediction accuracy and efficiency [32].

2.2.1. Big Data Analytics

Accordingly, big data analytics have now emerged as a transforming tool in precision farming, particularly in optimization processes of fertilizer dispersion. Large data systems capitalize on huge volumes of data from varied sources, such as soil sensors, satellite imagery, and meteorological forecasts, to be in a position to guide fertilizers to the crops with precision, giving them precisely what they need at exactly the right time. It is data-driven in nature, hence improving efficiency and thus reducing the over-application of fertilizers; this minimizes environmental impacts such as soil degradation and water contamination [33]. One of the main benefits that big data has in precision agriculture is the potentiality of integrating various datasets into one decision-making process. For example, a cyber-physical system could take up data analytics for real-time field conditions and further modify the application rate of fertilizer according to soil health and crop needs [34]. Big data analytics also automates fertilization operations for higher productivity and lower labor costs associated with the process [35]. Predictive analytics, on the other hand, based on historical and real-time data, provides predictions on nutrient requirements of crops that make proactive fertilization strategies to increase yields, while resource conservation also comes into play [36]. The large data-driven systems integrate machine learning algorithms to receive information on the needs of fertilizers; these are essential in assuring soil sustainability as well as optimizing production [37].

2.2.2. Decision Support System (DSS)

The decision support systems (DSS) are the main influence on effective fertilization management in precision agriculture, with a combination of real-time data, advanced algorithms, and spatial analysis for the most appropriate fertilizer usage. DSS tools in agriculture collect data from soil sensors, satellite images, and historical data to drive the farmers to an accurate decision on fertilization. Such systems can locate more precise areas of a field with the type of fertilizer most appropriate for that area and in what quantity, hence reducing costs and environmental hazards related to nutrient runoff [38]. One of the major benefits of a fertilization DSS is its site-specific nutrient management. This accuracy enables one to apply fertilizers at appropriate sites, applying the right amounts of nutrients to the crops according to the prevailing condition of the soil and stage of growth in real-time [39]. The inclusion of geographic information systems in some DSS tools for the development of nutrient maps further refines fertilization strategies [40]. Such DSS, integrated with IoT devices like soil sensors, takes the decision-making process forward through automated field data collection, hence making recommendations even more accurate [41]. Sophisticated DSS systems employ machine learning algorithms and fuzzy logic in handling complex data sets, thereby facilitating the adjustment of fertilization strategies dynamically during changes in the course of a growing season [42]. This will eventually lead to better yields due to reduced fertilizer waste and enhancement of sustainability in agriculture.

3. Types of Fertilizers

Precision agriculture technologies also include site-specific nutrient management that has assisted farmers in effectively using fertilizers by applying them in the right quantity and at the appropriate time and location. This reduces wastage and will increase yields [43]. Inventions of slow-release fertilizers and nano-fertilizers have been promising for improved nutrient absorption and reduced losses to the environment through leaching and runoff [44]. These fertilizers are prepared in such a way that advanced materials can ensure a slow release of nutrients to be made available to plants for longer periods, hence increased nitrogen use efficiency (NUE) and less frequency of application [45]. Besides, controlled-release fertilizers and biochar-based fertilizers are being applied in precision agriculture as a means to improve nutrient retention, hence enhancing fertilizer use efficiency (FUE) [46].

3.1. Nano fertilizer

Nano-fertilizers are prepared by encapsulation of plant-essential nutrients into nanomaterials, coating a thin layer of nanomaterials onto the nutrients, and delivering them in nano-sized emulsions [47]. Nano-fertilizers are a new frontier in precision agriculture, wherein nano-fertilizers greatly improve FUE through the delivery of nutrients in nanoscale form, thus enabling plants to absorb more nutrients through foliar or roots with specific modes of application and according to particle properties [48] due to its large surface area which enhances the penetration into the plant [49]. These fertilizers are specifically designed to provide nutrients to plants more effectively and for a longer period than conventional fertilizers, by minimizing nutrient leaching and runoff for optimum plant growth [50]. Nano-fertilizers have the potential to be designed for special nutrient deficiencies, hence reducing the amount of general fertilizer application, and consequently reducing environmental pollution [51].

Nano-fertilizers are often associated with sensors and decision support systems that monitor soil health and plant nutrient status for data-driven decisions on fertilization strategies by farmers. Nano-fertilizers formulated formulation enhances the effective nutrient uptake, restores fertility in the soil, promotes ultra-high absorption, boosts photosynthesis, increases crop yields, reduces soil toxicity, lowers the frequency of application, improves plant health, and minimizes environmental pollution [52]. Apart from enhancing FUE, nano-fertilizers can also have some additional advantages concerning crop resistance to stress and soil health due to micronutrient delivery at a nanoscale level [53].

3.2. Fertilizers with external coating

Some fertilizers have outer coatings, including polymer-coated and sulfur-coated urea, which have important applications in precision agriculture. These include increased efficiency of nutrient release and reduced environmental impact. The nutrient release is governed by such coatings that release the nutrients gradually and continually in time to the crop to meet the crop nutrient uptake rates. This method reduces nutrient losses through leaching or volatilization-particularly of nitrogenous fertilizers-and improves fertilizer use efficiency [54]. A good example includes polymer-coated fertilizers, which are designed to release nutrients over a period of weeks or months; this would decrease the frequency of application and reduce the chance of over-fertilization, leading to runoff and eventual water pollution [50]. Other emerging uses of nanotechnology involve the development of new, advanced coatings applied to fertilizers. These nanocoating could provide further development of controlled release formulations by releasing active nutrients more efficiently and, therefore, improving crop yield [55]. Higher growth in the use of bio-based and biodegradable coatings will become a trend in sustainable agriculture, as it reduces the concentration of non-degradable materials in the soils [56].

3.3. Lower Solubilize Fertilizers

Low-solubility fertilizers are very important for precision agriculture because they ensure efficiency in the use of nutrients while minimally affecting the environment. These kinds of fertilizers are also known as slow-release or controlled-release fertilizers and are usually designed in such a way that the nutrients contained within them can be released gradually over a specified time period to correspond better with the nutrient requirements of crops. This matter has helped control the rates of release and minimize the incidence of nutrient leaching and runoff quite common in the case of highly soluble fertilizers [46]. That is, in precision agriculture, less soluble fertilizers are applied with variable rate technology (VRT) and geographic information systems to apply the fertilizers at the right time, rate, and place [50]. This approach has the added advantage of minimizing the over-application of fertilizers that cause nutrient imbalance and degradation of the environment. Nanotechnology is also being applied in the formulation of fertilizers with lower solubility to give a better supply of nutrients, hence further improving fertilizer use efficiency [57]. Controlled-release fertilizers include sulfur-coated urea, among others, and have earned wide applications in precision agriculture because of their more sustainable nutrient delivery system. These improve crop yield with reduced frequency of application, besides minimizing nutrient losses [58].

4. Advanced Methods of Fertilizer applications

Advanced fertilization methods, within a modern agricultural context, are essential for improvement in nutrient uptake efficiency, minimization of environmental impacts, and furtherance of sustainable farming. Advanced fertilization techniques make nutrients available to the plant in the correct quantity and form at appropriate times so as not to undergo leaching loss, runoff, or volatilization processes. These improve nutrient use efficiency and restore soil fertility, eventually reducing the frequency of application, hence a cost-saving advantage for farmers. Besides that, they help plants grow in a better way and be more resistant, therefore their contribution to crop productivity is higher, and plants become healthier. Importantly, all of these methods mitigate negative effects due to traditional fertilization, such as soil degradation, water pollution, and greenhouse gas emissions supporting long-term environmental health and agricultural sustainability.

4.1. Variable Rate Technology (VRT)

Variable Rate Technology (VRT) is part of precision agriculture, which is the process of applying variables of inputs, such as fertilizers, seeds, and pesticides, variably across the field. VRT utilizes data from GIS, sensors, and satellite imagery to find any spatial variability in a given field and to thus apply inputs exactly where they are needed [59]. It applies fertilizers at variable rates across the field, depending on site-specific information on soil nutrient content and the growth stage of the crops [60]. VRT thus ensures that nutrients are applied only when and where they are needed, therefore minimizing the risk of over-fertilization and runoff.

One of the major advantages of VRT is the ability to optimize input applications based on real-time data, such as soil fertility and moisture levels, thus helping to improve fertilizer-use efficiency [61]. VRT is often combined with yield monitors and precision mapping to enable site-specific management. For instance, it can enable farmers to apply variable-rate fertilizer to high-yield areas so that those zones continue to have the nutrients that support high yields and only apply enough fertilizer to sustain healthy growth in the lower-yielding areas [62].

4.2. Fertigation

Fertigation is the method of precision agriculture wherein the delivery of fertilizers is carried out through irrigation flow. This technology manages nutrient supply and irrigation with high precision to make sure that the crop gets a satisfactory amount of nutrients at the proper time. Fertigation enhances nutrient use efficiency, diminishes the potential for nutrient loss through leaching or runoff, and boosts crop productivity [26]. This fertilization is integrated into precision agriculture technologies: GIS and VRT. It will ensure site-specific management of fertilizers and water, as the farmer will be able to adjust the rate of application regarding the nutrient requirements of the various zones in the field [63]. Fertigation also contributes to the economy in water and fertilizer use through its potential for better control of the application of inputs in consonance with real-time data from sensors and weather forecasts [64]. The fertigation system may also be integrated with IoT-based platforms for the automation of water and nutrient feeding. This intelligent framework of fertigation has already been applied to improving sustainable farming by optimizing resources used without affecting crop yield [26]. Fertigation allows the plants to absorb fertilizers more properly through irrigation systems for better health, thereby minimizing its impact on the environment.

5. Conclusion

In Conclusion, Precision agriculture has now opened up new fertilization methodologies that are enabled by high technology inputs like sensors, GPS, remote sensing, and data analytics, which allow for more precise, efficient, and sustainable methods of nutrient management. Different methods are VRT, fertigation, and nano-fertilizers, which increase the efficiency of fertilizers with the least harm to the environment, thus increasing agricultural yield. Farmers will be able to minimize losses in fertilizers by applying the right amount with the help of the IoT and WSN among other decision-making tools based on real-time data. This would provide a good chance to contribute towards meeting the global demand for food without compromising environmental integrity or jeopardizing the long-term sustainability of agriculture.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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