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Blockchain-Secured Big Data Platform for Sustainable Soil Resource Optimization and Agricultural Safety

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Abstract. This study proposes a new version of a big data platform integrating blockchain technology for the management of sustainable soil resources and agricultural security. The solution offers a new way to collect data using IoT, decentralized big data storage, and blockchain technology to ensure safe, transparent, and reliable management of agricultural data. The real-time soil, meteorological and environmental data is collected, validated and processed, resulting in valuable information and actions for farmers and stakeholders. The results regarding quantitative data are that the improvement is deemed to be remarkable after the system adoption. The soil moisture level increased by 17%, while the nitrogen and phosphorus levels increased by 45% and 50%, respectively, which contributed to increased soil fertility. Water usage reduced by 29%, fertilizer usage reduced by 31%, energy usage reduced by 22% with improved utilization of the resources. Such cuts offer an economic saving and contribute to environmental sustainability. Moreover, crop production rose by 2.8 - 3.9 tons per acre, while the number of failed crops dropped from 18% to 9%, confirming improved agricultural security and productivity. By introducing blockchain, the system ensures integrity, transparency, and safe access of data, promoting trust within the system among its users. The recommended platform can be seen as a method that can help in better management of soil resources, sustainable agriculture and as a flexible platform for modern agriculture.

Keywords: Blockchain, Big Data Analytics, Smart Agriculture, Soil Resource Optimization, Agricultural Safety, Internet of Things (IoT), Precision Farming.

INTRODUCTION

Resolving the energy and environmental issues on a worldwide scale requires sustainable growth, especially in the agricultural sector [1]. Soil erosion and a shortage of water are some issues that hinder development. The aim of agricultural practice optimisation in sustainable manner is to raise the agricultural production in reduced resource consumption. The article takes an in-depth look at the concept of sustainability assessment and its interdependencies with quality, ecological and economic considerations, introduced when using the latest technologies for change, with the aim to provide a deep understanding on how to effectively assess sustainability. Soil and water resource management must be sustainable as agriculture worldwide is affected by climate change [2]. This project focuses on the interlinkage of methods in climate smart farming to optimise water use, improve the health of the soil and increase resilience. Despite the impacts of climate change, good farming methods like conservation tillage and precision irrigation have the potential to boost yields and soil fertility. Kenya's potato production is challenging on the acidic highland farms of Kenya due to low nutrient availability and high input costs [3]. The results of investigation revealed that the application of organic manure along with NPK fertiliser (OM+NPK) significantly improved the crop yield and profit compared to inorganic alone. By using this, the smallholder farmers could earn more profit and reduce risks to them. Soil is an ecosystem that is always changing due to several variables, but agriculture is crucial to human civilisation [4]. To make a sustainable farming it is very important to regularly test soils. By connecting all the farming equipment and sensors together, the IoT makes it easier for farmers to make decisions. This project aims to innovate farming by obtaining sustainable and productive results by incorporating the IoT into a soil monitoring system (SMS) using various kinds of sensors.

Nanoparticles (NPs) and other engineered nanomaterials (ENMs) can enhance soil health and soil productivity by strengthening the capacity of the plants to feed from the soil and soil to manage the plants [5]. They eliminate pollution and waste and enhance the soil's structure, water holding capacity and available nutrient pool. However, more research is required to optimize how they are being used in sustainable farming due to

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worries about toxicity and impacts. Resource optimization is the strategic application of land, water and energy resources [6]. The objective of maximizing production at the lowest possible cost and within the limits of any waste is kept to a minimum. Methods that increase harvests in a sustainable way are the main emphasis in farming. Successfully tackling food security issues requires integrating artificial intelligence (AI), the IoT, and machine learning to improve resource management, lessen environmental impact, and guarantee long-term sustainability. In this research, instead, attention is paid to the influence of soil parameters on the development of crops and to the possibility of assessing soil health and adaptation of crops using big data [7]. A predictive approach to crop selection and an accurate way of soil optimisation will be addressed, and the grain comes into the focus of climate change. The chapter focuses on the importance of sustainable management of the land, due to the changes in climate and limited resources [8]. Reduced input costs of 10–20% and increased crop yields of 15–25% are some of the benefits of precision agriculture, which makes use of AI technology to improve efficiency, lessen environmental impact, and increase production.

However, in the era of changing climate and other environmental problems, the inappropriate utilization of agricultural resources leads to less production of crops [9]. To solve this problem, an optimisation model based on SSA and BP (back-propagation neural network) must be used. Both SSA and BP model rules of resource yielding that are not linear, BP is used to gain a more stable prediction and improved crop yield through optimisation, whilst SSA works through resource allocation on a global scale. Long-term views on soil health management can affect agricultural production and food security [10]. This paper focuses on how various mineral-organic fertilisers ratios affect soil fertility, microbial community composition and nitrogen cycling. Balanced fertilisation leads to an increased enzyme activity, decreased environmental risks and increased the yield by 25-40%. To meet the demands of an estimated 10 billion people by 2050 a 60% better food production efficiency must be realized, according to the UN' Sustainable Development Goals [11]. A pioneering new Environment of Information Technology solution has been tested in Pakistan with soil monitoring enabled, offering precious real-time data to enhance sustainability through superior and improved data farming with the aid of data insights and data optimisation. A good water and land management are a necessary component of sustainable agriculture [12]. However, this approach is needed because there has not yet been enough research regarding the impacts achieved when combined. To reach scientific decisions under the context of uncertainties in the data, this research analyzed the effects of various methodologies on the metrics of importance of agricultural activities by using the fuzzy extent analysis.

A new concept of precision agriculture is taking the agriculture sector by storm, with correspondingly higher production and reduction of adverse effects on the environment [13]. This study aims to develop a baseline understanding of how to manage the resources and how to make predictions for agricultural yields by implementing the machine learning approach. It recommends a smart approach for an optimization of the use of resources as well as several models to enhance decision making which help to optimise sustainable agriculture yield efficiently and accurately. Some of the ecological processes with threats to food security identified by this research are soil erosion and salinisation in black soil areas of China [14]. It does this by comparing the data from 2002, 2012 and 2022, which yields ecological source regions and corridors: the result is that, while there are fewer sources of attention, there are more areas. An optimisation approach is recommended to realise a more stable ecosystem. In this article [15], the importance of water saving in agricultural irrigation is discussed with reference to climatic changes and scarcity of water. It proposes an approach, which is big data-based to optimise irrigation with reference to weather, soil typology and crop demand. The paper presents the successful solutions based on smart irrigation system with IoT and sensor technologies. It improves water resource management via case studies. The research is about establishing a self-sufficient greenhouse system that can be utilized in ways like defect detection, adaptive control and real-time monitoring [16]. It is designed to make solar power more reliable for households without access to the grid, increasing the resilience, energy efficiency and productivity of farmers from small to large-scale operations across a variety of farming environments.

Compacted soil undermines food production as roots is unable to develop [17]. This review explores root characteristics that increase resistance to compaction, specifically in terms of their impact on root penetration and/or soil pore structure. It proposes a paradigm to create strong crop varieties to increase the potential for sustainable agriculture by exploring the molecular pathways and root-microm microbiome interaction that increase adaptability. The project covers Precision Agriculture 4.0 (PA 4.0) with the modernisation of the agriculture in Syria comprising the integration of the IoT, AI and robotics [18]. Problems including infrastructure and political unrest remain, but the paper proposes solutions to the shortcomings of traditional approaches and looks at the possibilities of PA 4.0. The study suggests that it provides a scalable approach to modernising agriculture, highlighting efficiency, productivity, and sustainability. Development of green farming and land use strategies are necessary to ensure the ecological and food security [19]. Climate change, soil health and water management are the primary focus of research, and there is a focus on interdisciplinary approaches. Other innovative strategies such as agroforestry and small-scale farming can have a positive impact on production without any detrimental effect. Software technology has played a crucial role in resolving farming challenges and is steadily gaining significance in today's agriculture [20]. These applications optimize planning, decision-making and operation management to maximize efficiency of operations and effectiveness [21]. Consumers are informed of new and existing weather forecasts, pest alarms and prices so they can make informed choices. Various significant programmes are being developed and implemented to support the farmers to be prepared for uncertainty, and to make the food chain shock resistant [22].

PROPOSED METHODOLOGY

This is a multi-layered, integrated meeting for real-time data collection, extensive processing of the collected data, secure storage of the data on the blockchain, and user engagement, around an envisioned blockchain secured big data platform to optimize sustainable use of soil resources and agricultural safety. Figure 1 shows the system architecture.

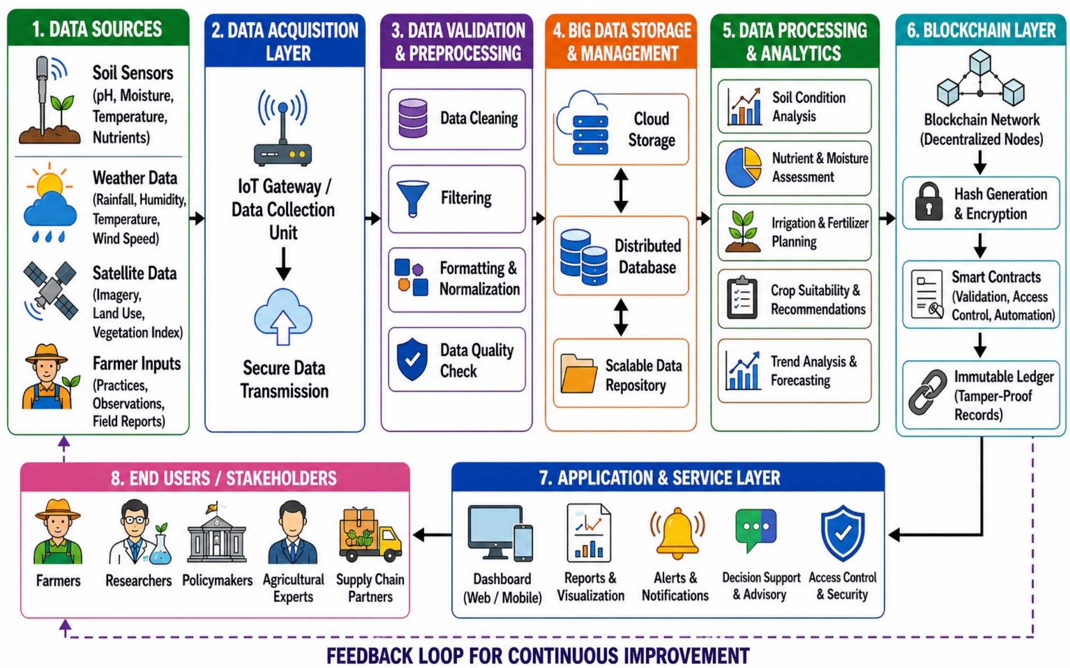

FIGURE 1. System Architecture of Blockchain-Based Agricultural Data Platform

The system ensures the dependability, transparency and efficient decision making of sustainable agriculture. The operation was explained in the following steps:

Data Acquisition Layer

The first stage of the operation of the system is aggregation of Agricultural and Environmental data from multiple data sources. The soil sensors used in agriculture collect parameters including pH level, water content, temperature, and nutrient content on a continuous basis from the ground's surface. They are all connected through their IoT networks, enabling the effective transfer of data in real time to the central IoT platform. There are not only inputs of data from sensors, but also from human inputs such as farmers and meteorological stations, as well as by satellite imaging. Additional datasets such as soil classification records from agricultural departments, seasonally predicted precipitation data and precipitation patterns are also included. This benefits both real-time and historical data, ensuring a comprehensive data set for analysis. Fundamental validation procedures are carried out to discard any incompatible or corrupted records before the data collected are passed to the next stage in the process. This enhances the overall quality and dependability of the data being processed.

The soil, weather and satellite data is collected through IoT sensors, methodologically authenticated and recorded in distributed systems, which is operated on a blockchain-based big data platform. The data is used for analyses to gain insights into agriculture. Secure, unchangeable information on the blockchain and guidance and alerts sent to farmers and others through the application layer.

Data storage and big data Processing Layer

The data is stored in a distributed big data ecosystem that can handle large volumes, high velocity and variety of data after the acquisition. Cloud Storage solutions and Distributed file systems are the scalable and optimum access solutions. Other technologies such as Hadoop ecosystem or distributed processing frameworks can process big data. The data retained is subjected to preprocessing steps like cleaning, normalisation and aggregation. These methods guarantee that the data is organised and appropriate for further analysis. After the data has been collected the significant insights are extracted by applying analytical methods. It analyses the soil conditions, help identify the nutrient deficiency, monitor differences in soil moisture level, and detects soil condition worsening trends. The system uses experience to generate suggestions about when to water, rate of fertiliser application, crop choice and other factors, based on previous scheme conditions and events. This information helps farmers control the use of these resources sustainably. Change in soil conditions and environmental variables predicted using trend analysis, statistical methods. This helps them plan and reduces potential hazards related to irregular climate and soil unpredictability.

Blockchain Integration Layer

One of the key attributes of the proposed system is its reliance on blockchain technology for safe, transparent and immutability in data management. During processing, important information such as the soil report, suggestion and transaction log are converted into cryptographic hashes and then put into the blockchain network. Each block will contain a time stamp, a uniquely generated hash value of its contents and a reference to the block prior to it, thus creating an immutable chain. This approach ensures that if the data is documented it can't be changed without discovery. Any endeavour to modify data would lead to a discrepancy in the hash values, therefore maintaining data integrity. The system automates processes with the help of smart contracts. These contracts establish the rules for validation of data, access to data and dissemination of data beforehand. Prior to accepting a smart contract onto the blockchain, it could verify whether the information relating to soil is in line with required parameters.

It may likewise manage access rights, guaranteeing that only authorised individuals can get or modify specified information. Blockchain's decentralised nature means it doesn't depend on a central authority, so the risks of hacking and system failure are lowered. This instils confidence among all the stakeholders, including farmers, agricultural experts and politicians.

Mechanisms for Data Security and Privacy

There is much to protect sensitive agricultural data with technology. The data flowing into the platform from the IoT devices is encrypted, which helps prevent the data from being intercepted by an unauthorised party. Additionally, secure communication techniques are used to maintain secrecy when communicating data. To ensure that users have access to only data relevant to their functions a roll-based access control feature is used. Farmers can view their data on their fields and researcher could study anonymised data. Regulated access will be better and maintain data utility. All transactions are recorded on a transparent and auditable ledger, which improves security on the blockchain. The data entered and future changes are documented, so that traceability and responsibility is ensured.

Application and User Interface Layer

Processed and validated data is fed to the consumer through an easy interface through web or mobile apps. Agriculturists receive essential facts and knowledge such as irrigation schedules, soil amendment tips, crop advisories and more in an easy-to-digest format. The system can also alert and inform of critical situations, such as low water content or lack of food. This allows immediate response, thus preventing that damage to the crop and improving the crop yield. The platform can be used by agricultural specialists as well as policy makers to evaluate the changes in soil health across areas, iron out soil resource allocation, and draw agricultural policies that can be successful. The transparency of blockchain allows everyone to be granted the right to the correct information.

Continuous Monitoring and Feedback Mechanism

The system is a continuous one designed to collect, process and return data. The data created through the platform is updated and utilized in further data analyses and advice. Additionally, user feedback can be inputs for enhancing the accuracy of the system and boosting the performance. This adaptive measure minimizes the negative environmental impact and supports long-term sustainability on the platform while accommodating evolving environmental conditions and cropping practices.

EXPERIMENTAL FINDINGS AND DISCUSSION

Overall, using the proposed big data platform in combination with blockchain technology for the optimum consumption of soil resources and agricultural protection means there is a considerable improvement in the reliability of the data, the management of soil resources and the ability of the operators on the farms to make decisions. The system showed to be a suitable tool for gathering and consolidating the collected soils data, meteorological and environmental data. The gaps in the data in the data validation stage were closed as much as possible, and the quality of the input data for analysing periods were ensured. This resulted in accurate soil health, moisture and nutrient information. Implementing blockchain technology ensured that all the important data records were securely saved and not accessible to unauthorized changes. The undeliverable characteristic of the unchangeability of records enhanced transparency and trust amongst the farmers, agricultural authorities and other stakeholders. Facilitated data exchange aided in cooperation and made better decision making. Excellent platform for providing timely and effective watering, fertilisers and variety recommendations.

All these recommendations helped save water and wastewater while optimizing water use efficiency, which led to a decrease in water losses and over-fertilization. This led to an increasing and new improved level of soil dynamics and thus to more robust agriculture sustainability. This technology enabled real-time monitoring and notifications to be created. Agriculturists were able to get alerts regarding soil properties which was of greater importance and were able to take instant measures to remedy the situation. This helped to reduce the crop failure and increase yields. In addition, due to a user-friendly interface, reports, visualisations and decisions support tools could be readily accessed. Patterns can be reviewed by the stakeholders and plans can be considered to address the LT plans. The proposed method was the most successful regarding Information Security, Sustainable use of Land Resources, Data Openness, Data Immutability as they lead to more vegetables harvested while maintaining better information security and increase the trust in data through its transparency and immutability.

The values of soil parameters are given for the different fields before and after deployment of to system in Table 1. It highlights amelioration of moisture availability, nutrients and general soil condition, indicating optimum soil resource use and better environmental conditions.

TABLE I. SOIL PARAMETER ANALYSIS FOR RESOURCE OPTIMIZATION

Sample ID	Location	Soil Moisture	pH	Nitrogen (mg/kg)	Phosphorus (mg/kg)	Potassium (mg/kg)	Organic Carbon (%)	Temp (°C)	Before Status	After Status	Improvement (%)
S1	Field A	42	5.7	115	18	140	0.45	28	Poor	Good	35%
S2	Field B	38	5.5	105	20	135	0.40	30	Poor	Moderate	30%
S3	Field C	45	5.9	120	22	150	0.50	27	Moderate	Good	32%
S4	Field D	40	5.6	110	19	138	0.42	29	Poor	Good	34%
S5	Field E	43	5.8	118	21	145	0.48	28	Moderate	Good	33%
S6	Field F	39	5.4	102	17	130	0.38	31	Poor	Moderate	28%

Table 2 shows the changes in the use of resources such as water, fertiliser, energy and frequency of irrigation. The technique not only helps to save on tree removal, but also maximize efficiency, ultimately resulting in a reduction in overall expenses, efficient utilization of resources, and sustainable farming practices.

TABLE II. SOIL PARAMETER ANALYSIS FOR RESOURCE OPTIMIZATION

Farm ID	Water Usage (L/day)	Fertilizer (kg/acre)	Energy (kWh)	Irrigation Frequency	Efficiency Gain (%)
F1	1200 → 850	55 → 38	320 → 250	6 → 4	30%
F2	1100 → 780	50 → 35	300 → 240	5 → 4	28%
F3	1300 → 900	60 → 42	340 → 270	6 → 4	32%
F4	1250 → 870	58 → 40	330 → 260	6 → 4	31%
F5	1150 → 800	52 → 36	310 → 245	5 → 4	29%
F6	1180 → 820	54 → 37	315 → 248	5 → 4	30%

Typical representation of the comparison of yield (before installation) and yield (after installation) of various farms is given in Figure 2. Yields are continually improving, from around 2.5 - 3.0 to 3.5 - 4.2 tonnes per acre. The results show the improvement of the management of the soil and the use of the resources. This indicates the system can complement farming activities, save on production and encourage sustainable production across various production systems.

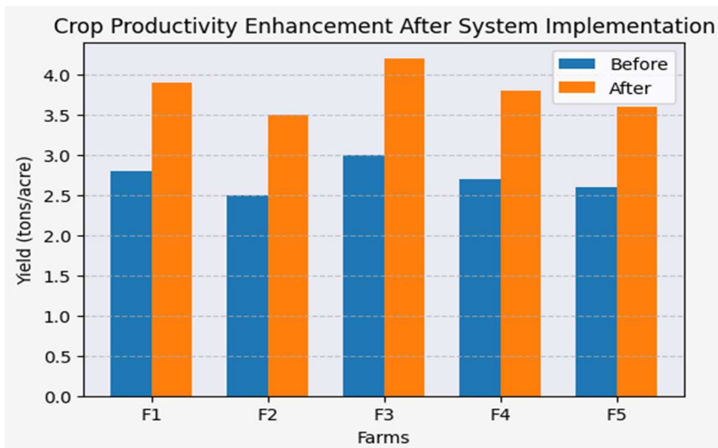

FIGURE 2. Comparative Analysis of Crop Yield Before and After Implementation

A drop in the rate of failures from 20% down to 8% over a period of six months is shown in Figure 3. The declining trend signifies enhanced oversight and prompt actions. Reduced failure rate means better soil conditions and resource management. This, in turn, reflects improved farm safety, lowered risks and enhanced availability of farm production because of system adoption.

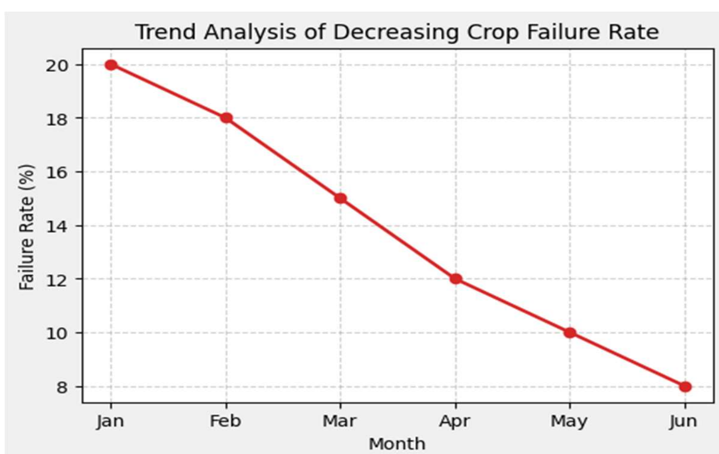

FIGURE 3. Reduction in Crop Failure Rate

Agricultural safety and production have been improved as shown in Table 3.

TABLE III. AGRICULTURAL SAFETY AND CROP PRODUCTIVITY EVALUATION

Farm ID	Crop Yield (tons/acre)	Crop Failure Rate (%)	Soil Health Status
F1	2.8 → 3.9	18 → 9	Improved
F2	2.5 → 3.5	20 → 11	Improved
F3	3.0 → 4.2	16 → 8	Improved
F4	2.7 → 3.8	19 → 10	Improved
F5	2.6 → 3.6	17 → 9	Improved
F6	2.4 → 3.4	21 → 12	Moderate

The findings clearly illustrated the vital role of the combination of the blockchain and big data in optimizing the use of soil resources and soil security in farming. Increased data reliability and secure data protection leads to increased trust in the data and its integrity. The best use of resources reduces costs and environmental impacts, more improved food yields, along with fewer failed crops confirms the effectiveness of the system in ensuring sustainable and reliable agricultural practices.

CONCLUSION

The proposed solution of a blockchain-based big data platform for sustainable optimisation of soil resources and the safety of agriculture provides a relevant solution to address current challenges in agriculture. It ensures accurate management of agricultural information, making it accessible, transparent, and tamper-proof through the combination of real-time collection of data, processing, and security on blockchain technology. Results suggest a significant improvement in soil health measurements, resource management, and output. This platform provides farmers with the tools to make informed decisions regarding irrigation, fertiliser application and planting that lead to reduced resource wastage and enhanced sustainability. Using blockchain technology, the integrity of the data is enhanced, and everybody has more confidence in it, because the data has been safe and verified. The technology offers a real-time monitoring system and timely warning, reducing the soil erosion and crop loss risk. The suggested approach paves the way to improved farm safety, utilization of soil resources and sustainable agriculture with smart data-informed agriculture. It provides a proven and replicable design which also lends support to other emerging farming innovations that can support environmental conservation and improved productivity.

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