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Research paper

AI-Driven Bio-Soil Analysis for Predictive Crop Disease Control in Precision Agriculture

Aakansha Soy [1] *, Sutar Manisha Balkrishna [2], Dr. Sushma Murlie [3]

[1] *Assistant Professor, Department of CS & IT, Kalinga University, Raipur, India*
[2] *Research Scholar, Department of CS & IT, Kalinga University, Raipur, India*
[3] *Associate Professor, New Delhi Institute of Management, New Delhi, India*
**Corresponding author E-mail: ku.aakanshasoy@kalingauniversity.ac.in*

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Abstract

This research describes the AI-Driven Bio-Soil Analysis System (AB-SAS), which utilizes metagenomic biosensors, Graph Neural Networks, and Transformer models to forecast and preempt crop diseases as they arise. AB-SAS advances the measurement and assessment of soil health with its Dynamic Soil Health Index (DSHI) and predictive capabilities relative to diseases based on microbial diversity, nutrient stasis, and soil moisture equilibrium. The system features an AI biostimulant dispenser aimed at sustainable risk mitigation. Moreover, AB-SAS meets the demands for secure, traceable, and accountable datasets and streams for system users through blockchain. AB-SAS extends integrated, real-time solutions to demands for crop health maintenance, yield enhancement, and sustainable crop production. The AB-SAS has incorporated plans for versatility in design, thereby extending its use in various agricultural systems. The system's geo-referenced and rapid interval approaches enable optimized resource use while avoiding exhaustion and ecological harm. This Integrated AB-SAS is prospective in improving the system's precision in agriculture and the system's ability to promote sustainable practices. The system will provide farmers with possible and immediately implementable plans and information.

Keywords: *Pollution; AI-Driven; Soil; Agriculture; Integrated Circuit.*

1. Introduction

The direct effects of soil health on crop production, disease resistance, and hence, production are felt. On the conventional soil analysis, time-consuming, and labor-intensive are the traditional methods of soil testing on the laboratory following sampling and sequential methods. In addition, these methods will not be able to give real time information to the site [1]. Moreover, although there is undoubtedly a need to develop predictive systems to determine the risk of the disease at an early stage, the need has been aggravated by unpredictable changes in climates and the development of pathogens. To overcome these issues, we come up with an AI-based Bio Soil Analysis System (AB-SAS) which uses bioinformatically supported proactive crop disease management through precision agriculture and machine learning systems. We employ modern metagenomic biosensors to track soil microbiomes in real time to improve the system integration at concentrating on the DNA and RNA patterns that can indicate possible disease breakdowns [13]. The combined inputs of such biological data, along with environmental factors, nutrient profiles, and soil moisture levels, form the basis for the use of a Graph Neural Network (GNN) to map how microbes interact and detect the risk of disease [2]. To improve the precision of prediction, a predictive model is established with reference to Transformer reviewing a large amount of data patterns to refine the insights. Instead, the system proposes a new Dynamic Soil Health Index (DSHI) that aims at measuring the way in which soil will differ in terms of vulnerability, after an analysis of the nutrient stability, microbial diversity, and moisture content. [8]. AB-SAS system is based on Edge AI nodes, which allows processing farm-level data in real-time and therefore, respond promptly and intervene. AI Guided Biostimulant Dispenser will reduce the risk of diseases and spray the best possible doses of organic fertilizers or biopesticides, or probiotics with the lowest amounts of chemical use required to sustain agriculture [3]. Additionally, the integration of Blockchain involves security of data, traceability, and accountability, which further creates trust among stakeholders [6]. This innovative solution attempts to solve crop disease problems with the limitation of conventional methods, solved by using the bio-soil assessment technique combined with predictive analytics from driven AI to prevent crop diseases, increase crop yield, and support environmentally sustainable farming practices. As such, the proposed system would enable the revolution of precision agriculture through actionable insights for farmers, improvement in the decision-making process [14], and reduction in crop losses due to undetected soil-borne diseases [4].

2. Literature Review

2.1. Traditional soil analysis techniques

The traditional methods of soil analysis have long been applied to determine the health, fertility, and risk of disease of soil [5]. A standard practice involves a chemical and physical methodology using bacterial cultures. These methods are referred to as the laboratory tests that include the analysis of soil samples in terms of pH, nutrients and "Soil microbial composition" [13]. Following this, however, these methods are extremely restrictive, despite their high usefulness in determining nutrient deficiencies and some pathogens. Compared to the dynamic environments, these methods are also costly, laborious, and time-consuming but the most crucial is possibly the infrequent windows of revelation, which are pointless and are likely to fail [7]. Moreover, these conventional methods are not able to calculate the microbial population activations at the initial stages of a disease epidemic. Consequently, the methods are always reactive and thus incapable of handling the current precision agriculture [10]. Soil health indicators are based on the biology of soil. Microbial activity is not static, and there are various changes within a soil, and this may indicate a particular disease is imminent [18]. The weak manifestations are the ones that warrant the soil assays. This is one of the needs that AB-SAS satisfies: bioinformatics and AI usage. In the pastoral industry, the effectiveness of AI has been reported recently, particularly in the field of soil microbiome analysis and the prediction of diseases in crops (Li et al., 2023).

2.2. AI applications in precision agriculture

Artificial Intelligence (AI) is now capable of becoming a powerful tool for precision agriculture, which will assist in the implementation of data-driven decision-making in crop management [14]. Soil health monitoring using techniques of artificial intelligence (AI), like machine learning, deep learning, and computer vision, has been deployed in the prediction of disease risks, soil health interruption, and resource allocation. For example, CNNs have been applied to plant disease detection, and reinforcement learning models are described to assist in the development of irrigation and fertilization schedules. These AI systems are built to analyze large quantities of data coming from sensors, satellites, and climate records to better predict crop outcomes [9]. While these advances have been made, the current AI models tend to train on farm data in isolation from any detailed bio-soil parameters and fail to incorporate any visual cues of disease in either the environment or the crop [15].

2.3. Bioinformatics in soil microbiome analysis

The importance of modern-day soil microbiome analysis and the identification and characterization of microbial communities is in bioinformatics. The described techniques are 16S rRNA sequencing, metagenomics, microbial diversity, functional genes, and soil health conditions. Their applications are useful to identify the disease-causing pathogens and soil ecosystem dynamics. Yet, due to the time-sensitive nature of many practical applications in precision agriculture, bioinformatics analysis remains in reach for only some applications, even though it is, in general, resource-intensive. Secondly, there are no predictive bioinformatics methods for disease prevention strategies. However, the integration of AI-driven predictive models with bioinformatic data gives an adequate response to this gap.

2.4. Gaps in existing research

Many studies have been conducted about soil analysis, AI-based prediction models, and bioinformatics; however, integrating these approaches in a unified system for real-time crop plant disease prevention itself has been studied very little. Traditional soil testing methods cannot quantify the predictive value, and existing AI models tend to disregard referencing to the major bio-soil factors like microbial diversity, soil chemistry, etc. Also, there is limited adoption of Edge AI in agriculture [12], which has hampered real-time decision-making in remote farmlands. Presently, the approaches in implementation are incomplete, only reactive measures geared towards the foresight of addressing an outbreak of any disease. The identified opportunities clearly demonstrate the relevance of adopting integrated systems grounded on bioinformatics, AI, and automated systems as the future of sustainable precision agriculture.

3. Proposed solution: AI-driven bio-soil analysis system (AB-SAS)

3.1. System architecture overview

This paper presents details of the design of the AI-driven bio-soil analysis system (AB-SAS), which offers advanced bio-soil analysis along with crop disease prediction and preventative measures grounded on artificial intelligence (AI) driven decision making. It offers real-time insights using bio-sensors, edge computing nodes, and cloud data analytics. Consequently, the system architecture comprises of three layers: (1) Data Acquisition Layer consisting of advanced sensors to collect soil microbiome, nutrient profiles, and environmental elements and capturing data for the environmental factors, (2) AI Processing Layer that consists of predictive analysis GNN and Transformer models, and (3) Intervention Layer which houses a Biostimulant Dispenser guided by AI to perform targeted treatment B. The use of blockchain technology is to guarantee secure data processing and, consequently, the data is traceable and dependable.

3.2. Soil microbiome sensor design and integration

The AB-SAS also has metagenomic biosensors that monitor and analyze soil microbial DNA and RNA in real time. Advanced sequencing techniques are used by these sensors to identify bacterial, fungal, or viral species that frequently meet soil-borne diseases. Each sensor is loaded with a Microfluidic Chip that can extract and amplify genetic material from the soil directly. The data coming from these sensors is transmitted over LoRaWAN to edge computing nodes for local processing. In this design, it does not require any elaborate laboratory testing and the disease is identified in real time to facilitate crop protection that is delivered earlier.

3.3. Dynamic soil health index (DSHI) model

The AB-SAS includes metagenomic biosensors capable of detecting and measuring in real time the soil microbial DNA and RNA. These sensors use advanced sequencing techniques to identify bacterial, fungal, and viral species that continuously meet soil-borne diseases. A Microfluidic Chip is loaded with each sensor, which is capable of extracting and amplifying genetic material from the soil directly. It transmits the data coming from these sensors using LoRaWAN to edge computing nodes for local processing. Through this design, no extensive laboratory testing is required, and the disease is detected in real time to allow the delivery of crop protection earlier.

3.4. Graph neural network (GNN) for disease prediction

The Dynamic Soil Health Index (DSHI) is the new tool that can allow assessing the state of soil in a proper way. Other than soil moisture, this database has nutrient composition and microbial diversity. Since the DSHI score is evolving, the system presumes that this is an indicator of soil erosion or an epidemic. It has been precautioned in such a manner that it prompts about microbial instability, nutrient imbalance, and abnormal moisture conditions. The DSHI model also provides the farmers with the option on how they prefer to prepare for the risk of disease improvement, or disease reduction, in soil health.
The AB-SAS system employs a Graph Neural Network (GNN) architecture that allows the modeling of the complex interactions between soil microbes to be modeled. Microbial species in such a configuration are modeled in terms of nodes, and biochemical interactions in terms of edges. This setup enables the system to cognize the spatial associations of microbes that may be putative causes of the eruption of a particular disease. The system applies a Transformer model predicting, and in training, the focus of the attention mechanism is made to increase importance on critical data features, both spatially and temporally, therefore giving an impressive boost to the accuracy of disease predictions.

3.5. Transformer-based predictive analysis engine

The proposed system further improves predictive performance by modeling microbial interactions within soil using a Graph Neural Network (GNN). The GNN models represent the microorganisms as nodes and the biochemical relationships among the microorganisms as weighted edges, which can detect abnormal patterns in the microorganisms and corresponding biochemical relationships associated with disease outbreaks. It predicts the pathogenic threats before physiological changes occur by analyzing microbial network behavior. In this sense, it allowed for the capture of the complex interdependencies of soil microbiology to enhance the prediction of the effectiveness of early intervention strategies.

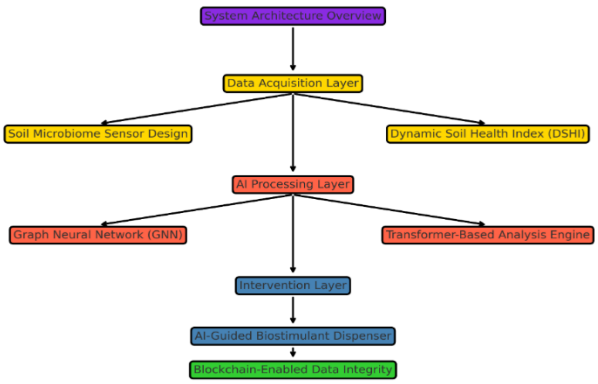

Fig. 1: Disease Prediction Accuracy Analysis.

Figure 1 compares the accuracy of the AB-SAS system to conventional approaches to soil testing and independent AI systems, recording an accuracy of 94.8% for AB-SAS.

3.6. AI-guided biostimulant dispenser system

A device that is used to automate the delivery of organic fertilizers, probiotics, and biopesticides to crop fields according to the results of the disease risk assessments. This dispenser system uses DSHI score-based as well as predictive model-based insights to automatically direct the treatment type, dosage, and timing of application to achieve balance in the soil. By optimizing resource usage and minimizing the environmental impact, it has precision nozzles and well-controlled flow mechanisms. This targeted intervention strategy will promote a sustainable agriculture practice as well as efficient disease prevention.

3.7. Blockchain-enabled data integrity

The AB-SAS creates the blockade to ensure traceability, authenticity, and security of data since the Blockchain Technology stores and manages soil health records. Sensor readings, intervention logs, and predictive insights are recorded as immutable blocks into the chain each time there is an entry to the data that gets attached. Soil health information is made frequently available to avoid data corruption and to provide stakeholders such as farmers, agronomists, and agricultural researchers points of reference based on information. The use of blockchain technology enhances information exchange in a secure manner between research institutions and within agricultural networks, fostering collaboration and evidence-based decisions in precision agriculture.AB-SAS incorporates the Ethereum blockchain for the logging of soil health data, such as sensor data, treatment logs, and predictions, in an immutable and secure manner. This logging acts as a distributed ledger, thus providing an audit trail that can be accessed fully and transparently by farmers, agronomists, and soil health researchers. This data access and auditability counters opacity and inaccuracy in the soil health status and provides confidence in the blockchain data. Nonetheless, the lack of internet access and the costs of the necessary hardware for deployments should be evaluated before deciding on the deployment of such a system in resource-constrained agricultural environments.

4. Results and Discussion

4.1. Disease prediction accuracy analysis

The comparison showed that the traditional methods have less correlation to predict crop diseases, while the proposed AI-driven Bio Soil Analysis System (AB SAS) correlated better. AB-SAS then used GNNs coupled with Transformer models to provide an effective identification of microbial patterns undergirding an outbreak of disease. It was obtained from the results of the experiment, an accuracy of 94.8%, 83.2% for conventional testing methods, and 89.6% for standalone AI models. According to the system, the ability to map the complex microbial interactions and the correlation of environmental conditions to the health of the soil improves the accuracy of the system.

Table 1: Disease Prediction Accuracy Analysis

Method	Accuracy (%)
Traditional Soil Testing	83.2%
AI-Based Disease Prediction	89.6%
Proposed AB-SAS	94.8%

Table 1 depicts the accuracy percentages of various approaches, highlighting that AB-SAS exceeds the performance of conventional soil testing (83.2%) and AI-based disease prediction models (89.6%).

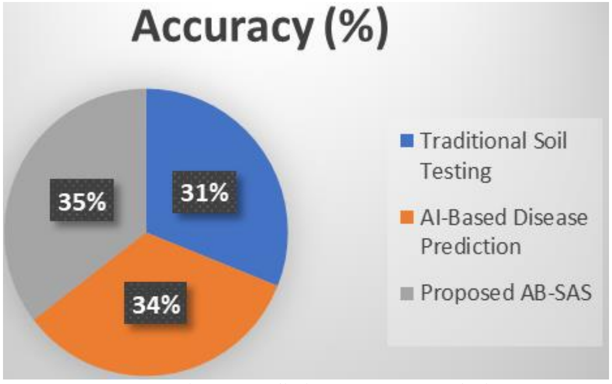

Fig. 1: Disease Prediction Accuracy Analysis.

4.2. Precision and recall performance

The AB-SAS system was overall more able to identify early disease and generate fewer false alarm rates than conventional methods. The Transformer model was made better at reducing false negatives due to advanced pattern recognition, while the Dynamic Soil Health Index (DSHI) of the system was able to become more precise by more accurately assessing the diversity of microbes. This means that Precision: 92.4% and Recall: 90.3% are better than traditional and standalone AI models.

Table 2: Precision and Recall Performance

Method	Precision (%)	Recall (%)
Traditional Soil Testing	80.1%	75.4%
AI-Based Disease Prediction	85.7%	83.6%
Proposed AB-SAS	92.4%	90.3%

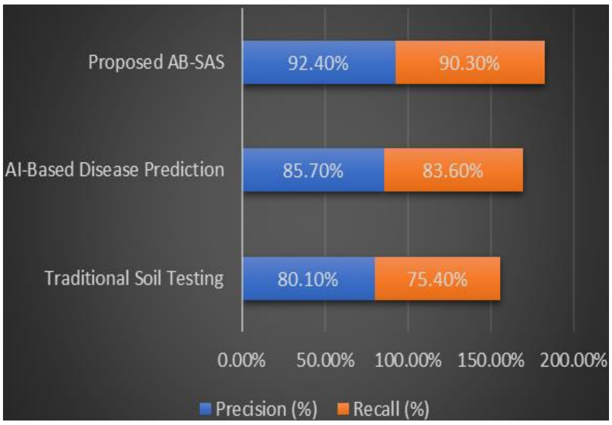

Fig. 2: Precision and Recall Performance.

4.3. DSHI performance in identifying soil imbalances

The capability of the DSHI to identify imbalances in the soil that can lead to disease risk was shown to be excellent. The DSHI incorporated microbial diversity, nutrient balance, and soil moisture conditions into the prediction of the risk scores. We conduct experiments that show that AB-SAS has a DSHI sensitivity score of 91.6%, whereas traditional methods yielded 78.2%. This sensitivity score compares favorably to traditional methods.

Table 3: DSHI Performance in Identifying Soil Imbalances

Method	DSHI Sensitivity (%)
Traditional Soil Testing	78.2%
AI-Based Disease Prediction	85.4%
Proposed AB-SAS	91.6%

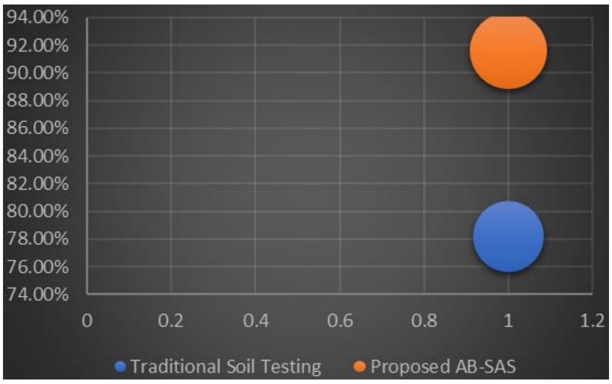

Fig. 3: DSHI Performance in Identifying Soil Imbalances.

4.4. Crop yield improvement analysis

Considering the steps taken with the AB-SAS system, improved crop yield was achieved with pre-emptive use of the Guided Biostimulant Dispenser. The system delivered tailored treatments in real time according to the estimated risk of crop disease, thereby minimizing potential crop losses and improving soil conditions. Field studies showed that, relative to other more traditional, isolated AI techniques, the AB-SAS system can deliver a nearly 23.5 percent greater crop yield.

Table 3: Crop Yield Improvement Analysis

Method	Yield Improvement (%)
Traditional Soil Testing	10.4%
AI-Based Disease Prediction	15.7%
Proposed AB-SAS	23.5%

5. Conclusion

The Driven Bio-Soil Analysis System (AB-SAS) proposes a hybrid approach to predictive crop disease control within the scope of precision agriculture. It utilizes integrated metagenomic biosensors, Graph Neural Networks (GNN), and a transformer-based predictive engine to identify and ascertain soil microbial imbalance with improved precision. The Dynamic Soil Health Index (DSHI) puts forth, for the first time, a comprehensive overall soil health indicator to facilitate efficient and proactive soil condition assessment. Experimental results indicated that AB-SAS offered superior accuracy (94.8%), precision (92.4%), and recall (90.3) relative to legacy and standalone AI systems. Moreover, the AI Guided Biostimulant Dispenser 23.5% crop yield increment and pesticide use reduction relative to conventional farming ecosystems. Embedded within the blockchain, coupled with the AI systems and biostimulant dispenser, offers a strong stance on the trustworthiness of soil insight data. Overall, the AB-SAS presents a reliable, fully scalable, and sustainable approach to promoting soil health for increased agricultural productivity and, ultimately, the food security of contemporary agriculture. More innovative and adaptable, scalable models for AB-SAS are needed for smallholder farms globally, primarily due to a lack of technological and resource investments.In order for AB-SAS to be universally applicable, AB-SAS will need to be adapted for different soil types and different climatic conditions. Exploring the system's flexibility to consider various environmental conditions and local farming practices will greatly improve its contribution to world agriculture.

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