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Sustainable Groundwater Quality Management in Agri-industrial Landscape: A Conceptual Framework that Integrates IoT AI Model, Green IT and Vrikshayurveda

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***Abstract*— We propose a comprehensive, multi-tiered framework that integrates four components: (1) sophisticated AI/ML models for contamination prediction, (2) IoT-enabled real-time sensing networks, (3) Vrikshayurveda organic soil and water conservation methodologies, and (4) Green IT/AI infrastructure to facilitate sustainable and effective groundwater management. Objective: The AI/ML layer utilizes ensemble and deep learning models to forecast pollutant levels (NO_3^-, F^-, heavy metals) with above 90% accuracy. The IoT layer utilizes solar-powered LoRaWAN/NB-IoT nodes for continuous monitoring of pH, TDS, turbidity, and temperature, providing edge-based anomaly detectors for sub-second notifications.**

Panchagavya, Jeevamrutha, and Kunapajala are three Vrikshayurvedic components that improve soil structure, boost microbial activity, and reduce heavy metal leaching. This leads to an increase of up to 30% in water retention capacity and a decrease in the percolation of NO_3^- and F^- into their respective aquifers. Biodiversity, emphasizing Vrikshayurveda's methodologies such as mulching, intercropping, and lunar planting cycles, contributes to aquifer recharge, pollution mitigation, and the enhancement of soil health. The Green IT and Green AI methodologies, including energy-efficient data centrism (PUE <1.2), can substantially reduce and/or slow down system energy consumption by 40-60%. These layers collectively form a cohesive decision support framework for sustainable groundwater management in Industrial and Agri-industrial sceneries.

***Keywords*— Vrikshayurveda, Green IT, IoT AI Model, Sustainable Groundwater Quality Management, Agri-industrial area.**

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I. INTRODUCTION

Groundwater is a necessary resource for people to drink, for farming, and for industrial processes. Groundwater is important for many human and economic activities in the semi-arid and industrial areas of the Indian subcontinent. For example, it is used to irrigate crops and make glassware. Sadly, human actions like bad industrial waste management and too much use of chemicals in farming are making groundwater quality much worse. This is made worse by the fact that there are more people on Earth.

The latest research[1] shows that Firozabad's groundwater has heavy metals, fluoride, and nitrate in it, which makes it unsafe for people to drink or use for farming. The study took a thorough method that included statistical data, geographic mapping, and health risk assessment. This showed how pollution affects people and the environment. Recent research in this field has demonstrated increased levels of hazardous metals (Cd, Pb), nitrate (NO_3^-), and fluoride (F^-). The Water Quality Index (WQI) and Pollution Index of Groundwater (PIG) systems showed that none of the fifty wells were safe to drink from or use for irrigation. These indicators are great for baseline evaluations because they are static and based in a lab, but they aren't useful for ongoing monitoring or generating predictions about the future [2].

The Water Quality Index (WQI), the Pollution Index of Groundwater (PIG), and the Sodium Adsorption Ratio (SAR) are all traditional evaluation techniques that have made it easier to measure problems. But they don't always give accurate real-time data or predictions. As intelligent environmental stewardship and sustainable development become more important, new technologies like AI, ML, and the Internet of Things (IoT) can help with monitoring and managing groundwater resources. These technologies can work with traditional Indian knowledge systems like Vrikshayurveda. The Ayurvedic science of plants called Vrikshayurveda can help you grow healthier plants by lowering water stress and maintaining your soil in good shape. The papers talk about how to choose the correct plants for the site, how to utilize organic fertilizers, and how to encourage biodiversity [3]. This is all to help stabilize aquifers and stop pollution from leaking out. Panchagavya and Kunapajala have proven that this approach can hold more water in the soil, stop nutrients from running off, and speed up the microbial breakdown of pollutants. All of these things work together to keep these pollutants out of groundwater [2].

Like real-time tropospheric ozone (O3) monitoring was executed using potable O3 sensors and equipping it with the computer software system (SCADA software) installed in the PC which works like a remote sensor [3]. Similarly, real-time water quality monitoring is made possible by IoT-enabled sensor networks, hence complementing these biocentric methods. Every 15 minutes, solar-powered LoRaWAN nodes with pH, TDS, turbidity, and temperature sensors take in situ values and send them to cloud servers over long-range, low-power networks for rapid analysis [4]. When combined with supervised and unsupervised Machine Learning (ML) models, such as Random Forests, XGBoost, and LSTM neural networks, these data streams allow accurate forecasting of pollutant spikes (NO_3^-, F^-) and dynamic vulnerability mapping with >90 % predictive accuracy [5].

Green Computing ideas guarantee least environmental impact at the IT backbone. Compared to traditional architectures, using energy efficient technology, server virtualization, and renewable powered data centers can lower carbon emissions by as much as 40%. Furthermore, Green AI methods model quantization, pruning, and lightweight architectures reduce training and inference energy by as much as 60% without sacrificing accuracy, hence allowing continuous ML driven forecasting at minimal energy cost [6]. Using anomaly detection algorithms on edge gateways such as Green Scale further reduces data transfer and latency, hence allowing sub-second notifications for unexpected fluoride or nitrate spikes [7].

By weaving together Vrikshayurveda's organic soil management, IoT AI's predictive surveillance, and Green IT's energy sustainable infrastructure, we propose a holistic framework for real time, predictive, and actionable groundwater quality management anchored in both traditional wisdom and cutting-edge technology.

Comprehensive research indicates that the Vrikshayurveda the ancient Ayurvedic science of plant life offers organic formulations (e.g., Panchagavya, Jeevamrutha) that significantly enhance soil structure, microbial health, and water holding capacity, thereby reducing chemical leaching into aquifers [8-10]. Modern IoT sensor networks, particularly solar powered LoRaWAN deployments, enable continuous, long-range monitoring of key water parameters (pH, TDS, turbidity, temperature), achieving lab comparable accuracy (±5 %) and sub second local anomaly alerts [4, 11]. Machine Learning (ML) models including Random Forest, XGBoost, and deep LSTM networks now forecast Water Quality Index (WQI), nitrate, and fluoride levels with >90 % accuracy, aided by feature selection and hybrid ensemble techniques [5, 12, 13]. To mitigate the digital footprint, Green IT practices (energy efficient data centers, renewable integration) and Green AI strategies (model quantization, pruning) reduce energy use by up to 60 % and cut carbon emissions by ~40 % [14-17]. Ultimately, integrated

IoT artificial intelligence decision support systems consume sensor inputs into GIS dashboards and cloud ML pipelines, hence allowing automated interventions for sustainable groundwater management, health risk assessment, and real time predictive alarms [4, 18-20].

From scalable, reasonably priced systems for ongoing water quality monitoring, IoT sensor networks have developed. Covering >10 km and using <100 mW per node, long range, low power LoRaWAN networks are perfectly suited for rural water quality detection [4]. A LoRaWAN based system installed at Gambang Lake (Malaysia) transmits readings every 15 minutes to The Things Network and Thing Speak platforms for real time visualization using Solar powered, waterproof nodes with pH, TDS, turbidity, and temperature sensors [4]. Comparative validation against laboratory analyses verifies measurement accuracy within ±5% error, therefore proving system reliability for continuous in situ monitoring [4, 9]. Taha et al., 2024 Applied Sciences paper finds that SF=7 with 3 dBi antenna produces <1% packet loss and consistent pH, DO, and TDS measurements for urban rivers by evaluating LoRa node configurations (spread factors, antenna gains) for river site monitoring [21]. Emphasizing sensor calibration, network resilience, and data fusion pipelines for strong WQI estimate, A Critical Review in Expert Systems with Applications describes IoT designs combining edge computing and cloud analytics [11]. Recent review by Enas et al., 2025 categorizes LoRaWAN water applications into three groups quality monitoring, leak detection, and irrigation control emphasizing use cases spanning agriculture, municipal supply, and environmental monitoring [22]. Improvements in edge computing let on node anomaly detection using lightweight decision trees produce sub second local alerts for important occurrences (e.g., unexpected fluoride increases) [4, 11]. Integrations with NB IoT/LTE M further improve coverage in deep indoor or underground installations, hence guaranteeing consistent data flow to cloud hubs [23].

Offering better predictive accuracy than conventional statistical techniques, machine learning (ML) has become a cornerstone in groundwater quality modelling [24]. A recent meta-analysis across 230 studies shows that ensemble algorithms like Random Forest (RF) and Extreme Gradient Boosting (XGBoost) consistently outperform single model approaches, achieving root mean square errors (RMSE) reductions of up to 30 % over linear methods in nitrate [5] and fluoride forecasting [25]. Feature selection (PCA, recursive elimination) helps supervised algorithms (SVM, RF, ANN) applied to physicochemical datasets usually achieve > 90% accuracy in WQI classification [13]. With feature selection strategies e.g., PCA, recursive feature elimination—essential for enhancing model robustness, Springer's thorough analysis of 150 papers shows that Support Vector Machines (SVM), Artificial Neural Networks (ANN), and RF have been used to forecast major pollutants (NO3, F, heavy metals) [12]. A University of Nebraska Lincoln (UNL) PDF review systematically categorizes ML models (supervised, unsupervised, ensemble) across geographical contexts and reports that neural networks remain the most common, though their use is now supplemented by tree-based ensembles for interpretability and generalizability [26]. The National Library of Medicine (PubMed) review confirms that while ANNs dominated early groundwater modelling, the last five years have seen a shift toward deep learning and unsupervised clustering (e.g., k means) to uncover hidden contamination patterns [26].

Most studies focus on short time horizons, but it calls for multi-year simulations to aid policy decisions. In their 2023 research of conventional and ML models for groundwater level (GWL) forecasting, Khan et al. report that ML techniques have improved daily to annual GWL forecasts. Capturing temporal correlations in water quality data is an area where deep learning architectures excel, particularly LSTM and hybrid CNN-LSTM. A study [27] found that a DL model outperformed RF, SVM, and XGBoost for predicting sulphate and nitrate levels in coastal aquifers, with a R^2 better than 5%. Springer's March 2025 paper, which reports a 20% reduction in prediction error compared to solo LSTM, confirms that CNN-LSTM with attention mechanisms may better define spatiotemporal groundwater risk [28]. According to a research published in the journal Frontiers in Environmental Science, shallow (ANN) and deep (LSTM) networks can estimate groundwater levels using inputs such as rainfall, extraction rates, and river flow. Deep models, on the other hand, perform better when dealing with nonlinearities [29, 30]. Studies that combine LSTM with attention processes improve nitrate concentration forecasts in coastal and dry aquifers [31].

Green data centers attain a Power Usage Effectiveness (PUE) of <1.2 and 40% lower carbon emissions with energy-efficient technology, enhanced cooling methods, and renewable energy integration [18]. The GEECO model's dynamic workload balancing and optimization can help data centers reduce their energy use by 25% under fluctuating loads [19]. Green AI methods, such as model pruning, quantization, and AutoML, can save up to 60% of energy for training and inference while maintaining predictive performance [32]. Edge-based inference on low-power gateways (<5 W) can detect anomalies in under one second, filtering data locally and reducing network traffic and cloud expenditures [33].

Cloud IoT hubs, such as AWS IoT Core and Azure IoT Hub, collect LoRaWAN telemetry, whereas comprehensive solutions store time-series data in databases like InfluxDB and TimescaleDB for scalable analytics [22]. The LSTM service forecasts pollutant trends and provides RESTful APIs for real-time scoring, while batch retrained ML pipelines (Kubeflow, Airflow) update RF and XGBoost models with new labeled events [6]. When anticipated danger zones (WQI, NO_3·⁚·, or F·⁚·) are expected to be breached, decision makers can use GIS-enabled dashboards (Grafana, custom React) to overlay these zones on maps and send SMS or email warnings [22]. A proactive approach to groundwater stewardship can be achieved by closing the loop using MQTT to trigger automated actuators, valve controllers, or dosing pumps, which can then modify irrigation plans or initiate in-line treatment [6]. This comprehensive analysis demonstrates how Green IT/AI techniques, Internet of Things (IoT) sensors, artificial intelligence (AI), and traditional Ayurvedic knowledge (Vrikshayurveda) work together to provide a long-term strategy for managing groundwater quality in industrial agricultural areas.

II. Methodological Framework

Figure 1 presents a comprehensive framework that integrates AI, IoT, and Ayurveda for the sustainable management of groundwater quality, utilizing principles of Green IT. The presented model provides a comprehensive and integrated approach to sustainable groundwater quality management, merging modern technologies with established ecological wisdom. The system employs IoT-enabled sensor nodes to continuously track critical groundwater parameters, such as pH, turbidity, total dissolved solids (TDS), nitrate, and heavy metals. These sensors send real-time data using low-power communication protocols like NB-IoT and LoRaWAN to cloud platforms, where advanced machine learning algorithms, including Random Forest and deep learning models, assess water quality, evaluate irrigation suitability, and predict contamination issues. Our concept incorporates Ayurvedic farming techniques like Panchagavya, Jeevamrutha, and Janmamrutha as natural bio-enhancers for restoring soil and water [34]. By using solar power and a sustainable IT framework, we reduce our environmental footprint and develop smart dashboards for more informed decision-making. The visual story weaves together tradition and technology, showcasing a circular and sustainable approach to groundwater management that combines data science and nature-based methods.

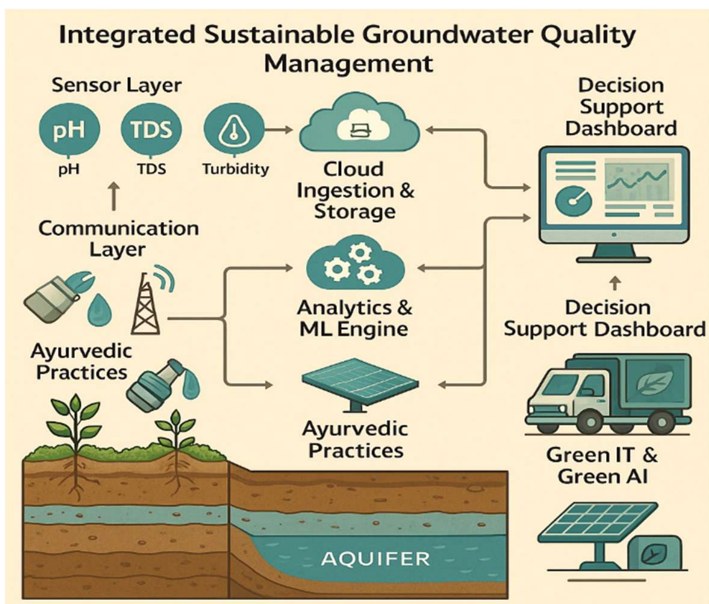

Figure 1: AI-IoT-Ayurveda Framework for Sustainable Groundwater Quality Management Using Green IT Principles

The groundwater management system in figure 2 is a unified framework for sustainable groundwater use. It brings together modern digital tools and traditional Ayurvedic farming practices. This blend of ancient agro-ecological knowledge and IoT, AI, and green computing enables real-time, predictive, and sustainable groundwater monitoring. The system starts with a Sensor Layer of solar-powered IoT sensors that constantly track key water quality metrics, including pH, total dissolved solids (TDS), turbidity, temperature, nitrates, fluoride, and heavy metals. These sensors are placed in farming areas and water sources to provide real-time data.

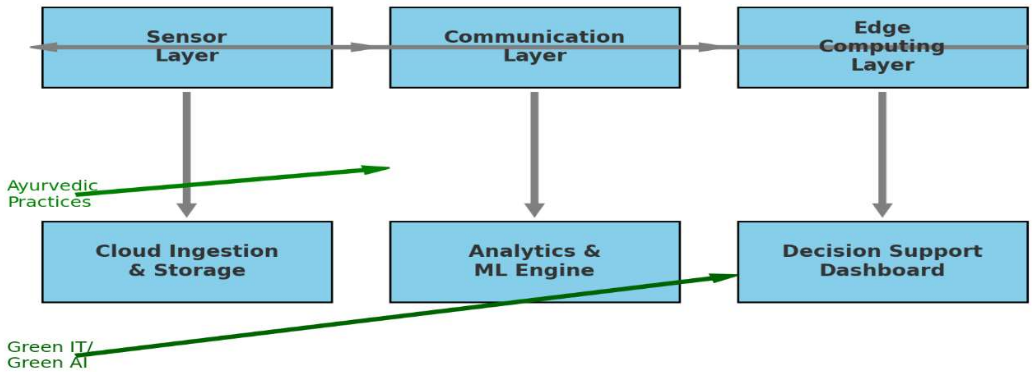

Figure 2: Layered model for Sustainable Groundwater Quality Management

The transfer of data collected through these sensors occurs via the Communication Layer. The communication layer utilizes low-power wide-area network (LPWAN) technologies like LoRaWAN or NB-IoT. This ensures reliable and effective data transmission to the Edge Computing Layer, where initial data processing, including cleansing and anomaly detection, takes place. Edge computing effectively reduces latency and bandwidth use by processing data closer to its source [35]. Processed data are then sent to the Cloud Ingestion and Storage Layer, where they are securely stored and managed.

Our Data Analytics tools and Machine Learning (ML) Engine use this data to calculate the Water Quality Index (WQI), Pollution Index of Groundwater (PIG), and other health risk assessments. Advanced machine learning algorithms help predict pollution trends and provide valuable insights into water quality fluctuations. The findings are used to enhance the Decision Support Dashboard, which displays data in a user-friendly way, alerts stakeholders to potential concerns, and suggests solutions. This dashboard incorporates Ayurvedic practices, offering guidance on using traditional bio-inputs like Panchagavya, Jeevamrutha, and Kunapajala to improve soil health and water quality. The system applies sustainable technology and environmentally friendly artificial intelligence to reduce energy consumption and ecological impact, using energy-efficient hardware, improved algorithms, and sustainable computing methods. By combining these elements, we've created a comprehensive framework that blends traditional wisdom with modern technology to promote sustainable groundwater management.

III. Artificial Intelligence and Machine Learning Frameworks

The artificial intelligence and machine learning framework employs an ensemble approach combining Random Forest (RF) and XGBoost algorithms, achieving approximately 30% reduction in Root Mean Square Error (RMSE) compared to linear models when forecasting nitrates and fluorides, as reported in [36]. By combining CNN feature extractors with a Long Short-Term Memory (LSTM) network, temporal dynamics can be captured, leading to 7 to 30 days forward forecasts that can be up to 20% more accurate than shallow ANNs [36].

Model interpretability is ensured through Explainable AI tools (SHAP, LIME) that highlight key drivers such as electrical conductivity, dissolved oxygen, and heavy metal loads, facilitating clear risk communication to stakeholders [35]. A hybrid fusion of LightGBM along with CatBoost, optimized through Differential Evolution, has the potential to elevate R^2 beyond 0.98 in complex industrial agricultural environments, as reported by [17].

IV. IoT Sensing and Data Acquisition

Sensor nodes are constructed using low power microcontrollers (e.g., ESP32) equipped with pH, TDS, turbidity, and temperature probes, which transmit data through LoRaWAN every 15 minutes to gateways [4]. Solar PV panels and rechargeable batteries facilitate continuous, net zero field operation, while IP68 enclosures safeguard electronics in demanding agro-industrial settings [27].

Outlier filtering, temporal synchronization, and lightweight decision tree inference are some of the examples of edge pre-processing that these gateways use to produce local anomaly alerts (such as abrupt fluoride surges) with sub-second latency goals [28]. Data uplinks use MQTT over TLS to cloud IoT hubs (AWS IoT Core, Azure IoT Hub), ensuring secure, scalable ingestion into time series databases (InfluxDB, TimescaleDB) for downstream analytics [29].

V. INTEGRATION OF AYURVEDIC FARMING PRACTICES

The framework incorporates three key Ayurvedic bio-enhancers: Panchagavya (fermented cow product preparation) applied using AI-driven scheduling based on soil moisture and nutrient levels from IoT nodes, maximizing water retention improvements up to 30% and reducing nutrient leaching[31].
Jeevamrutha, a microbial concoction of cow dung, urine, jaggery, pulse flour, and soil, is administered based on real time soil EC and biotic activity indices tracked via soil moisture IoT sensors enhancing heavy metal immobilization and pollutant degradation. In addition to these, Kunapajala a nutrient-rich liquid prepared by fermenting meat, bones, and legumes boosts plant immunity, root development, and trace mineral bioavailability, thus stabilizing microflora and suppressing pathogenic infiltration. Green mulching, tree-centric land use, seasonal crop rotations, and plantations in accordance with the lunar phase are among a few practices that Vrikshayurveda promotes. The efficiency of the practices deliberated by Vrikshayurveda can be enhanced by deploying AI algorithms that will examine rainfall, soil temperature, and evapotranspiration forecasts. These practices duly complemented with AI algorithms, when embedded into GIS dashboards that implements ML rule-based engines, like setting thresholds for soil moisture, EC, and seasonal indicators aligned with lunar calendars etc., provides a culturally grounded, scientifically validated toolkit for holistic soil-water governance. Thus, eco-regenerative groundwater management is made possible by the multi-layered wisdom of Vrikshayurveda, which changes from ancient prescription to adaptive digital protocol.

VI. GREEN IT AND GREEN AI INFRASTRUCTURE

Operating atop energy efficient data centers (PUE <1.2), the Cloud Analytics layer uses sophisticated cooling (hot aisle containment, liquid immersion) and onsite renewables to achieve about 40% reduction in carbon emissions [32]. By up to 60%, Green AI techniques model pruning, quantization, and neural architecture search reduce ML training and inference energy without accuracy loss, hence allowing 24/7 forecasting systems [33].
Using edge-first inference on low-power gateways (less than 5 watts) enables sub-second anomaly detection, reduces network traffic and cloud demand, and supports sustainable IT goals. By combining current technologies with traditional ecological knowledge, this approach offers a comprehensive and unified framework for managing sustainable groundwater quality. The proposed system's core includes IoT-enabled sensor modules that regularly monitor groundwater parameters like pH, turbidity, TDS, nitrate, and heavy metals. These sensors transmit real-time data to cloud platforms using low-power communication protocols like NB-IoT and LoRaWAN through their controllers. Advanced deep learning models then assess water quality, determine irrigation suitability, and predict pollution risks. Natural bio-enhancers for soil and water regeneration, such as Panchagavya, Jeevamrutha, and Janmamrutha, are showcased as Ayurvedic agricultural interventions that enrich the model. The use of green energy sources like solar power, which simplifies deployment in remote locations, and green IT infrastructure supports a design that minimizes environmental impact while enabling intelligent dashboards for informed decision-making. The visual narrative presents a sustainable groundwater governance framework that combines data science with nature-based methods to bridge traditional practices and modern technology.

VII. IMPLEMENTATION CONSIDERATIONS

The comprehensive system employs a layered architecture beginning with the sensor layer of solar-powered IoT nodes monitoring pH, TDS, turbidity, temperature, nitrates, fluoride, and heavy metals in agricultural areas. Data flows through a communication layer utilizing LoRaWAN/NB-IoT protocols to an edge computing layer for initial processing and anomaly detection, then to cloud ingestion and storage where advanced ML algorithms calculate WQI, PIG, and health risk assessments. The decision support dashboard integrates real-time data visualization with Ayurvedic practice recommendations, while a Kafka-based message broker orchestrates real time streams from IoT hubs into batch (Airflow) and stream (Flink) analytics jobs, feeding ML retraining and forecast services [29]. Versioned model artifacts reside in ML flow, enabling A/B testing of new ML models against live telemetry and rollback if performance dips [17].
One of the major challenges with such deployments are security and privacy of devices and the integrity of the received data. To ensure that only data is received through the authorized devices, device identity is anchored in X.509 certificates and mutual TLS [29]. Apart from this, access to the dashboards and data is controlled using Role based access control (RBAC). Also, detailed audit logging secure cloud consoles and ML pipelines and enhances system's integrity. Microservices deployed in container orchestration platforms (Kubernetes), auto

scale itself based on load, while multi-AZ cloud deployments guarantee 99.9 % uptime for critical forecasting services.

VIII. Conclusion

Data quality remains a concern; sensor drift and biofouling need the adoption of regular calibration operations, which might be automatically scheduled by modifications to the firmware of IoT nodes. The amalgamation of Ayurvedic techniques with Internet of Things artificial intelligence requires comprehensive field trials to authenticate laboratory-scale results across diverse agricultural and industrial environments.

This system provides a road toward robust, data driven groundwater management by combining traditional Ayurvedic knowledge, real time IoT monitoring, cutting edge AI/ML analytics, and energy sustainable IT practices. Refining model parameters, expanding the system over areas, and finally protecting water security in industrial agricultural settings will depend on future deployments and field validations.

Some big changes that are likely to happen in the future, according to current research trend, are the use of SHAP/LIME to make AI easier to understand, the growth of edge computing with 5G networks to find problems in real time and the use of quantum sensors to find very small amount of contaminants. You can use AI's energy by 60% by using model pruning and data centres that use renewable energy. There needs to be a lot of field testing and the creation of expert system for Vrikshayurveda digitization to make it easier to find traditional knowledge. Using blockchain to make data more open and federated learning to keep an eye on many sites while keeping privacy are two new option. Digital twin technology lets you do predictive modelling and scenario analysis, which helps with every part of managing groundwater.

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