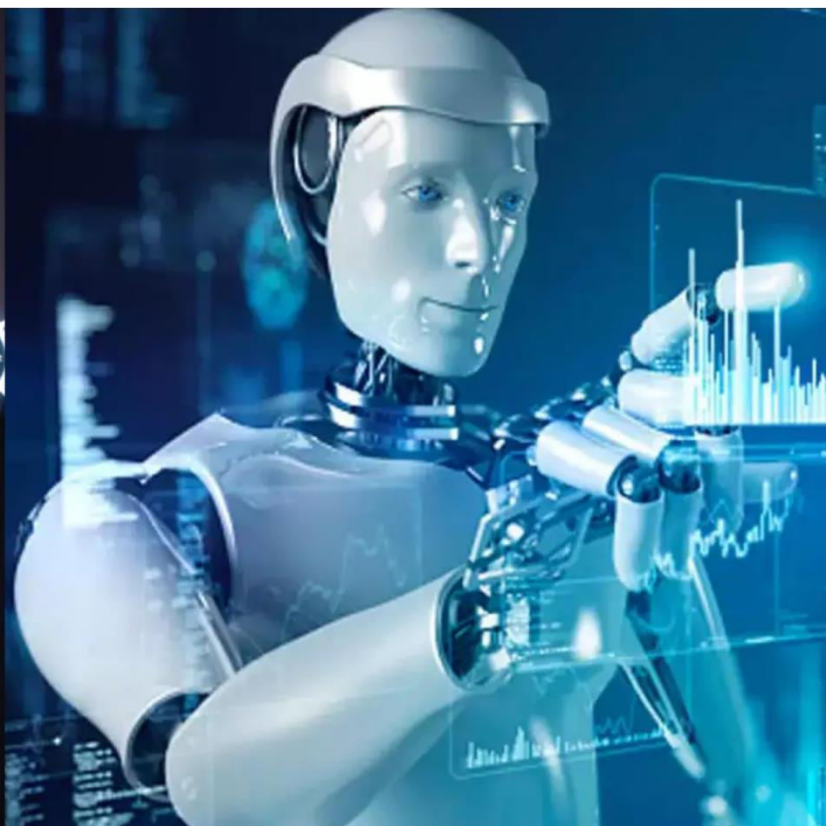




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Federated Edge AI Framework for Climate-Resilient Precision Agriculture: A Privacy-Preserving Approach for Crop Health, Irrigation, Climate Stress, and Disease Risk Prediction

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ABSTRACT: This Proposed federated edge AI system designed for multi-task agricultural prediction in order to support climate-resilient precision farming. The suggested method reduces data transmission delays and maintains confidentiality while enabling safe collaborative model creation across multiple agricultural datasets using federated learning and edge computing. A variety of agricultural problems, such as yield prediction, pest identification, and soil moisture assessment, may be effectively handled by multitasking learning depending on the surrounding circumstances. Tests using numerous datasets demonstrate that our method performs better than conventional AI systems in terms of accuracy and reliability. It is a useful instrument for sustainable agriculture due to its scalability and climate change adaptability. Our solution is more resilient to network outages and stable since it takes decisions in real time without relying on a central cloud server. Farmers and other stakeholders gain from the use of explainable AI technologies, which promote transparency and trust. This article discusses developments in artificial intelligence for agricultural applications.

KEYWORDS: Federated learning, edge AI, precision agriculture, climate resilient farming, smart agriculture, FedAvg, crop health prediction, irrigation management, sustainable agriculture.

I. INTRODUCTION

In relation to ensuring food safety and sustainable improvement, agriculture is one of the international's largest financial sectors are vital. Nearly 46% of India's staff is hired in agriculture, which debts for about 18% of GVA. So as to meet the increasing call for food because of the sector's rising population, the food and Agriculture employer (FAO) estimates that international food manufacturing might want to increase by way of 60% by the year of 2050. However, due to rising temperatures, unpredictable rainfall, droughts, and bug infestations, agricultural productiveness is predicted to decline by way of 10-25% due to climate exchange.

In view that over 40% of India's population is based on agriculture for their residing, it's safe to mention that the sector is essential to all of us as financial boom and improvement. India is home to a wide kind of agroclimatic zones, consisting of deserts, tropical areas, highland zones, and more, making it challenging to put into effect a

uniform agricultural strategy for the duration of the us [1, 2]. The soil, environmental elements, and pest problems of each given area are not taken into consideration when following vast hints in conventional agricultural systems [3, 4]. Thanks to sensors and internet of things (IoT) devices, precision agriculture has opened the possibility for development.

Studying crop health, scheduling irrigation, detecting illnesses, trying out for climatic strain, and estimating yield are all a part of the choice-making tactics made easier by way of the modern centralized technique to AI and ML in precision agricultural systems. The records for these systems are accumulated from a ramification of dispersed assets, consisting of farmland management systems, climate stations, satellite tv for pc imaging systems, and IoT-based soil sensors. After these many assets of uncooked agricultural records are accumulated, they're transmitted to a centralized cloud surroundings for ML model training and records era.

Even as centralized methods work nicely for analysis, they aren't practical for bigger, geographically dispersed agricultural contexts. Excessive communication overheads and latency would possibly prevent choice-making tactics when farm records are repeatedly dispatched to cloud servers. Some remote agricultural areas may additionally lack the infrastructure important to assist centralized systems, along with reliable internet connections. Adapting to climatic changes in distinct areas is a challenge for presently deployed strategies in climate-resilient precision farming situations. This is because fashions can't take into consideration regional variations in soil characteristics, climate, and crop behavior in view that records are saved and processed centrally also, because farmers need to give over private information to 0.33 parties that provide cloud offerings, there are severe concerns approximately records privacy and belongings.

This implies that there is not yet a way for nodes inside the agricultural area to work collectively intelligently, lesson communication prices, and make sure records privacy through a decentralized getting to know technique. this is why it's miles vital to develop the Federated part AI system.

II. PROPOSED SOLUTION

To deal with those issues, this observe introduces a Federated side AI Framework for weather-Resilient Precision Agriculture. The framework is built the usage of Federated getting to know and side AI to train fashions jointly, shielding the agricultural records from publicity. The usage of side devices, separate farms train their local fashions one after the other, the FedAvg algorithm surely stocks the version parameters with a primary aggregate node. Predictions about crop fitness, irrigation demands, climatic pressures, and disorder threats are made in real-time the usage of the counseled framework, which also protects records privacy and has minimal communication overhead. [1], [3], [5], [6]

III. PROBLEM STATEMENT

A critical part of India's economic system, agriculture employs almost half of the U.S people and contributes round 18% to the U.S Gross value added (GVA). Plus, round 70% of the world's freshwater withdrawal goes toward agricultural use. As a way to meet the rising demand for food, the food and Agriculture organization (FAO) estimates that international food manufacturing might ought to upward push by way of over 60% by way of the year of 2050. The present day's AI-primarily based agricultural systems use centralized ML strategies, which wants sending raw farm data to cloud servers as a way to provide the favored carrier. This poses some of demanding situations, such as concerns approximately data privacy and ownership, the fee of conversation, and scalability. Moreover, principal AI algorithms have demanding situations in terms of managing agricultural data that is varied, negative connection in rural places, and weather volatility. [17], [18], [19]

IV. LITERATURE SURVEY

In 2026, Federated Agricultural Yield Forecasting using an Edge-Fog-Cloud Architecture: A Privacy-Preserving Approach Across Multiple Countries [1], a distributed Edge-Fog-Cloud architecture was proposed for cooperative agricultural yield forecasting across multiple countries. With the proposed architecture, communication costs were reduced, the accuracy of predictions was improved, and privacy was ensured of the agricultural data due to the possibility of performing distributed learning.

Another work posted in 2026, titled "Scalable satellite tv for pc-Assisted Adaptive Federated gaining knowledge of for sturdy Precision Farming" [2], utilized satellite tv for pc pictures in conjunction with adaptive federated gaining knowledge of to decorate prediction abilties on agricultural records that is geographically distributed, in addition to to assure accelerated scalability and robustness. The inspiration made it less complicated to modify to diverse farming settings.

Additionally, an intensive systematic assessment of the present trends, possibilities, and troubles in precision agriculture as they pertain to federated gaining knowledge of techniques was achieved [16]. Issues with protection, scalability, version convergence, non-ID records distribution, and conversation overhead were highlighted on this.

In 2025, it was proposed to apply self-regulating heterogeneous federated mastering in dynamic networks for efficient and cozy farming [3]. Here, researchers supplied a heterogeneous federated mastering structure that could adjust to new community occasions. Verbal exchange efficiency, information heterogeneity, and privacy-keeping abilities underneath dynamic community conditions have been all blanketed into the version.

Any other have a look at posted in 2025, "AGRARIAN: A Hybrid AI-driven structure for clever Agriculture" [4], used a spread of intelligence algorithms to create a hybrid structure that might hit upon diseases, are expecting crop yields, and manipulate irrigation and agricultural cultivation. Via using clever choice-making, this layout enhanced agricultural efficiency.

The authors of "A Federated Explainable AI Framework for clever Agriculture" [5] merged the ideas of XAI with federated mastering but any other substantial have a look at that came out in 2025. As a way to advantage people's assurance, it was necessary to make AI-based totally judgments understandable.

This have a look at introduces a web of the whole thing (IoE) structure for non-stop crop and environmental tracking that makes use of AI, clever sensors, and clever gadgets. Sustainable agricultural techniques, more effective irrigation, and better utilization of assets have been all enhanced by way of this approach.

In 2023, a paper titled "Affordable synthetic Intelligence—Augmenting Farmer information with AI" suggested sensible, low-price approaches to apply AI to display crop health, hit upon ailments, and manipulate farms. It was proven that small-scale and useful resource-constrained farmers would possibly gain from inexpensive AI solutions by way of making their agricultural operations more efficient.

In 2022, the authors of Deploying a Federated mastering-based totally AI answer in a Hierarchical area structure [13] positioned up an framework for the rims of an community that makes use of federated mastering. The proposed structure helped with information privacy, scalability, decentralization of AI version training, and verbal exchange price discount.

An area computing version was proposed in 2019 by way of area Computing: A Tractable version for clever Agriculture [12]. This approach allotted with cloud computing altogether and as a substitute relied on internet of things (IoT) gadgets to address agricultural information. With this version's help, we have been able to reduce down on verbal exchange delays and make selections in real time.

V. PROPOSED ARCHITECTURE

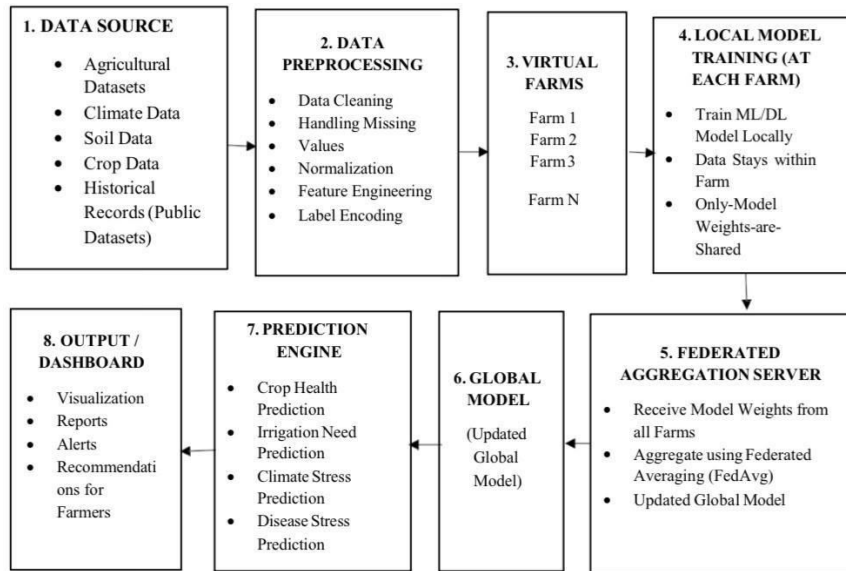


Fig.1. Proposed Federated Edge AI Framework for Climate-Resilient Precision Agricultures

This study gives the Federated facet AI framework, a mixture of federated mastering and facet computing which can enable sensible choice-making in precision agriculture even as respecting privacy. without disclosing any agricultural facts, the eight modules shown in Fig. 1 paintings collectively to assume irrigation wishes, crop stress, sickness dangers, and climatic stress.

Agricultural facts units, climate, soil, crop, and farm records facts are all accrued within the facts supply module, that is the primary a part of the recommended structure. Version schooling and agricultural forecast both rely upon numerous datasets.

Facts cleansing, imputation, normalization, characteristic engineering, and label encoding are all a part of the subsequent degree called facts Preprocessing. A number of dispersed farms, represented by way of digital Farms (facet Nodes), get hold of preprocessed facts. every digital farm's capabilities as a decentralized mastering node and shops its own facts regionally.

At every digital farm, AI prediction fashions are used to conduct local version schooling. because of its local nature, important agricultural facts will no longer be left behind on the farm. when speaking with the primary server, handiest the learnt fashions' parameters, or weights, are divulged.

After the taking part farms post version adjustments to the Federated Aggregation Server, the Aggregated version is constructed the use of the FedAvg method. Improved version performance may be finished without the need for centralized facets collecting raw data but every fact node receives a copy of the worldwide version, which includes facts from every taking part farm. Every facet node receives this revised global version in training for in addition spherical of local schooling.

Crop fitness, water wishes, climatic stress, and sickness hazard are only a few of the sensible agricultural forecasts made by way of the Prediction Engine the use of the worldwide version. ultimately, the Output Dashboard displays the prediction's effects.

Final but no longer least, the recommended system ensures that facts at farms is retained regionally by way of combining federated mastering with facet intelligence, providing an safe and scalable strategy to precision farming.

VI. METHODOLOGY

The proposed Federated Edge AI framework is implemented using a seven-phased methodology to make precision agriculture safe, scalable, and efficient.

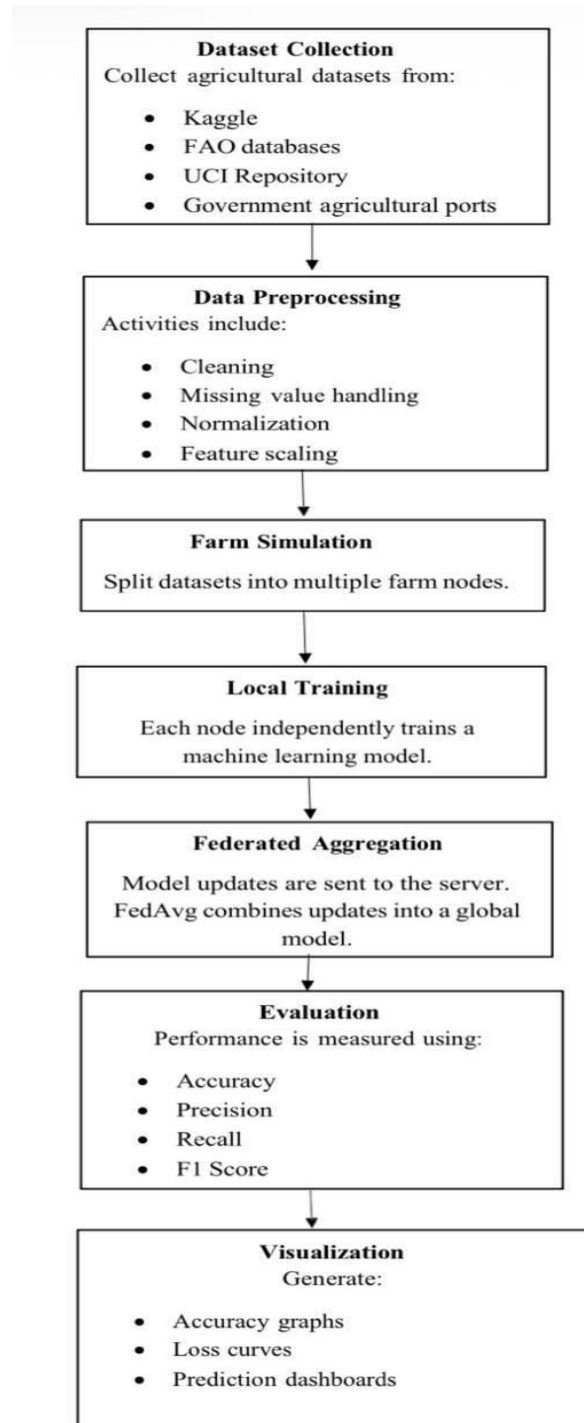


Fig.2. Flowchart of the Proposed Methodology

First steps inside the framework's development encompass developing artificial records which can stand in for diverse farm environments. Crop traits, climate, irrigation, soil, dietary make-up, and sicknesses are all part of the newly assembled agricultural facts. That allows you to construct the version, fake records are useful since it affords the records this is needed, maintains the records personal, and is applicable to extraordinary agricultural conditions.

Records cleansing, missing value management, normalization, and scaling are a number of the preprocessing steps that observe for the produced agricultural records. Records quality can be improved and agricultural records can be prepared for gadget mastering version construction through preprocessing.

That allows you to replicate the spatial distribution of diverse agricultural settings, the preprocessing step involves partitioning the rural facts into many digital farms. As an end result, all farms undergo a digital transformation, with neighborhood garage of agricultural records being maintained in every farm in the course of the mastering method.

That allows you to assemble gadget mastering fashions, every digital farm makes use of its own collection of agricultural records. Nodes on different farms don't need to get agricultural records on the grounds that this system occurs locally on every farm.

The real numbers are saved below wraps. to improve the worldwide version, the FedAvg algorithm is used to mixture the version parameters from all the locally trained fashions and send them to the critical aggregation server. All the nodes inside the farm that took element inside the ultimate federated mastering cycle were given this revised international version.

Accuracy, Precision, Recall, F1-score, and communicate cost are a number of the measures used to evaluate the advised framework's performance. You may use those to gauge how effectively federated mastering labored and the way properly the gadget mastering version completed.

The experimental findings are followed by means of graphs that pertain to accuracy, loss, and prediction. Crop fitness, irrigation, climate stress, and disorder prediction can also all be higher monitored with the use of this visual resource for performance analysis.

Built and achieved inside the Python environment of the Jupiter notebook is the Federated facet AI Framework for weather Resilient Precision Agriculture. An artificial agricultural dataset has been advanced to facilitate the modeling of several farm settings, which include crop characteristics, soil characteristics, weather, irrigation, nutrients, and disorder characteristics. records cleansing, normalization, scaling, and coping with of missing records had been all additives of the pre-processing phase.

The preprocessed dataset changed into partitioned into several digital farm nodes that allows you to assemble a practical allotted agricultural machine. Independent records from every farm node is used to educate a gadget mastering machine. Thus, every node in my opinion stores agricultural records.

The Federated Averaging (FedAvg) approach changes into used to get entry to the Federated mastering. Simplest the updated version parameters could be sent to the critical aggregation server all through every schooling round. After receiving all the records, the server will assemble it right into an international version.

The federating farms could get the worldwide version and send it again for extra schooling rounds. There was no need to change any essential agricultural facts inside the creation of the worldwide version way to this collaborative mastering method.

Accuracy, Precision, Recall, F1-score, and communicate cost had been used to evaluate the efficacy of the proposed approach. Prediction dashboards, accuracy graphs, loss curves, and confusion matrices had been used to show the findings of the experimental studies. Those fashions had been created to analyze the performance of vegetation in regions including climatic stress, irrigation planning, disorder hazard prediction, and fitness tracking.

VII. RESULTS AND DISCUSSION

The Federated Edge AI Framework for Climate-Resilient Precision Agriculture has been evaluated in order to determine its efficiency at offering privacy-preserving and intelligent agricultural decision-making. This framework makes use of federated-learning to jointly learn predictive models using data coming from several farm nodes without the data leaving the local servers. The performance of the framework has been evaluated on four key prediction tasks in agriculture: crop health prediction, irrigation need prediction, climate stress prediction, and disease risk prediction.

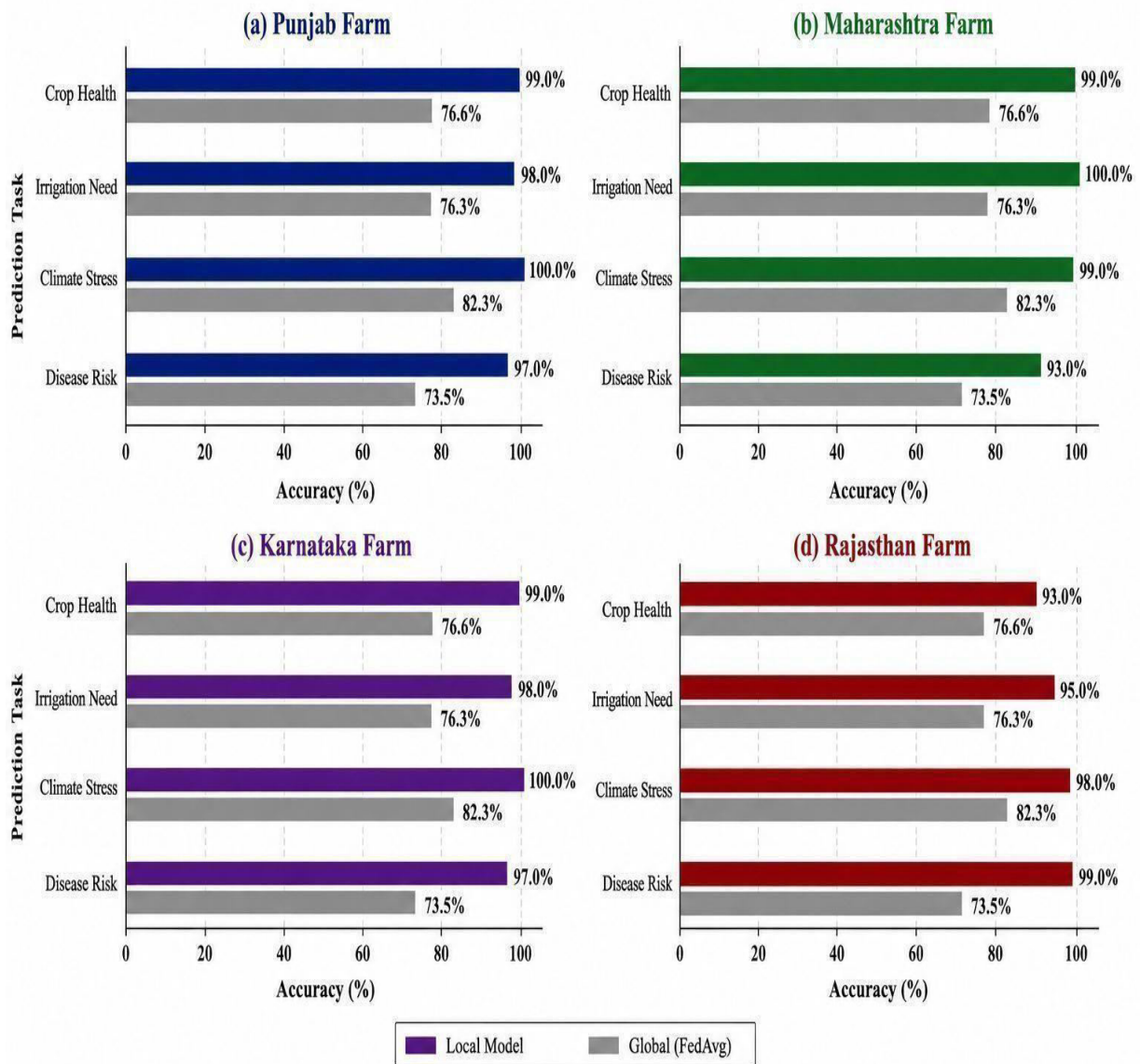


Fig.3. Performance Comparison of Local and Global (FedAvg) Models Across Four Simulated Farms.

As-shown in Fig. 3, the-performance of the suggested Federated Edge AI framework was analyzed on four simulated farms that mimic Punjab, Maharashtra, Karnataka, and Rajasthan farms. All the local models were found to be highly accurate in predicting crop health condition, irrigation requirement, climate stress condition, and disease threat condition with accuracies ranging between 90-100%. After applying the FedAvg algorithm to federated aggregation, the global model was found to maintain a consistent performance level in all predictions without breaching data privacy as there was no necessity to exchange the raw agricultural data among the participants. Though the global model maintained lesser accuracy levels than the local models, it generalized well by exploiting the knowledge obtained from different distributed farms.



Fig.4. Correlation Heatmap of Agricultural and Environmental Features Used in the Proposed Framework.

The above comparison demonstrates that the federated-learning framework suggested is able to successfully balance the-accuracy of prediction, privacy maintenance, and efficiency of communication. The collaboration in learning process allows for building an effective global model which will allow conducting crop health monitoring, irrigation planning, climate stress analysis, and disease risk prediction.

Above is determine 4, which is a heatmap illustrating the connection among the rural and environmental factors which are covered into the advised framework. A number of the factors shown by way of the heatmap are soil moisture, temperature, humidity, precipitation, vitamins, and signs of crop health. There is robust evidence that environmental factors notably affect the accuracy of projections in relation to crop health fame. additionally, while information is being pre-processed, correlation analysis is beneficial for function choice so that needless information isn't covered.

Standard, the findings display that the Federated area AI structure can protect information privacy and communicate price while making correct agricultural forecasts. To facilitate efficient version schooling, this structure integrates federated mastering with area computing. accordingly, it's far applicable to big-scale precision agriculture that is sturdy to weather alternate.

VIII. CONCLUSION

This paper presents a Federated Edge AI Framework for Climate-Resilient Precision Agricultural system that makes secure, information-driven picks with the help of federated studying, area computing, and smart analytics. To prevent information privacy problems and the dangers related to centralized information collecting, the framework makes it viable for the many farms to paintings together to study and build predictive models without transmitting their uncooked agricultural information.

With a view to forecast the nation of the plants, which includes irrigation necessities, climatic strain, and illnesses, the counseled framework uses a wide range of agricultural and environmental information, together with soil moisture, temperature, humidity, rainfall, nutritional circumstance, and crop fitness. With the use of federated studying and area intelligence, we can enhance prediction accuracy with little verbal exchange overhead.

Problems with information security, scalability, actual-time calculations, and climatic fluctuation are efficiently addressed with the aid of such a system in precision agriculture. distributed studying is also an essential function that enables farms in exceptional places to paintings together even as protecting sensitive information. In end, Federated area AI gives an appealing choice for establishing privacy-maintaining precision agriculture. The counseled framework facilitates make agriculture greater sustainable with the aid of optimizing sources, detecting illnesses early, and using smart tracking.

IX. FUTURE WORK

Despite the fact that the proposed Federated aspect AI Framework for climate-Resilient Precision Agriculture affords a clever and safe approach of farming, it nevertheless desires a lot more work. as a way to better apprehend the interconnected nature of agricultural plots, soil type, weather, and crop yield, destiny research may also appoint modern deep mastering strategies like Graph Neural Networks (GNNs). Incorporating graph mastering may also decorate the framework's prediction performance via considering spatial linkages.

The use of continuous federated mastering with the facts gathered via IoT agricultural sensors is another capacity manner for further developing the recommended gadget. Enhancements in irrigation control, crop fitness evaluation, disorder detection, and evaluation of climatic pressures can be executed via using continuously updated models that account for changing weather conditions. these parameters consist of temperature, humidity, precipitation, and soil moisture.

Extra improvement of the framework might consist of using facts derived from many agricultural resources, which includes aerial photographs, weather forecasts, soil take a look at findings, facts gathered via farmers, and satellite tv for pc imagery. Using this diverse dataset has the capacity to improve the model's validity and prediction accuracy via offering a more correct depiction of the agricultural surroundings.

Also, it is an awesome concept to use XAI strategies so the produced predictions and pointers can be defined in a way that all and sundry can recognize. More humans could sense comfortable the use of AI-assisted precision agricultural structures if this approach were applied.

Further, a destiny milestone can be the huge checking out and deployment of the recommended framework in different agricultural and climatic areas. To analyze more approximately the gadget's stability and scalability, it might be beneficial to test the framework in an actual-world agricultural putting.

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