HYBRID EDGE–FOG–CLOUD ARCHITECTURES FOR SMART AGRICULTURE: A REVIEW OF IOT DATA PROCESSING, INTELLIGENT DECISION-MAKING AND RESOURCE EFFICIENCY

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ABSTRACT:

Smart agriculture has become reliant on the use of continuously monitoring sensor's that wirelessly communicate information. Many different forms of data processing and decision support systems can now be applied to the gathered information. Smart agriculture differs to other IoT applications due to its possibility of easily covering large areas of land. Nevertheless, it will most likely face constraints in energy and computing resources. Network connectivity may also be poor or intermittent. In this paper the authors analyse literature regarding IoT, smart sensors, wireless communications and edge/fog/cloud computing. In addition to that, artificial intelligence and precision agriculture are covered. The authors have analysed these topics using a data flow diagram as a reference point. The topics are analysed and discussed in terms of how data flows from the sensor towards decision making process. There is a focus on how far the data needs to travel before it is processed. Some research suggests using Edge computing where the system can process some of the data closer to the source. This can help filter out unwanted data and identify events or actions that need to be taken immediately. Fog and cloud computing can

still be used to collect the filtered data and store data or perform more complex tasks on it. Such system could reduce data that is sent significantly when connectivity is intermittent. This paper looks at how Edge computing can help enable smarter agriculture and allow for data driven decisions in low resource areas.

Keywords: *precision agriculture, smart sensing, wireless sensor networks, edge intelligence, agricultural data analytics, digital agriculture.*

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1. INTRODUCTION

As technology advances there is a greater amount of data that can be collected from an agricultural environment. Using technology to monitor the environment around the crops or animals can allow farmers to make more informed decisions about what they need to apply to their farm. By collecting data, by using smart sensors, we can reduce waste only with applying what the crop or animal requires. Over recent years researchers have looked at how to use smart sensors to gather information from the environment around them. They have afterwards used that information to make predictions and take actions [1–6]. As agriculture is usually spread over large distances and is affected by weather conditions the issues with the technology for that big area of coverage and climate change and global warming negative effects has arised. Having internet access at the farm, especially in rural areas, can be equally difficult issue.

Where should this data be processed is a big question that needs answering. Using the cloud based systems supports scalability and the use of more advanced forms of AI. Nevertheless, in that scenario the farmer needs to be reliant on Internet connection. The research study identifies this problem and suggests using a combination of edge, fog and cloud computing to solve it. This allows a farmer to get quick responses to any data that needs acting upon immediately. The more complex processing can be done higher up in the data chain.

In this paper the authors look at the contemporary literature and analyse data flows in Edge-Fog-Cloud architecture systems. This applies from the point of collection at sensors up to the decision making layer. The authors also look at how the research studies in the contemporary literautre can provide an example of how these concepts can be implemented in the real world. This can give an insight into how far the data needs to be sent and the benefits of doing so.

2. METHODOLOGY

This paper follows a narrative style review by looking at the provided references. All topics were analysed based on the data flow from the sensor to decision making. Systematic and non-systematic review's were used. The authors researched the different forms of IoT technology and how they can be applied to an agricultural scenario. These include reviews on smart sensors, wireless communications, irrigation and machine learning. Data storage and management were also analysed as well as edge and cloud computing [1-18].
No data was extracted from each paper. A common new technology in smart agriculturetopics are discussed, as well as how each paper relates to the developed data flow diagram. The contemporary literature was used as an example to show how some of these techniques can be applied in a real-world scenario.

2.1. Smart sensing and agricultural data acquisition

Using smart sensors to collect data from the environment around the farm is the key to having a smart agriculture system. There are many different types of sensors that can be used to collect data. From soil sensors that measure aspects such as moisture content and temperature to camera's that can detect disease in plants. All of these sensors can be used to give a farmer a better understanding of what is happening on his farm. Smart sensors consist of many components that allow them to not only collect data but also send it to another location. This allows the data to be analysed at another point [6, 7] with the resources for advanced point of view processing.
It is not only important to have the right sensor for the job but also where it is placed. Pascoal et al. (2016) in detail present how to place sensors to ensure getting accurate readings [2]. If the sensor is placed too close to the water line the farmer may think that the soil is wetter than it actually is. There are many factors that can affect where the farmer should place sensors.
The trend toward multisensor fusion addresses this limitation. By combining soil, plant and atmospheric variables this can provide a more informative representation of crop conditions than a single variable. Recent literature also extends sensing to UAV imagery, thermal and multispectral observations, and animal monitoring [4, 6]. Such heterogeneous data

increases analytical potential but also creates greater requirements for synchronisation, storage, preprocessing and interoperability.

2.2. Communication and connectivity

Communication technology determines how far data can travel, how much energy is consumed, and how frequently measurements can be transmitted. The contemporary literature references identify Wi-Fi, Bluetooth, ZigBee, LoRa/LoRaWAN, NB-IoT, LTE-M and other wireless options. Short-range technologies are suitable for local clusters or gateways, whereas LPWAN technologies are attractive for geographically distributed battery-powered agricultural nodes because of their long range and low power requirements [1, 3, 15].

There is no single communication technology that is the most optimal to use. The multiple criteria aspects include farm size, how many sensors farmer plans to use, how much data needs to be sent, the topography of the land and existing infrastructure.Last but not leaste is the criteria of how much energy the device can handle and what are the application needs. There is no need to constantly send large amounts of data if an irrigation threshold is utilized. If the goal is to detect diseases from images, the higher bandwidth or alternatively local preprocessing before sending are needed. There are many factors to consider when designing an IoT system for agriculture such as data frequency, number and placement of sensors, distance and power consumption [15].

As discussed above connectivity will play a major role when choosing the appropriate and the optimal architecture. Many recent studies have mentioned that lack of broadband or cell reception can limit the deployment of technology in rural areas [3, 5, 6]. The ones that use only the cloud are reliant and completely dependent on their connection which may not always be available. Allowing the system to process locally can now support certain level of intelligence while the network connection is unavailable.

2.3. Edge, fog and cloud computing

Edge computing can be used to perform certain tasks on the device itself. On an agricultural scale the data can be filtered, compared against a threshold, events can be detected, compressed or light ML molde can be performed. Edge computing can reduce the system’s response time, reduce

the amount of bandwidth needed and allow it to stay online when there is no connection. In this research paper, an ESP32 is used as sensor node and a Raspberry Pi 4 as the gateway to do local decision making.
Fog computing is another tier of computation that is located in between edge and cloud layer of computing. It can be used to gather data from multiple nodes, display local dashboards or perform analytics. It can even upload the data to the cloud when a connection is established. Fog computing can be used when there are no conditions to process on the local node and the uploading all of the data to the cloud is not a feasible option. Studies have mentioned the combination of edge and cloud computing to reduce latency and bandwidth usage [5, 10].
The Cloud can still be beneficial as it allows access to more computing resources. Storing large amounts of data or running more intensive machine learning are some of the examples. By having past time series data allows for models' training and using that data to support all of the end to end system. As seen in many of the contemporary referenced studies edge and cloud computing can work together to create an efficient smart agriculture system.

2.4. Artificial intelligence and machine learning

By implementing an AI and machine learning into the smart agriculture supports predicting and making rational and intelligent decisions. The referenced contemporary studies utilize machine learning to help predict crop yields, detect diseases and help control irrigation and other aspects of agriculture [6, 12–15]. Certain techniques such as deep learning can be used to find complex patterns in data. However, the simpler methods can be utilized if needed, for example in scenario of computer resources' limitation.
When using AI in the architecture the place of the task should be considered. If the farners are only looking to irrigate when a soil moisture value is below a certain point a microcontroller device is sufficient for this task. For a more advanced tasks a model could be run on the target gateway that has less latency. Or running it on the fog/cloud node that may have access to more resources.
As seen with irrigation, local rules for making a decision are quite simple method to implement indicating or automatizing when to turn on the sprinklers. Additionally, more advanced techniques can be utilized, such as fuzzy logic and machine learning to predict when the crops need watering

[12, 13]. Referenced contemporary studies analyze and cover this topic by supporting the use of rules on the computer resources constrained device in order to turn on the irrigation and/or use more advanced techniques on the gateway.

2.5. Synthesised data-flow model

A similar theme can be detected throughout all of these referenced contemporary studies. Sensors collect data that gets sent through a communication protocol to an edge or fog node. The data can then be uploaded to the cloud and used to make decisions. Building the architecture for such system requires to keep focus at these aspects. Every additional step can increase the amount of data and bandwidth that are utilized. The more sensors are used, the more data is collected. Sending the data at higher frequencies will give more detail, but will drain the battery faster and use more bandwidth. Nevertheless, having more data allows to run more advanced analytics on the system.



Fig. 1. Reference hybrid edge–fog–cloud architecture for agricultural data processing

3. COMPARATIVE SYNTHESIS OF ARCHITECTURAL APPROACHES

The referenced contemporary research and literature support three broad configurations: edge-centric, cloud-centric and hybrid. Their comparison is useful because no single architecture simultaneously maximises latency, scalability, autonomy and analytical complexity.

Table 1. Comparative characteristics of edge-centric, cloud-centric and hybrid architectures

Dimension	Edge-centric	Cloud-centric	Hybrid edge–fog–cloud

Decision latency	Very low for local actions	Depends on network RTT + processing	Low for critical actions; higher layers for advanced analytics
Offline resilience	High	Low/none	High for critical functions
Bandwidth demand	Low	High when raw data are transmitted	Reduced through filtering and aggregation
ML complexity	Low to moderate	High	Layered according to computational demand
Scalability	Moderate	High	High with distributed orchestration
Hardware cost	Low	Low at field, but cloud-dependent	Moderate
Cloud operating cost	Low	Highest	Reduced by selective synchronisation
Best use	Time-critical control	Central analytics	Resilient integrated farming

The edge approach will be beneficial in a scenario when a task needs to be done quickly. The rules can be set for certain thresholds and action perform, such as turning on an irrigation system or sending out alerts. The disadvantage is the computing power it can hold as well as storage space. Not being able to run more complex algorithms on the device will limit its potential.

By using the cloud approach the user will have access to a central location to store data. As well as having the ability to compute with more resources. The cloud can be helpful in scenarios of storing and using the long term data or having more complex models to use. A disadvantage of using only the cloud in an agricultural setting is if the network connection is unreliable.The system may lose effectiveness due to the delay of a slow network connection or lose its functionality if there is no connection.

By using a hybrid, the best of both worlds is taken. In the referenced contemporary research ESP32 was selected to read sensor data and use a rule based irrigation system. The raspberry pi was used to collect the data from each node and predict using a Naive bayes algorithm. In addition to that, the fog/cloud solution is utilized to process and store data that require more computing power. Many studies have started using different levels of processing to allow for faster and efficient use of bandwidth and memory [5, 6, 10, 15].

3.1. Evidence from the research prototype

The prototype that the authors developed which is based upon contemporary literature was built off of and it can be used to better understand some of the principles that are discussed. The prototype was used with an ESP32 node, raspberry pi 4 and a fog/cloud solution. By placing different components on each tier of the prototype enables measuring latency, packet loss, bandwidth and memory. Additionally, measurement can be done of how much power the solution is using.
The prototype showed that their ESP32 took 8.329ms to complete one full cycle of reading sensors, predicting and sending over MQTT. The raspberry pi 4 showed that it only took 0.037ms to predict using the naive bayes algorithm. That means the raspberry pi was able to process data locally in 0.141ms. The prototype was able to show that the fog solution took between 0.04 and 0.09ms to make a prediction. It allowed for quick decision making without needing to rely on Internet.
The prototype also showed that by disconnecting the Internet and increasing the amount of time the raspberry pi would collect data before sending to the cloud. The traffic decreased by 85.4%. It allowed the cloud to do the processing by using an example of ML model - XGBoost. The prototype estimated that the cloud solution was using 6.78W. This showed that having more powerful solutions can be significantly costly.
These results can be helpful to understand how the different tiers can affect the system. The prototype should not be used as a basis for other agricultural projects. There are many limitations that the research pointed out. The prototype was tested in an indoor environment only. Additionally, it did not test enough samples to know the sensors reaction to changes in their environment. More testing should be done in the field to provide more accurate readings.

3.2. Irrigation as a representative closed-loop application

As shown by many research papers smart irrigation is a significantly beneficial application to develop. When creating a closed loop system the sensing aspect detects when the soil/plant needs water, predicts if the soil needs water and then activates a pump/valve to supply crops with the water. Relying on a cloud to provide the user with the decision when to irrigate may face issues like delays or outages that effect yield of the crops. Having a local solution that can predict when to irrigate will help the system be more effective. Additionally, by implementing the proposed system the user can still be able to use the cloud for analysis and future predictions.
Multiple research papers have implemented fuzzy logic in smart irrigation. Others have used deep learning to predict soil moisture and irrigation. Some have built an IoT solution to automatically irrigate the crops [12, 13].

3.3. Data quality, security and reliability

There are many issues that can occur when trying to collect data from a distributed system. Bad sensor readings, poor communication and abnormal values can cause issues with the system. Referenced contemporary papers have analyzed how to improve data accuracy and integrate different types of sensors [2, 6, 7]. The data needs to be cleaned and filtered before sending it to the cloud or using it to make predictions.
The data can be preprocessed on the device in order to send only clean data to the next tier of the system. By aggregating data certain events that occured at the local node might not be detected. This could cause a spike in soil moisture that might not be caught by the system.
This system is based upon many different devices communicating with each other. The data needs to be secure from any hackers or false readings. There are many ways that the system can be compromised. From poor communication to fake data being sent to the users'cloud storage.

3.4. Economic and sustainability considerations

The total price of the system and its implementation as well as the overall benefits are of highest importance. Contemporary papers have discussed how to make the systems more affordable by using microcontrollers and single board computers. Lowering the cost of the system supports smaller farmers to adopt similar technologies.

Using edge computing will lower the amount of data that are sent to the cloud. This approach supports cost reduction on the cloud bill and bandwidth usage. However having more devices to maintain can increase the overall cost.
There are many aspects to consider when thinking about sustainability benefits. Using smart agriculture can lower the usage of water, fertilizer and chemicals on farmers' crops. On the other hand, electricity will be used to run the devices.

3.5. Research gaps and future directions

There are many aspects that need to be considered when trying to implement smart agriculture. But there are still areas that need more research. One area is that most of the prototypes that are built are not tested in real world scenarios. One of the contemporary paper's research notes that they need to test their prototype with 4-10 ESP32s in the field. The goal is to see if the results hold up when exposed to the elements and different network conditions.
Another area that needs to be considered is the prediction of the model. Just because some model can predict quickly does not mean it is giving the accurate information. The contemporary research emphasized that they need to collect more data over the course of a season to validate the model. When collecting data important aspect is not to lose essential information. By only collecting data every x seconds may cause to miss spikes or dips in the data. Future research should look into changing the collection rate depending on the situation.
By using different methods of communication the one can ensure the system will have a better chance of staying online. LoRa is a an optimal option if a farmer has a large area to cover. But the cellular is another optimal option if the farmer wants to connect the system to the Internet.
Research should continue to look into using AI with smart agriculture. Using multiple sensors can help to get a more accurate picture of crops health. Looking into using UAVs to help detect disease in crops is another important application.

4. CONCLUSIONS

Smart agriculture has grown to include many technologies that can help farmers do the agricultural production more efficiently. From using IoT to monitor the crops to AI predicting when the farmer should water the fields. By looking at the different tiers of a system the one can ensure that each system is utilized to its fullest. This is the case whether by using the edge to make quick decisions or the cloud to analyze the data. There are many ways to implement these technologies into the farms.
There are pros and cons to using each tier of a system. By using a hybrid solution the best of each tier can be selected and a system that can benefit farmers' agricultural practices can be created.

5. REFERENCES

[1] Prakash, C., Singh, L. P., Gupta, A., & Lohan, S. K. (2023). Advancements in smart farming: A comprehensive review of IoT, wireless communication, sensors, and hardware for agricultural automation. Sensors and Actuators A: Physical, 362, 114605. https://doi.org/10.1016/j.sna.2023.114605

[2] Pascoal, D., Silva, N., Adão, T., Lopes, R. D., Peres, E., & Morais, R. (2024). A technical survey on practical applications and guidelines for IoT sensors in precision agriculture and viticulture. Scientific Reports, 14(1), 29793. https://doi.org/10.1038/s41598-024-80924-y

[3] Choudhary, V., Guha, P., Pau, G., & Mishra, S. (2025). An overview of smart agriculture using internet of things (IoT) and web services. Environmental and Sustainability Indicators, 26, 100607. https://doi.org/10.1016/j.indic.2025.100607

[4] Mansoor, S., Iqbal, S., Popescu, S. M., Kim, S. L., Chung, Y. S., & Baek, J.-H. (2025). Integration of smart sensors and IoT in precision agriculture: Trends, challenges and future prospectives. Frontiers in Plant Science, 16, 1587869. https://doi.org/10.3389/fpls.2025.1587869

[5] Navarro, E., Costa, N., & Pereira, A. (2020). A systematic review of IoT solutions for smart farming. Sensors, 20(15), 4231. https://doi.org/10.3390/s20154231

[6] Azlan, Z. H. Z., Junaini, S. N., Khan, A. S., & Mustafa, W. A. (2025). Data-driven agriculture: Unveiling the power of internet of things and data analytics for transformative farming practices. Journal of Sensors, 2025(1), 6205646. https://doi.org/10.1155/js/6205646

[7] Miller, T., Mikiciuk, G., Durlik, I., Mikiciuk, M., Łobodzińska, A., & Śnieg, M. (2025). The IoT and AI in agriculture: The time is now—A systematic review of smart sensing technologies. Sensors, 25(12), 3583. https://doi.org/10.3390/s25123583

[8] Karunathilake, E. M. B. M., Le, A. T., Heo, S., Chung, Y. S., & Mansoor, S. (2023). The path to smart farming: Innovations and opportunities in precision agriculture. Agriculture, 13(8), 1593. https://doi.org/10.3390/agriculture13081593

[9] Rajak, P., Ganguly, A., Adhikary, S., & Bhattacharya, S. (2023). Internet of things and smart sensors in agriculture: Scopes and challenges. Journal of Agriculture and Food Research, 14, 100776. https://doi.org/10.1016/j.jafr.2023.100776

[10] Ayaz, M., Ammad-Uddin, M., Sharif, Z., Mansour, A., & Aggoune, E.-H. M. (2019). Internet-of-Things (IoT)-based smart agriculture: Toward making the fields talk. IEEE Access, 7, 129551–129583. https://doi.org/10.1109/ACCESS.2019.2932609

[11] Dhanaraju, M., Chenniappan, P., Ramalingam, K., Pazhanivelan, S., & Kaliaperumal, R. (2022). Smart farming: Internet of Things (IoT)-based sustainable agriculture. Agriculture, 12(10), 1745. https://doi.org/10.3390/agriculture12101745

[12] Kashyap, P. K., Kumar, S., Jaiswal, A., Prasad, M., & Gandomi, A. H. (2021). Towards precision agriculture: IoT-enabled intelligent irrigation systems using deep learning neural network. IEEE Sensors Journal, 21(16), 17479–17491. https://doi.org/10.1109/JSEN.2021.3069266

[13] Krishnan, R. S., Julie, E. G., Robinson, Y. H., Raja, S., Kumar, R., Thong, P. H., et al. (2020). Fuzzy logic based smart irrigation system using Internet of Things. Journal of Cleaner Production, 252, 119902. https://doi.org/10.1016/j.jclepro.2019.119902

[14] Boursianis, A. D., Papadopoulou, M. S., Gotsis, A., Wan, S., Sarigiannidis, P., Nikolaidis, S., et al. (2021). Smart irrigation system for precision agriculture—The ARETHOU5A IoT platform. IEEE Sensors Journal, 21(16), 17539–17547. https://doi.org/10.1109/JSEN.2020.3033526

[15] Joshi, P., Das, D., Udutalapally, V., & Misra, S. C. (2021). FarmEdge: A unified edge computing framework enabling digital agriculture. In 2021 IEEE International Symposium on Smart Electronic Systems (iSES). https://doi.org/10.1109/iSES52644.2021.00065

[16] Srichanpiyom, K., Puangploy, P., Phowong, S., Euafua, C., & Phothisonothai, M. (2023). A low-cost edge and cloud computing based smart agriculture platform for lifecycle Andrographis Paniculata planting. In 2023 20th International Conference on Electrical Engineering/Electronics, Computer, Telecommunications and Information Technology (ECTI-CON). https://doi.org/10.1109/ECTI-CON58255.2023.10153270

[17] Vu Khanh, Q., Nguyen, V.-H., Anh, D., Quy, N., Ban, N., Lanza, S., Randazzo, G., & Muzirafuti, A. (2022). IoT-enabled smart agriculture: Architecture, applications, and challenges. Applied Sciences, 12(7), 3396. https://doi.org/10.3390/app12073396

[18] Liakos, K. G., Busato, P., Moshou, D., Pearson, S., & Bochtis, D. (2018). Machine learning in agriculture: A review. Sensors, 18(8), 2674. https://doi.org/10.3390/s18082674

[19] Ikram, A., Aslam, W., Aziz, R. H. H., Noor, F., Mallah, G. A., Ikram, S., Ahmad, M. S., Abdullah, A. M., & Ullah, I. (2022). Crop yield maximization using an IoT-based smart decision. Journal of Sensors, 2022, 2022923. https://doi.org/10.1155/2022/2022923