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REGULAR ARTICLE

Nano-Enhanced IoT Sensors and Hybrid Scheduling Algorithms for Smart Agriculture: A Multi-Layered Framework Towards Sustainability

Sneha[1,*] ✉, P.D. Singh[1], V. Tripathi[1], S. Maurya[2]

[1] *Graphic Era (Deemed to be University), Dehradun, India*
[2] *Symbiosis International University, Pune, India*

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Several changes are observed in the agricultural domain, especially with the technological IoT framework that integrates cloud computing, fog computing and nanotechnology. All these innovations are designed to enhance productivity, optimize resource use, and respect the environment. Smart agriculture is now recognised as a method of farming that helps farmers gather data freely, carry out analysis in real-time, and automate particular processes. This study presents a Multi-Layered Smart Agriculture Framework, a layered architecture that propounds solutions to the proper execution of smart agriculture. The IoT Nano-Enhanced Layer uses nanosensors for monitoring soil, crop, and environmental health, while the fog layer processes data instantly, and the cloud layer handles large-scale computation and storage. To handle the huge amount of data being generated by Nano-Enhanced IoT devices, a Hybrid Scheduling Algorithm GA+WRR is used to manage the resources at its disposal better and keep the execution time to a minimum. Performance analysis with Eclipse IDE shows better results of the presented framework than basic scheduling techniques. The proposed framework optimizes resources and minimizes execution time, ensuring sustainable and efficient agriculture to meet global food demands.

Keywords: Nano-Enhanced IoT layer, Fog, Cloud computing, Hybrid algorithm.

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1. INTRODUCTION

Crop production, the pillar of human lives in today's society, is under much pressure. The modern age brings new and complex problems, such as climate alteration, limited resource access, and food demand due to population increase [1]. To achieve these, it is evident that the evolution of simpler technologies has become inevitable in agricultural practices. The strategy of smart agriculture is reinventing agriculture – and making the process more efficient thanks to modern technologies like IoT, nanotechnology, fog computing, and cloud computing.

1.1 Application of Nanosensors for the Agriculture Industry

It has been observed that nanosensors become the latest species in technological advancements concerning precision agriculture. These sensors, nano-engineered, provide the best possible views on critical parameters of agricultural production. For instance:

Soil Fertility Monitoring: Flexible and efficient nanosensor machinery determines the concentration of nitrogen, phosphorous, and potassium (NPK) in the soil and, hence, the portions of fertilisers to be used.

Crop Disease Detection: Nanosensors incorporating nano barcodes or using fluoro tagging allow the early detection of pathogens and crop diseases so that timely action may be taken [2].

Water Quality Assessment: Nano tribometers track contaminants in irrigation water to examine the safety of its application. Nanosensors are incorporated with IoT to improve data reliability and give farmers solutions that help them create sustainable agricultural practices.

1.2 Importance of Cloud Computing in Smart Agriculture

Cloud computing provides a way of analyzing this field's huge volume of data into usable knowledge. It offers the solution to developing infrastructure or growth of large structures where data accumulated from IoT devices and nanosensors are stocked, preprocessed, and analyzed. Key contributions of cloud computing includes:

Real-Time Monitoring and Control: Essential field conditions and agricultural operations are available

* Correspondence e-mail: bvv260170@ukr.net

on cloud-based dashboards and accessed through mobile applications.

Scalability and Collaboration: The cloud provides an excellent medium for sharing data with various stakeholders to encourage cooperation strategies and research partnerships [3]. With the help of nanosensors and cloud computing systems for smart agriculture, the organization can make real-time and medium-term decisions simultaneously. Such corporate synergy enhances productivity and guarantees the sustainability of implementing agricultural practices as the demand for food is steadily rising globally.

2. METHODOLOGY

A Multi-Layered Smart Agriculture Framework is designed and analysed, integrating Nano-Enhanced IoT sensors, fog computing, cloud computing, and a Hybrid Scheduling Algorithm (GA+WRR) to enhance efficiency and data processing in precision farming. The framework comprises multiple layers:

IoT Nano-Enhanced Layer: Collects real-time agricultural data, denoted as a time-series dataset $D = \{d_1, d_2, \ldots, d_n\}$, where each data point d_i represents sensor readings at time t_i.

Fog Computing Layer: Processes data locally, reducing latency L_f such that $L_f < L_c$ (where L_c is cloud latency).

Cloud Computing Layer: Performs large-scale computations, optimising resource usage R, defined as:

$$R = \sum \frac{Ci}{Ti}$$

Where T_i task execution is time and C_i is computational capacity [4].

Communication Layer: Ensures seamless data exchange, governed by transmission delay T_d:

$$T_d = \frac{S}{B}$$

Where S is data size, and B is network bandwidth.

To enhance scheduling efficiency, we implement the GA+WRR Hybrid Scheduling Algorithm:

1. Genetic Algorithm (GA) [5] optimises task allocation by minimising execution time (TeT_eTe), represented as:

$$Te = \min(\sum wi \cdot f(Ti))$$

where w_i is the weight of task i, and f(T_i) is its processing function [5].

2. Weighted Round Robin (WRR) balances task distribution across virtual machines (VMs), with weight W_j calculated as:

$$W_j = C_j \,/\, \sum C_k$$

where C_j is the capacity of VM_j and $\sum C_k$ is the total capacity of all VMs.

Simulations are conducted in Eclipse IDE with CloudSim libraries, evaluating scheduling strategies (**GA+WRR, WRR, RR, FCFS**) under different configurations. Performance is assessed based on execution time (T_e), resource utilization (R), latency reduction (L), and scalability (S). Results confirm that GA+WRR significantly improve smart agriculture operations by minimizing execution time and optimizing resource allocation.

3. PROPOSED FRAMEWORK

Smart agriculture relies on real-time data collection and analysis to optimize farming practices. However, the geographical distribution of agricultural fields often leads to significant latency issues when transmitting data to distant cloud data centers [6]. To address this challenge, this study proposes a Multi-Layered Framework towards Sustainability that integrates Nano-Enhanced IoT Layer, fog, and cloud computing layers to enable efficient data processing and decision-making in smart agriculture. Additionally, to optimize resource utilization and mitigate load balancing challenges, a hybrid scheduling algorithm, GA+WRR, is introduced in the layers, ensuring efficient allocation of tasks and resources across the network. Fig. 1 shows the Multi-Layered Framework.

3.1 IoT Nano-Enhanced Layer

The IoT Nano-Enhanced Layer represents the foundation of the smart agriculture framework, integrating nanosensors and other IoT devices to monitor and manage critical agricultural parameters. This layer ensures precision, efficiency, and sustainability in modern farming practices. IoT Nano-Enhanced Layer puts nanosensors alongside actuators, water pumps, fans, and other systems like shading mechanisms so that activities like irrigation, temperature control, and pest control happen automatically [7]. This layer produces a rich and high-rate data flow that includes crop health, soil moisture, pests, and environmental conditions fundamental to precision agriculture. Due to the high volume of data generated, the proposed Hybrid Scheduling Algorithm integrates GA with WRR to address load balancing, chain interoperability and resource optimisation for the framework. Table 1 shows the key components of the IoT Nano-Enhanced Layer.

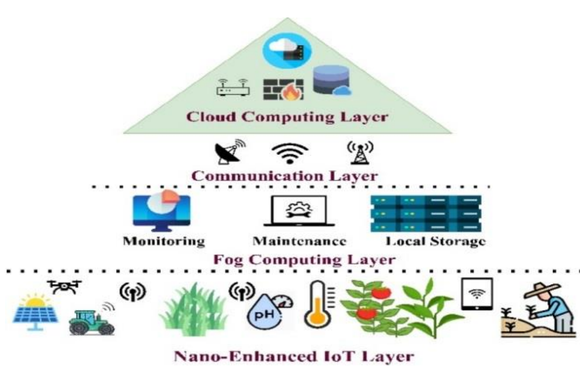

Fig. 1 – Multi-Layer Framework [8]

Table 1 – Key Components of the IoT Nano-Enhanced Layer [9]

Component	**Description**	**Nano-Enabled Sensors**
Nanosensors for Soil Analysis	Measure soil pH, nutrient levels, residual pesticides, and moisture content.	QD Nanosensor (Quantum Dots, Fluorescence Sensor), Electrochemical Nanosensors (ECN)
Water-Sensitive MEMS Nanosensors	Detect and optimise soil moisture levels for irrigation purposes.	Piezoelectric Nanosensor (PZN)
Nanobiosensors	Identify specific plant signals for targeted nutrient or fertiliser delivery.	DNA Nanobiosensor (Carbon Nanotubes, Immunosensor)
Nanobarcodes	Monitor pathogens and plant diseases via fluorescence-based tagging systems.	Surface-Enhanced Raman Scattering (SERS) - Fluorescence Resonance Energy Transfer (FRET)
Environmental Nanosensors	Track temperature, humidity, and pest activity for environmental monitoring and control.	Artificial Nose (Carbon Nanomaterials, VOC Sensor)
Pathogen-Specific Nanosensors	Detect specific crop pathogens for early disease management.	Ag NP-ssDNA (Phytophthora ramorum Detection) - Au-NP-ssDNA (Bacterial Wilt Detection)
Nano-Fertilizer Delivery Sensors	Release nutrients based on real-time crop needs using plant root signals.	TiO2-NP-dsDNA (Phytophthora spp. Detection), Pt-NP-IgG (Potato Rot Detection)

The proposed Hybrid Algorithm GA + WRR (Load Balancer) solves several crucial issues in cloud computing. It improves load distribution in two ways: avoiding workloads that can maximize the distribution of workloads among virtual machines. It increases resource efficacy by eliminating idle virtual machines. The execution time of tasks is drastically reduced with the help of the algorithm, which distributes the tasks and prioritizes the most important ones to allocate them to the most productive VMs. It also minimizes execution time by scheduling tasks through GA evaluations, which then constantly reshape tasks according to live feedback from the WRR. The hybrid approach fits well in flex staffing environments since it can easily adjust to changes in the workload and variably available resources. Fig. 2 shows a flowchart of the Eclipse GA+WRR scheduling algorithm.

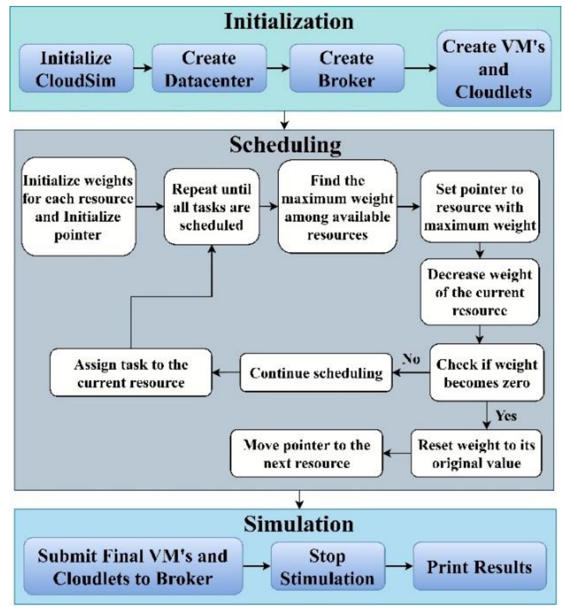

Fig. 2 – Flowchart of GA+WRR Scheduling Algorithm [10]

3.2 Fog Computing Layer

The Fog Computing Layer solves the problems of high latency of fog computing by placing the fog data centres near the data sources or farms. This layer also enables real-time analysis of data gathered from the IoT devices within the first layer. Fog computing is an alternate model to cloud computing that takes benefit of the widespread availability of computers and the huge amounts of data they create. By bringing resources and transactions closer to endpoints, increasing bandwidth at access points like routers, and decreasing the requirement for massive data transmission to faraway cloud servers, fog computing decentralises information and processes in contrast to cloud computing. Fig. 3 shows the Fog Computing architecture.

Tasks of the Fog Computing Layer:

• Prediction: Applying past information to predict the agriculture status and result.

• Planning: Helping farmers plan when, what, and where to get the seeds/plants from [11].

• Diagnosis: Data analysis may detect problems in the crops or the type of soil, allowing for the desired results.

• Monitoring: Predominantly, monitoring parameters of the agricultural environment to maintain the most favourable for crop growth.

• Fingering: Using percentages to identify specific areas that need intervention among a given population sample.

• Maintenance: Keeping track of the system health by checking the devices and Sensors.

• Local Storage: Files are passed to other Applications to save bandwidth when transferring to Cloud Storage.

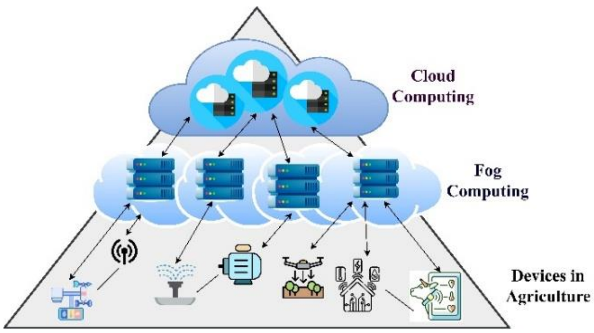

Fig. 3 – Fog Computing Architecture [12]

3.3 Communication Layer

The Communication Layer is an intermediary layer between all layers of the smart agriculture framework. It comprises multiple communication channels between IoT devices, fog nodes, and the clouds they use. The main characteristics of the Communication layer:

• Interoperability: Requires that Devices from different manufacturers are interoperable or integrated.

• Protocols: Includes high-level data transfer protocols, for example, MQTT or CoAP [13].

• Data Transmission Management: controls the flow or the packaging, transmission and reception of data over the network.

3.4 Cloud Computing Layer

The Cloud Computing Layer offers profound computation capabilities due to which massive computations are possible and required for data mining [14]. It involves cloud nodes, data centers, satellite communications, and others to support enhanced sophistication of the analysis.

Roles of the Cloud Computing Layer:

• Data Storage: Provides potential data storage capacity to accommodate a large number of data collected from different sources [15].

• Advanced Analytics: Helps to run analytical work using machine learning techniques to extract the required findings from agricultural data.

• Remote Access: This feature lets farmers view data online from a Web browser or smartphone application to make informed decisions.

• Scalability: Enables the delivery of materials that can be easily increased or decreased in terms of the outputs depending on a particular client's requests without having to construct formal infrastructures.

4. PERFORMANCE EVALUATION

Experimental Deployment: The experiment uses Eclipse and CloudSim to simulate cloud settings, analyzing execution time based on computation duration and resource allocation [16]. Recorded and tabulated the execution timings for various scheduling strategies across different numbers of CloudLets(100, 200, 300, 400). The burst time analysis presented illustrates the superior performance of GA+WRR compared to round-robin (RR) and First-come Firat Server (FCFS) algorithms. Cloudlets subjected to GA+WRR exhibit notably shorter total execution times, indicating more efficient resource utilization and reduced processing delays. For instance, when compared against RR and FCFS, WRR demonstrates consistently lower total execution times across cloudlets with varying burst times. This efficiency translates into improved system responsiveness and enhanced user satisfaction, particularly in environments with diverse workloads and fluctuating resource demands.

Configuration 1: Comprises 5 Virtual Machines (VMs), VMs with RAM = 5,120, bandwidth (BW) = 1,000, and a Host with RAM = 102,400 and BW = 100,000. Table 2 and Fig. 4 show the burst time of cloudlets.

Table 2 – Burst Time of Cloudlets

Scheduling Algorithms	**100**	**200**	**300**	**400**
GA+WRR	51	82	135	208
WRR	145	184	223	311
RR	186	200	254	329
FCFS	253	312	401	449

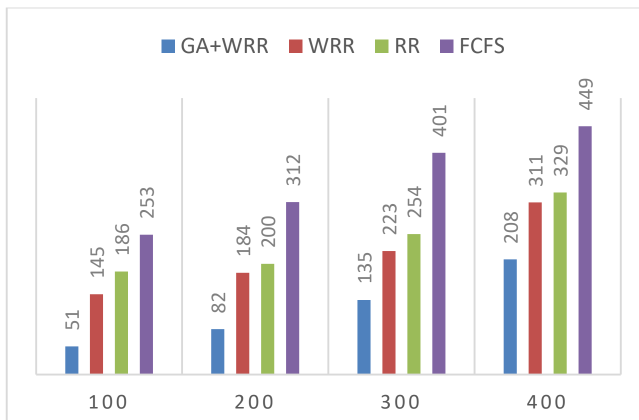

Fig. 4 – Burst Time of Cloudlets

Configuration 2: Comprises 5 Virtual Machines(VMs), VMs with RAM = 92160, bandwidth (BW) = 50,000, and a Host with RAM = 10,02,400 and BW = 1,00,000. Table 3 and Fig. 5 shows the burst time of cloudlets.

Table 3 – Burst Time of Cloudlets

Scheduling Algorithms	**100**	**200**	**300**	**400**
GA+WRR	45	73	131	199
WRR	132	178	211	273
RR	176	197	245	312
FCFS	242	305	399	416

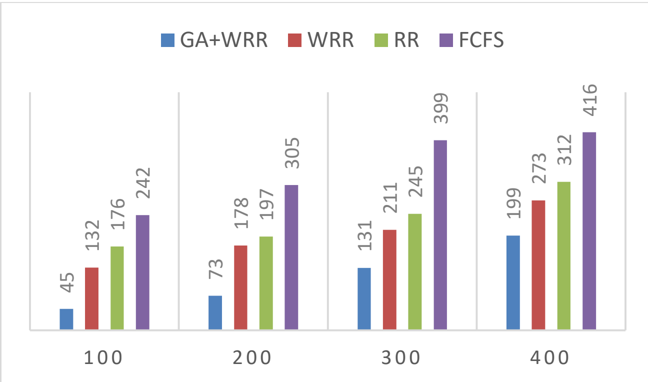

Fig. 5 – Burst Time of Cloudlets

5. CONCLUSION

The agriculture sector is positioned for a revolutionary shift by integrating novel technologies like cloud and fog computing. This study ultimately asserts that by integrating Nano-enhanced- IoT devices, fog, and cloud computing, the architecture comprehensively resolves the challenges faced in smart agriculture. Fog computing can be utilized by Nano-Enhanced IoT sensors implanted in agricultural fields to collect and process data in real-time, thereby reducing data transfer and latency requirements. The fog computing layer is an intermediary for processing localized data to enhance operational effectiveness and promptness at the network's periphery. The cloud computing layer provides centralized processing and storage capabilities and ensures optimal data transfer across the fog layer. A hybrid scheduling method, Genetic Algorithm with Weighted Round Robin (GA+WRR), has been proposed as a critical solution to mitigate network load balancing challenges and enhance resource allocation efficiency. GA+WRR improves system responsiveness and user satisfaction over traditional scheduling. The architecture enhances agriculture through data-driven decisions, boosting sustainability and productivity. Integrating cloud, fog, and smart agriculture drives innovation, essential for tackling global farming challenges.

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Нано-вдосконалені IoT-датчики та гібридні алгоритми планування для розумного сільського господарства: багаторівнева структура для сталого розвитку

Sneha[1], P.D. Singh[1], V. Tripathi[1], S. Maurya[2]

[1] *Graphic Era (Deemed to be University), Dehradun, India*
[2] *Symbiosis International University, Pune, India*

У сільськогосподарській сфері спостерігається кілька змін, особливо з технологічною структурою Інтернету речей, яка інтегрує хмарні обчислення, туманні обчислення та нанотехнології. Усі ці інновації розроблені для підвищення продуктивності, оптимізації використання ресурсів та охорони навколишнього середовища. Розумне сільське господарство зараз визначається методом ведення сільського господарства, який допомагає фермерам вільно збирати дані, проводити аналіз у режимі реального часу та автоматизувати певні процеси. У цьому дослідженні представлена багатошарова структура розумного сільського господарства, багаторівнева архітектура, яка пропонує рішення для належного виконання розумного сільського господарства. Нано-розширений шар Інтернету речей використовує наносенсори для моніторингу стану ґрунту, врожаю та навколишнього середовища, тоді як туманний шар миттєво обробляє дані, а хмарний шар обробляє великомасштабні обчислення та зберігання. Для обробки величезної кількості даних, що генеруються нано-розширеними пристроями Інтернету речей, використовується гібридний алгоритм планування GA+WRR для кращого управління ресурсами, що є в його розпорядженні, та мінімізації часу виконання. Аналіз продуктивності за допомогою Eclipse IDE показує кращі результати представленої структури, ніж базові методи планування. Запропонована структура оптимізує ресурси та мінімізує час виконання, забезпечуючи сталий та ефективний сільський господарство для задоволення світового попиту на продукти харчування.

Ключові слова: Нано-покращений шар інтернету речей, Туман, Хмарні обчислення, Гібридний алгоритм.