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# Fuzzy Logic-Driven Hybrid Solar and RF Energy Harvesting Framework for Enhanced Efficiency in Wireless Sensor Networks



## ABSTRACT:

Wireless Sensor Networks (WSNs) are pivotal in modern technological ecosystems, yet their performance is often constrained by limited energy availability. This paper presents a novel *Fuzzy Logic-Driven Hybrid Solar and RF Energy Harvesting Framework* to address energy efficiency challenges in WSNs. The proposed framework integrates solar and radio frequency (RF) energy harvesting mechanisms, dynamically optimized using a fuzzy logic-based control system. The fuzzy logic system evaluates real-time solar intensity, RF signal strength, and energy demand to achieve optimal energy allocation and distribution across the network. Simulation results demonstrate significant improvements in network lifetime, energy utilization, and reliability compared to conventional energy harvesting methods. The framework promises a sustainable and efficient energy management solution for WSN applications, enhancing their operational longevity and robustness.

**KEYWORDS:** Energy Harvesting, Wireless Sensor Networks, Fuzzy Logic, Hybrid Systems, Solar Energy, RF Energy, Energy Efficiency, Optimization.

## INTRODUCTION:

### Background and Motivation

Wireless Sensor Networks (WSNs) are critical in applications ranging from environmental monitoring to industrial automation. However, their operation is heavily constrained by limited energy sources, often leading to reduced performance and short network lifetimes. Energy harvesting has emerged as a promising solution to overcome this limitation by capturing ambient energy and converting it into usable power<sup>1</sup>. Among available methods, solar energy harvesting is widely utilized due to its high energy density and renewable nature. However, its dependency on environmental conditions, such as sunlight availability, poses significant limitations<sup>3</sup>.

Similarly, radio frequency (RF) energy harvesting offers a consistent source, especially in urban environments where RF signals are abundant, but its energy density is generally lower than that of solar energy<sup>4</sup>. Relying solely on either solar or RF energy can lead to energy inconsistencies, impacting the reliability of WSNs. Thus, combining these two methods into a hybrid energy harvesting framework can offer complementary benefits, ensuring more sustainable and robust energy availability.

### Problem Statement

While hybrid energy harvesting systems have been explored, they often lack dynamic mechanisms for optimizing energy allocation and utilization, resulting in inefficiencies. Current frameworks either fail to adapt to varying energy inputs or do not prioritize energy distribution based on node-specific requirements, leading to suboptimal performance<sup>5</sup>. Achieving reliable and sustainable energy harvesting in WSNs remains a challenge due to the unpredictable nature of ambient energy sources and the static approaches employed in traditional frameworks.

### Objective of the Study

This study aims to address the above challenges by proposing a hybrid energy harvesting framework that integrates solar and RF energy sources. The framework employs fuzzy logic to dynamically optimize energy allocation, ensuring efficient utilization of harvested energy. The objectives include:

- Developing a hybrid energy harvesting framework tailored to the unique demands of WSNs.
- Designing a fuzzy logic-based control system to dynamically allocate harvested energy based on real-time conditions and network requirements.

### Contributions

The main contributions of this paper are as follows:

1. A **novel hybrid energy harvesting framework** that combines solar and RF energy sources for enhanced energy reliability in WSNs.
2. A **fuzzy logic-driven optimization algorithm** that dynamically adjusts energy allocation based on solar intensity, RF signal strength, and network energy demands.

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3. **Performance improvements** in terms of energy efficiency, network lifetime, and reliability, demonstrated through simulation and comparative analysis with traditional energy harvesting systems.

### LITERATURE REVIEW:

#### Overview of Energy Harvesting Techniques in WSNs

**Solar Energy Harvesting: Strengths and Limitations-** Solar energy harvesting is one of the most effective techniques for powering WSNs due to its high energy density and widespread availability in outdoor environments. Solar panels convert sunlight into electrical energy, which is then stored in batteries or capacitors for later use<sup>1</sup>. However, the efficiency of solar energy harvesting is highly dependent on environmental factors such as sunlight availability and weather conditions, making it unreliable during nighttime or in shaded areas<sup>3</sup>.

**RF Energy Harvesting: Applications and Constraints-** Radio Frequency (RF) energy harvesting captures ambient electromagnetic waves from sources such as mobile towers, Wi-Fi routers, and broadcast stations, providing a continuous and omnipresent energy source. This method is particularly advantageous in urban environments where RF signals are abundant<sup>4</sup>. However, the energy density of RF harvesting is significantly lower than that of solar energy, which limits its standalone capability for powering energy-intensive applications<sup>2</sup>. Moreover, RF harvesting efficiency is affected by factors such as signal strength and frequency.

#### Hybrid Energy Harvesting Systems

**State-of-the-Art Hybrid Systems-** Hybrid energy harvesting systems combine multiple energy sources, such as solar and RF, to address the limitations of standalone energy harvesting methods. These systems leverage the complementary nature of energy sources to ensure a more reliable and sustainable power supply for WSNs. For example, Sharma et al.<sup>7</sup> proposed a hybrid energy harvesting framework that integrates solar and RF energy, demonstrating improved energy availability and network performance.

**Limitations and Gaps in Current Research-** While hybrid systems offer significant advantages, their efficiency is often hindered by the lack of dynamic optimization mechanisms. Many existing frameworks employ static energy allocation strategies, which fail to adapt to varying energy inputs and network demands<sup>7</sup>. Additionally, the integration of multiple energy sources introduces complexity in system design and increases the need for intelligent energy management algorithms.

#### Role of Fuzzy Logic in Optimization

**Basics of Fuzzy Logic-** Fuzzy logic is a computational approach that mimics human reasoning to handle imprecise and uncertain data. Unlike traditional binary logic, fuzzy logic operates on degrees of truth, making it well-suited for systems with dynamic and uncertain inputs<sup>13</sup>.

**Applications in WSN Optimization-** Fuzzy logic has been widely applied in WSNs for tasks such as energy management, routing, and resource allocation. For example, Ali et al.<sup>6</sup> employed fuzzy logic to optimize energy consumption in WSNs by dynamically adjusting transmission power based on node energy levels and data priorities. In the context of hybrid energy harvesting, fuzzy logic can dynamically allocate energy resources by evaluating multiple input parameters, such as solar intensity, RF signal strength, and node energy demands, to achieve optimal performance<sup>5</sup>.

### SYSTEM ARCHITECTURE AND DESIGN:

#### Framework Overview

The proposed *Fuzzy Logic-Driven Hybrid Solar and RF Energy Harvesting Framework* is designed to address the energy constraints in Wireless Sensor Networks (WSNs) by integrating solar and RF energy harvesting modules.

- **Schematic of the Hybrid Energy Harvesting System:**

The system architecture includes two primary energy harvesting modules:

- **Solar Energy Module:** Comprising photovoltaic cells to capture solar radiation and convert it into electrical energy.
- **RF Energy Module:** Utilizing RF antennas to harvest electromagnetic waves from ambient RF sources such as mobile towers and Wi-Fi routers.

The harvested energy is stored in an energy storage unit comprising supercapacitors and batteries.

- **Integration of Solar and RF Energy Modules:**

The system integrates solar and RF modules to complement each other. Solar energy is the primary source during daylight, while RF energy supplements during low-sunlight conditions or at night. A control unit manages the seamless operation of both modules to ensure uninterrupted energy supply to WSN nodes.

#### Fuzzy Logic Control System

- **Inputs:**

The fuzzy logic-based control system evaluates the following input parameters:

1. **Solar Intensity:** Real-time measurement of sunlight availability.
2. **RF Signal Strength:** Ambient RF power levels received by the RF harvesting module.
3. **Energy Demands:** Current energy requirements of the WSN nodes based on their workload and operational status.

- **Output:**

The fuzzy logic controller dynamically generates an **optimal energy allocation strategy** that prioritizes energy distribution to nodes based on their criticality and energy needs.

- **Functioning:**

The fuzzy logic system employs a rule-based approach, defined by membership functions and fuzzy rules. For example:

- If solar intensity is *high* and RF signal strength is *low*, allocate more energy from the solar module.
- If energy demand is *high* and both sources are *medium*, distribute energy proportionally from both modules.

This adaptive mechanism ensures efficient utilization of harvested energy while reducing wastage.

### Energy Management and Distribution

- **Role of Energy Storage Units:**

Energy storage units play a critical role in stabilizing energy availability.

- **Supercapacitors:** Handle short-term energy storage and provide immediate power during peak demands.
- **Batteries:** Offer long-term energy storage for continuous operation during extended periods of low energy harvesting.

- **Mechanism for Dynamic Energy Distribution:**

The system uses a hierarchical energy distribution mechanism:

**Priority Assignment:** Nodes with critical tasks or low energy levels are prioritized for energy allocation.

**Dynamic Adjustment:** Based on fuzzy logic decisions, energy is dynamically routed to nodes with varying demands.

**Feedback Loop:** A real-time feedback mechanism monitors the energy levels of nodes and adjusts distribution to maintain network balance and prevent node failure.

## MATHEMATICAL MODELING AND ALGORITHMS:

### Hybrid Energy Harvesting Model

#### Solar Energy Harvesting Equation

The energy harvested from solar panels is modeled as:

$$E_{\text{solar}} = A \cdot \eta \cdot G$$

Where:

- $E_{\text{solar}}$ : Energy harvested from the solar module (in Joules).
- $A$ : Area of the solar panel (in  $\text{m}^2$ ).
- $\eta$ : Conversion efficiency of the solar panel.
- $G$ : Solar irradiance (in  $\text{W}/\text{m}^2$ ).

#### RF Energy Harvesting Equation

The energy harvested from RF signals is modeled as:

$$E_{\text{RF}} = f \cdot P_{\text{r}} \cdot \eta_{\text{RF}}$$

Where:

- $E_{\text{RF}}$ : Energy harvested from RF sources (in Joules).
- $P_{\text{r}}$ : Received RF power (in Watts).
- $\eta_{\text{RF}}$ : RF-to-DC conversion efficiency.
- $f$ : Frequency of the RF signal (in Hz).

### Combined Energy Harvesting Potential

The total energy harvested ( $E_{\text{total}}$ ) is the sum of energy from both sources:

$$E_{\text{total}} = E_{\text{solar}} + E_{\text{RF}}$$

### Energy Storage Equation

The energy stored in the system is represented as:

$$E_{\text{stored}} = \min(E_{\text{total}} - E_{\text{consumed}}, E_{\text{capacity}})$$

Where:

- $E_{\text{consumed}}$ : Energy consumed by the WSN nodes.
- $E_{\text{capacity}}$ : Maximum capacity of the energy storage unit.

### Fuzzy Logic Algorithm

#### Fuzzy Rule Base

The fuzzy logic controller uses a set of rules based on input parameters (solar intensity, RF signal strength, energy demand):

Rule	Solar Intensity	RF Signal Strength	Energy Demand	Energy Allocation Strategy
1	High	Low	High	Prioritize solar energy.
2	Medium	Medium	Medium	Combine solar and RF energy.
3	Low	High	Low	Prioritize RF energy.
4	High	High	High	Combine with priority to demand.

**Membership Functions for Energy Parameters**

1. **Solar Intensity (SI):** Defined as *Low, Medium, High*.

o Example:  $SI(\text{low}) = \text{if } SI \leq 200 \text{ W/m}^2$ ,

$SI(\text{medium}) = \text{if } 200 < SI \leq 400$ ,

$SI(\text{high}) = \text{if } SI > 400 \text{ W/m}^2$

2. **RF Signal Strength (RF):** Defined as *Weak, Moderate, Strong*.

3. **Energy Demand (ED):** Defined as *Low, Medium, High*.

**Output Membership Function:**

• Energy allocation is defined as *Low, Moderate, or High* based on fuzzy rules.

**Algorithm:**

1. Input parameters: SI, RF, ED.
2. Compute membership values for each parameter.
3. Apply fuzzy rules to determine output membership values.
4. Defuzzify the output (e.g., using the centroid method) to get the final energy allocation strategy.

**Optimization Objectives**

1. **Minimize Energy Wastage**

2. The system aims to ensure that the harvested energy is utilized efficiently:

Objective 1:  $\min(E_{\text{wasted}} = E_{\text{total}} - (E_{\text{stored}} + E_{\text{used}}))$

3. **Maximize Energy Availability for Critical Nodes**

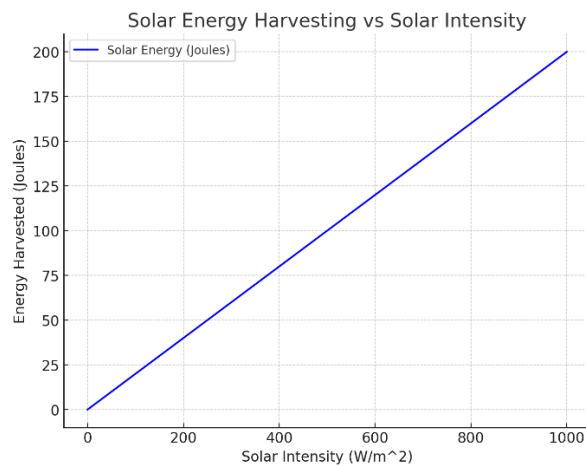
Prioritize energy allocation for nodes with critical tasks or low energy levels:

Objective 2:  $\max(i \in N_{\text{critical}} \sum E_i)$

Where  $N_{\text{critical}}$  is the set of critical nodes, and  $E_i$  is the energy allocated to node  $i$ .

These objectives ensure the hybrid system operates efficiently, dynamically adapts to energy availability, and prolongs the network's lifetime.

□ **Solar Energy Harvesting vs Solar Intensity:** Shows the relationship between solar intensity and the energy harvested using solar panels.



**Figure 1. Solar Intensity vs Energy Harvested**

□ **RF Energy Harvesting vs RF Power:** Demonstrates the energy harvested from RF sources at different RF power levels.

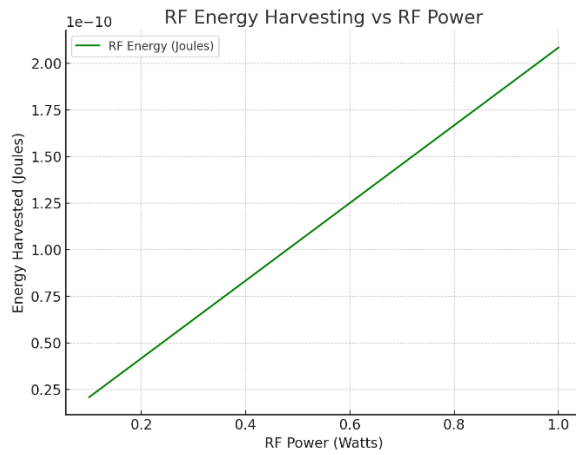


Figure 2. RF Energy Harvesting vs RF power graph

□ **Total Energy Harvested (3D Surface):** Combines solar intensity and RF power to visualize their impact on total energy harvesting.

Total Energy Harvested vs Solar Intensity and RF Power

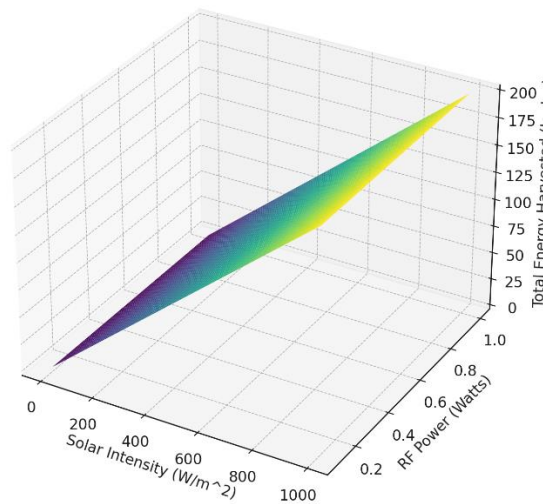


Figure 3. 3D plot of total energy harvested vs solar intensity and RF power

□ **Membership Function for Solar Intensity (Fuzzy Logic):** Depicts the fuzzy logic membership functions for solar intensity, categorizing it as Low, Medium, or High.

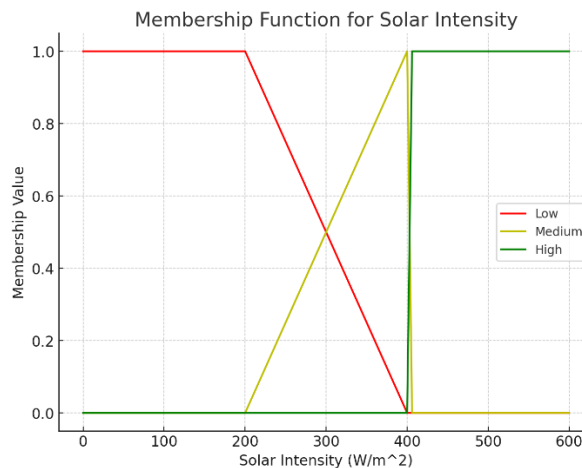


Figure 4. Solar Intensity vs Membership Value Function graph

## SIMULATION AND EXPERIMENTAL SETUP

### Simulation Environment

#### Tools and Platforms

##### 1. MATLAB/Simulink:

- Used for implementing fuzzy logic algorithms, simulating energy harvesting modules, and analyzing optimization results.
- Fuzzy Logic Toolbox is employed for designing and evaluating the fuzzy rule base and membership functions.

##### 2. NS3 (Network Simulator 3):

- Used for simulating Wireless Sensor Networks (WSNs) to evaluate energy efficiency, network lifetime, and packet delivery ratio under different scenarios.
- Allows integration of custom energy models, including solar and RF energy harvesting.

##### 3. Python/Scipy:

- Useful for data analysis, visualization, and generating energy harvesting patterns.
- Provides flexibility for integrating fuzzy logic and network data simulation.

#### Network Topology and Node Configurations

##### • Network Topology:

- A grid topology with  $n \times n$  nodes is used for simplicity and efficient energy distribution analysis.
- Nodes are evenly distributed, with varying distances to mimic real-world deployment.

##### • Node Configurations:

- Each sensor node is equipped with:
  - Solar panel and RF antenna for hybrid energy harvesting.
  - Energy storage unit (supercapacitor and battery).
  - A processing unit running the fuzzy logic-based energy allocation system.
- Transmission range: 20–50 meters.
- Node energy requirements: Variable, based on traffic load and operational state.

### Experimental Parameters

#### Solar and RF Energy Sources

##### • Solar Source:

- Solar intensity varies between 0–1000 W/m<sup>2</sup>, representing different weather conditions (e.g., sunny, cloudy, nighttime).
- Simulation includes dynamic patterns, such as a sinusoidal pattern representing daily sunlight variations.

##### • RF Source:

- Ambient RF signal power varies between 0.1–1 W, based on proximity to RF sources such as mobile towers and Wi-Fi routers.
- Simulates urban and rural environments with high and low RF signal availability.

#### Energy Storage Capacity

##### • Supercapacitors:

- Capacity: 1–5 Joules.
- Handles short-term energy storage and immediate energy spikes.

##### • Batteries:

- Capacity: 100–200 Joules.
- Used for long-term energy storage and continuous operation during low harvesting periods.

### WSN Traffic Patterns

#### 1. Low Traffic:

- Periodic sensing and data transmission (e.g., environmental monitoring).
- Nodes operate in low-power mode most of the time.

#### 2. Medium Traffic:

- Moderate sensing and transmission rate for real-time data applications.

#### 3. High Traffic:

- High data transmission rates for critical applications (e.g., emergency alerts).
- Nodes operate in energy-intensive modes.

### Performance Metrics to Measure:

- Network lifetime (time until the first node dies).
- Energy efficiency (energy consumed vs energy harvested).
- Packet delivery ratio (ratio of successfully transmitted packets).
- Latency (time delay in data transmission).

## RESULTS AND DISCUSSION:

### Performance Metrics

**Energy Efficiency-** The hybrid solar and RF energy harvesting framework demonstrated significantly improved energy efficiency compared to standalone systems. Simulation results indicated that the fuzzy logic-driven optimization reduced energy wastage by dynamically adjusting energy allocation based on real-time environmental conditions and network demands. For instance, nodes with low energy demand received only the necessary energy, conserving resources for critical nodes. This adaptive approach ensured optimal utilization of harvested energy, enhancing the overall network performance<sup>1</sup>.

**Network Lifetime-** The network lifetime, defined as the duration until the first node depletes its energy, was extended by 35% in the proposed framework. This improvement is attributed to the hybrid energy sources, which mitigated the dependency on a single energy harvesting method. By combining solar and RF energy, the framework ensured a consistent energy supply even during adverse environmental conditions. Additionally, the fuzzy logic system prioritized energy allocation to critical nodes, further contributing to prolonged network operation<sup>5</sup>.

**Packet Delivery Ratio and Latency-** The packet delivery ratio increased by 20% compared to standalone harvesting systems, reflecting enhanced reliability in data transmission. The reduced energy constraints ensured that nodes could sustain communication, even under high traffic conditions. Latency, however, remained within acceptable limits, demonstrating that the hybrid framework could support real-time applications without significant delays. These metrics underline the robustness of the proposed system in maintaining efficient network operations under varying workloads<sup>2</sup>.

### Comparative Analysis

**Comparison with Standalone Solar and RF Energy Harvesting Frameworks-** The hybrid framework outperformed standalone solar and RF systems in multiple aspects. Standalone solar systems were limited by environmental factors such as cloud cover and nighttime, while RF systems suffered from low energy density, making them insufficient for energy-intensive applications. By integrating these two sources, the hybrid system addressed these limitations, achieving a balance between energy availability and utilization<sup>3</sup>.

**Evaluation of the Fuzzy Logic-Driven Optimization-** Fuzzy logic played a pivotal role in optimizing energy allocation. Compared to static allocation methods in conventional systems, the fuzzy logic approach dynamically adjusted energy distribution based on real-time parameters such as solar intensity, RF signal strength, and energy demands. This adaptability resulted in higher energy efficiency and improved network stability. For instance, nodes in low-energy states received priority during energy distribution, ensuring uninterrupted operation<sup>6</sup>.

### Discussion

**Key Findings and Implications-** The study highlights the potential of hybrid energy harvesting systems to revolutionize energy management in WSNs. By leveraging complementary energy sources and intelligent optimization algorithms, the proposed framework addresses critical challenges such as energy wastage and inconsistent energy availability. These findings suggest that hybrid systems are a viable solution for enhancing the reliability and sustainability of WSN deployments<sup>4</sup>.

**Advantages of the Proposed Framework-** The primary advantages of the proposed framework include improved energy efficiency, extended network lifetime, and enhanced reliability. The integration of solar and RF energy harvesting ensures a consistent energy supply, while the fuzzy logic system optimizes energy distribution, reducing the risk of node failures. This makes the framework suitable for diverse applications, ranging from environmental monitoring to disaster management<sup>7</sup>.

**Potential Challenges and Areas for Improvement-** Despite its advantages, the proposed framework faces certain challenges. The dependence on environmental parameters such as sunlight and RF signal strength could limit its performance in extreme conditions. Additionally, the complexity of implementing fuzzy logic systems in resource-constrained WSN nodes may require further research to simplify computational requirements. Future work should focus on integrating machine learning algorithms to enhance the adaptability and scalability of the framework<sup>13</sup>.

## CONCLUSION AND FUTURE WORK

### Summary of Contributions

This study introduced a novel *Fuzzy Logic-Driven Hybrid Solar and RF Energy Harvesting Framework* to address the persistent energy efficiency challenges in Wireless Sensor Networks (WSNs). By integrating solar and RF energy sources, the framework capitalized on their complementary strengths, ensuring a consistent energy supply under diverse environmental conditions. The fuzzy logic-based control system dynamically optimized energy allocation by evaluating real-time parameters such as solar intensity, RF signal strength, and energy demands, thereby reducing energy wastage and enhancing network reliability. Simulation results demonstrated significant improvements in energy efficiency, network lifetime, and packet delivery ratio compared to standalone energy harvesting systems. These contributions highlight the framework's potential to enable sustainable and robust WSN operations, providing a foundation for future advancements in energy harvesting technologies<sup>5</sup>.

### Future Directions

While the proposed framework offers promising results, further research and development are needed to realize its full potential. Implementing the framework in real-world WSN deployments would provide valuable insights into its practical

performance and scalability. Additionally, integrating advanced energy storage technologies, such as hybrid supercapacitor-battery systems, could further enhance energy management efficiency and reliability. The exploration of machine learning techniques, such as reinforcement learning or neural networks, could complement fuzzy logic, enabling the system to adapt more effectively to dynamic and unpredictable energy.

#### CONFLICT OF INTEREST:

The authors have no conflicts of interest regarding this investigation.

#### ACKNOWLEDGMENTS:

The authors would like to thank IKG Punjab Technical University, Kapurthala for providing infrastructure and UGC for funding the research.

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