RESEARCH RESONANCE

The Research Bulletin of GM University
Volume 3 | Issue 1 | January 2026
ISBN: 978-81-991111-3-4

Research & Innovation Division

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PREFACE

It is with immense pride and renewed enthusiasm that we present Volume 3, Issue 1 of GMU Research Resonance, the official multidisciplinary research bulletin of GM University. This edition represents another significant step in our sustained endeavor to strengthen a vibrant, inclusive, and impact-driven research culture across the University.

GM University continues to advance as a dynamic center of scholarly excellence and innovation. Our faculty members, research scholars, and students are actively engaged in forward-looking inquiry that responds to contemporary societal and technological challenges while expanding disciplinary and interdisciplinary knowledge. Research Resonance serves as a distinguished platform for disseminating these intellectual contributions, featuring cutting-edge work in Computer Science, Artificial Intelligence, Internet of Things, Civil and Mechanical Engineering, Information Science and Engineering, Electronics and Communication Engineering, Management, and a range of emerging interdisciplinary domains.

In a time characterized by accelerated technological transformation and complex global realities, the role of rigorous research, collaborative scholarship, and ethical knowledge dissemination is more critical than ever. Through this issue, we reaffirm our institutional commitment to fostering interdisciplinary engagement, nurturing innovative thought, and advancing research that transcends conventional academic silos to generate tangible societal value.

We extend our sincere gratitude to the contributing authors, dedicated peer reviewers, and esteemed members of the editorial board whose scholarly rigor and commitment uphold the quality and vision of this publication. We also express our appreciation to our readers, whose engagement and intellectual curiosity continually motivate us to pursue higher standards of academic distinction.

We invite you to explore the insightful contributions presented in this volume and to engage with the pioneering research initiatives shaping the future trajectory of GM University. May this issue inspire new ideas, strengthen collaborative networks, and encourage the sustained pursuit of knowledge, innovation, and societal advancement.

Sincerely,
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Design and Development of a Low-Cost Quadrupedal Robo Dog Using Arduino Nano, Servo Motor and Ultrasonic Sensor

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ABSTRACT

Quadrupedal robots provide superior mobility in unstructured environments compared to wheeled platforms; however, their development is often constrained by high costs and complex control systems. This paper presents the design, implementation, and evaluation of a low-cost quadrupedal Robo Dog using an Arduino Nano microcontroller, MG995 servo motors, and an HC-SR04 ultrasonic sensor. The objective of the project is to demonstrate basic legged locomotion and reactive behavior using accessible hardware and simple control logic. The robot integrates sensing, processing, and actuation to perform fundamental movements and proximity-based responses. Although mechanical limitations prevented the realization of advanced autonomous navigation, the prototype successfully validated core robotics principles such as multi-joint actuation, sensor feedback, and embedded control. The project serves as an effective educational platform and a foundation for future research in low-cost legged robotics.

Keywords: Quadrupedal Robot, Arduino Nano, MG995 Servo Motor, Ultrasonic Sensor, Legged Locomotion, Low-Cost Robotics

I. INTRODUCTION

Legged robots have gained significant attention in mobile robotics due to their ability to traverse uneven and cluttered terrains where traditional wheeled robots fail. Among legged platforms, quadrupedal robots offer a balance between mechanical stability and maneuverability. However, most existing quadrupedal systems rely on expensive actuators, advanced sensors, and high-performance processors, making them inaccessible for educational and low-budget applications.

This work presents a compact Robo Dog designed with a focus on simplicity, affordability, and instructional value. The system is built around an Arduino Nano microcontroller, MG995 servo motors for actuation, and a single HC-SR04 ultrasonic sensor for environmental perception. The robot follows a hierarchical control approach where sensor data is processed by the microcontroller to trigger reactive behaviors.

The main contribution of this paper is the demonstration of a cost-effective quadrupedal platform that integrates sensing, control, and actuation while highlighting real-world mechanical and power constraints encountered in low-cost robotic systems.

Developing an autonomous quadrupedal robot using low-cost hardware presents several challenges. While legged locomotion provides superior terrain adaptability, it requires precise coordination of multiple joints, stable mechanical design, and efficient control algorithms. These requirements are difficult to achieve using standard servo motors and limited microcontroller resources.

The problem addressed in this work is the design and implementation of a functional Robo Dog using an Arduino Nano and MG995 servo motors capable of basic locomotion and reactive behavior. The challenges include generating stable gait patterns, managing limited computational and power resources, and translating simple ultrasonic distance measurements into meaningful physical responses.

The objectives of this project are:

1. To design and fabricate a quadrupedal robotic structure with twelve degrees of freedom using MG995 servo motors.
2. To develop firmware for the Arduino Nano to control coordinated servo motion for basic locomotion.
3. To integrate an ultrasonic sensor for proximity detection and implement reactive behaviors based on sensor input.
4. To evaluate the performance and limitations of the low-cost quadrupedal platform.

Quadrupedal robotics has been an active research area for several decades, with applications ranging from rough-terrain exploration to service and companion robots. Early research primarily focused on achieving dynamic stability and high-speed locomotion using advanced control strategies and expensive hardware. Playter et al. introduced BigDog, a hydraulically actuated quadruped capable of maintaining balance on uneven terrain through dynamic control and force feedback. While highly effective, such systems rely on complex mechanical designs, high-power actuators, and sophisticated processors, making them unsuitable for low-cost or educational use [3].

In contrast, several researchers have explored servo-based quadrupedal robots aimed at reducing system complexity and cost. Silva and Machado presented a comprehensive survey on legged robotic technologies, highlighting the trade-offs between actuator selection, control complexity, and mechanical design. Their work emphasizes that statically stable gait generation is more suitable for low-cost platforms using servo motors and microcontrollers with limited computational capabilities [2].

Arduino-based quadrupedal robots have gained popularity in educational and hobbyist communities due to the simplicity and accessibility of Arduino platforms. Studies such as Design of a Low-Cost Quadruped Robot for Research and Education demonstrated the feasibility of implementing basic walking gaits using pre-programmed joint trajectories without real-time inverse kinematics [1]. These systems prioritize affordability and ease of implementation over performance, aligning closely with the objectives of the present work.

Behavior-based control architectures have also been widely adopted for resource-constrained robotic systems. Unlike deliberative or model-based control, behavior-based systems rely on direct sensor-to-actuator mappings, enabling real-time responsiveness with minimal computational overhead. This approach has been successfully applied in wheeled robots for obstacle avoidance and object following using ultrasonic sensors [4,6]. However, the integration of such reactive control strategies into quadrupedal robots remains relatively limited due to the added complexity of leg coordination.

Ultrasonic sensors such as the HC-SR04 have been extensively used for proximity sensing in mobile robotics because of their low cost, ease of interfacing, and acceptable accuracy for short-range detection. While their application in legged robots is typically restricted to simple obstacle detection, recent studies have demonstrated their effectiveness in triggering reactive behaviors such as stopping, turning, or gesture-like responses in social and interactive robots [5].

From the literature, it is evident that there exists a gap between high-performance quadrupedal robots and affordable educational platforms. Most low-cost quadrupeds lack integrated sensing and reactive behavior, while advanced systems remain inaccessible due to cost and complexity. The present project addresses this gap by developing a low-cost quadrupedal Robo Dog that combines multi-joint actuation, ultrasonic sensing, and behavior-based control using simple and widely available hardware components.

II. MATERIAL AND METHODS

The methodology adopted for the development of the quadrupedal Robo Dog follows a systematic engineering approach involving mechanical design, electronic integration, control logic development, and experimental validation. The overall system is designed to maintain simplicity and affordability while effectively demonstrating the fundamental principles of legged robotics.

A. System Architecture

The Robo Dog system is structured around three primary functional modules:

1. Sensing Module
2. Processing and Control Module
3. Actuation Module

The interaction among these modules follows a closed-loop reactive control architecture. The HC-SR04 ultrasonic sensor continuously monitors the surrounding environment and provides distance measurements to the Arduino Nano micro-controller. Based on this sensor input, the controller executes predefined logic and generates appropriate control signals for the servo motors to perform locomotion or reactive behaviors.

B. Mechanical Design and Leg Configuration

The mechanical structure of the Robo Dog consists of a quadrupedal frame fabricated using a sun board material. The robot has four legs, each comprising three joints:

- Hip joint – controls forward and backward motion of the leg
- Knee joint – enables lifting and lowering of the leg
- Ankle joint – provides additional stability and posture control

Each joint is actuated using an MG995 servo motor, resulting in a total of twelve degrees of freedom (12-DOF). The legs are symmetrically arranged to maintain balance during static walking. The mechanical design prioritizes ease of assembly and low cost; however, it imposes limitations on load-bearing capacity and structural rigidity.

C. Electronics and Control Hardware Integration

The Arduino Nano serves as the central processing unit of the system. Due to its limited PWM outputs, servo motors are controlled using time-multiplexed signals and shared power distribution. All servo motors are powered through an external battery source to prevent overloading the onboard voltage regulator of the Arduino.

The HC-SR04 ultrasonic sensor is interfaced with the Arduino using two digital pins:

- Trigger pin for transmitting ultrasonic pulses
- Echo pin for receiving reflected signals

The sensor measures the time-of-flight of ultrasonic waves, which is converted into distance values using standard timing calculations.

D. Locomotion Control Strategy

Due to limited computational resources and the absence of real-time feedback from joint encoders, the Robo Dog employs a predefined gait-based locomotion strategy. Instead of complex inverse kinematics, joint movements are generated using pre-calibrated servo angle sequences.

The locomotion follows a static walking gait, ensuring that at least three legs remain in contact with the ground at any given time. This approach enhances stability and reduces the risk of tipping. The gait sequence consists of the following steps:

1. Lifting one leg by adjusting knee and ankle angles
2. Moving the hip joint forward
3. Lowering the leg back to the ground
4. Repeating the process cyclically for all legs

Servo motion is controlled using timed delays to synchronize joint movements and prevent sudden jerks that could destabilize the structure.

E. Sensor-Based Reactive Behavior

The ultrasonic sensor provides real-time distance measurements, which are used to trigger reactive behaviors rather than autonomous navigation. When an object is detected within a predefined threshold distance, the Arduino executes a conditional control routine. Due to mechanical constraints and limited maneuverability, the ultrasonic sensor was repurposed to activate a tail-wagging behavior, simulating an interactive response similar to a pet dog. This behavior demonstrates sensor-actuator integration and real-time responsiveness without requiring complex navigation algorithms.

The reactive behavior logic follows a behavior-based control model, where sensor inputs directly influence actuator outputs with minimal processing overhead.

F. Software Development and Firmware Implementation

The control firmware was developed using the Arduino IDE and written in embedded C/C++. The software architecture includes:

- Servo initialization and calibration routines
- Ultrasonic distance measurement functions
- Gait sequencing logic
- Conditional behavior execution based on sensor input

Modular programming practices were followed to simplify debugging and allow future expansion of the system. The Servo library was used to generate PWM signals, and timing functions were carefully managed to ensure coordinated movement.

G. Testing and Performance Evaluation

The Robo Dog prototype was tested on flat indoor surfaces to evaluate:

- Stability during static walking
- Responsiveness of ultrasonic sensing
- Accuracy of servo movements
- Power consumption under load

Observations from testing revealed that while electronic and control components performed reliably, mechanical instability limited speed and maneuverability. These results informed the discussion on system limitations and future improvements.

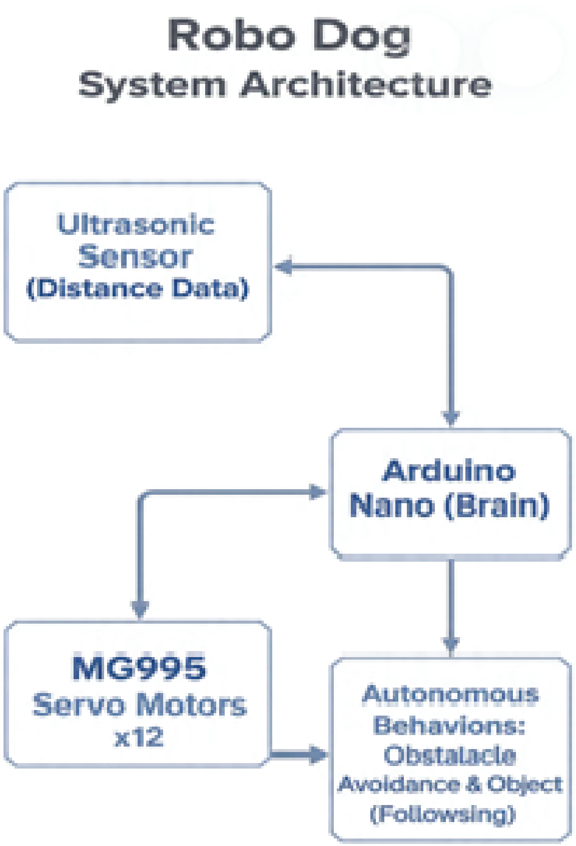

Figure 1: Block diagram of the project

A block diagram illustrates the interaction between the sensor, microcontroller, and actuators. The control strategy follows a reactive model, emphasizing simplicity and real-time responsiveness.

A. Hardware Components

1.Arduino Nano: The Arduino Nano served as the central brain of the Robo Dog. This compact board is based on the ATmega328P microcontroller, providing sufficient I/O pins to control multiple servos and process sensor data. Its small size, low power consumption, and ease of programming make it ideal for embedded robotics projects.

Specifications: Microcontroller: ATmega328P, Operating Voltage: 5V, Digital I/O Pins: 14 (of which 6 provide PWM output), Clock Speed: 16 MHz.

2.MG995 servo motor: The MG995 is a high-torque, digital servo motor used as the actuator for all the robot's joints. Each leg is driven by three servos, providing a total of twelve degrees of freedom for the quadruped. These metal-geared servos provide the necessary force to lift the robot's body and execute walking motions.

Specifications: Operating Voltage: 4.8V - 7.2V, Stall Torque: 10 kg/cm (at 6V), Gear Type: Metal, Rotation: 120 degrees.

3.HC-SR04 Ultrasonic Sensor: The HC-SR04 ultrasonic sensor was the primary sensor for environmental perception. Mounted on the front of the robot, it measures the distance to obstacles by emitting an ultrasonic pulse and calculating the time taken for the echo to return. This information is crucial for the obstacle avoidance and object following behaviors.

Specifications: Operating Voltage: 5V, Measuring Range: 2cm - 400cm, Measuring Angle: 15 degrees

4.Power Supply: External battery source to handle high current demands of multiple servos.

B. Software Tools

1.Arduino IDE: The Arduino IDE was the primary software used for writing, compiling, and uploading the code (firmware) to the Arduino Nano. Its simple interface and extensive library support for servos and sensors streamlined the development process.

Specifications: Version: 2.0+, Programming Language: C/C++

III. RESULTS AND DISCUSSION

The Robo Dog prototype was successfully assembled, and all electronic components functioned as expected. However, mechanical limitations of the sun board frame resulted in insufficient structural rigidity. This led to gait instability and restricted the robot to basic forward and backward movement rather than full autonomous navigation.

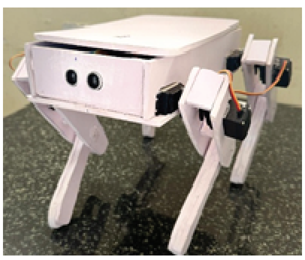

Figure 2: Prototype of the Robodog

The ultrasonic sensor reliably detected objects within a range of approximately 150 cm. Due to mechanical constraints, the sensor was repurposed to trigger a reactive tail-wagging behavior rather than navigation-based obstacle avoidance. This adaptation ensured functional demonstration despite design limitations.

ADVANTAGES, DISADVANTAGES, AND APPLICATIONS

A. Advantages

• Low-cost and accessible design
• High educational value
• Modular and customizable architecture
• Open-source development environment

B. Disadvantages

• Insufficient mechanical rigidity
• Limited processing power
• High power consumption
• Narrow sensor field of view
• Limited autonomy

C. Applications

• Educational robotics demonstrator
• Interactive robotic companion
• Mobile sensor platform
• Rehabilitation and therapy aid

IV. CONCLUSION

A. Conclusion

This paper presented the design and development of a low-cost quadrupedal Robo Dog using an Arduino Nano microcontroller, MG995 servo motors, and an HC-SR04 ultrasonic sensor. The primary objective of the project was to demonstrate fundamental principles of legged robotics namely multi-joint actuation, basic gait generation, and sensor based reactive behavior using affordable and easily accessible hardware components.

The developed prototype successfully integrated sensing, processing, and actuation within a compact quadrupedal framework. Static gait-based locomotion was achieved through predefined servo angle sequences, allowing the robot to perform basic forward and backward movements. The ultrasonic sensor reliably provided proximity information, which was effectively utilized to trigger reactive behaviors, thereby validating real-time sensor actuator interaction.Although the system faced mechanical challenges due to limited structural rigidity and power constraints, these limitations provided valuable insights into real-world design trade-offs encountered in low-cost robotic platforms. Overall, the project met its educational and experimental objectives, demonstrating that meaningful quadrupedal robotic behavior can be achieved without complex control algorithms or high-end hardware. The Robo Dog thus serves as an effective learning platform for undergraduate robotics education and introductory research in legged locomotion.

B. Future Work

While the current implementation demonstrates basic functionality, several enhancements can significantly Robo Dog. Future work will focus on the following aspects:

1. Mechanical Improvements: Replacing the existing sun board structure with a rigid 3D-printed or lightweight aluminum frame to improve structural stability and load distribution.
2. Advanced Gait Algorithms: Implementation of more stable and efficient gait patterns such as crawl, trot, or pace using inverse kinematics and trajectory planning techniques.
3. Enhanced Sensing: Integration of additional sensors such as inertial measurement units (IMUs), infrared sensors, or multiple ultrasonic sensors to improve balance, terrain adaptation, and obstacle avoidance.
4. Improved Power Management: Designing a dedicated power distribution system with voltage regulators to handle high current demands of multiple servo motors and extend operational time.
5. Autonomous Navigation: Incorporating closed-loop control and decision-making algorithms to enable autonomous navigation and environment interaction.
6. Wireless Communication: Adding Bluetooth or Wi-Fi modules for remote control, monitoring, and firmware updates.
7. Artificial Intelligence Integration: Future versions can incorporate basic machine learning or behavior learning algorithms for adaptive locomotion and interaction.

These enhancements will transform the Robo Dog from a reactive demonstrator into a fully autonomous quadrupedal robotic system, expanding its applicability in research, education, and real-world assistive scenarios.

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Influence of SiC and Graphite Reinforcements on Mechanical and Tribological Properties of AA6061 Hybrid Composites

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ABSTRACT
The increasing demand for lightweight materials with enhanced wear resistance has driven significant interest in hybrid aluminium matrix composites. In this work, the mechanical and tribological behaviour of AA6061 aluminium alloy reinforced with graphite (4 and 6 wt.%) and silicon carbide (2 and 3 wt.%) was investigated. The composites were fabricated using the stir casting technique. Hardness measurements and dry sliding wear tests were performed using a pin-on-disc apparatus in accordance with ASTM G99 standards. Taguchi L27 orthogonal array was employed to analyse the effects of applied load, sliding speed, and sliding distance on wear performance, while analysis of variance (ANOVA) was used to determine the significance of each parameter. The results indicated that increasing reinforcement content led to improved hardness, with hybrid composites showing a maximum enhancement of 4.83% compared to the base alloy. The combined presence of graphite and SiC resulted in improved wear resistance due to solid lubrication and increased surface hardness. The minimum wear rate of 4.3×10^{-6} g/m was observed at a sliding speed of 1.2 m/s and an applied load of 19.62 N for the AA6061–6%Gr–3%SiC composite. Response surface methodology and regression analysis confirmed the reliability of the experimental model. The study demonstrates the suitability of AA6061–SiC–Gr hybrid composites for lightweight, wear-resistant applications in automotive and aerospace sectors.

Keywords: ANOVA, ASTM G99, Composite Material, Regression Analysis

I. INTRODUCTION

Composite materials are gaining popularity due to their unique properties and high strength-to-weight ratio. Of these Aluminium Metal Matrix Composites (AMCs) are being used in structural materials due to their superior mechanical properties, high thermal conductivity, and good corrosion resistance [1]. For this, it has great demand in automobile and aerospace sectors. AMCs are generally reinforced with ceramic particles such as silicon carbide (SiC), aluminium oxide (Al_2O_3), graphite (Gr) and others [2]. In AMCs, the reinforcements in the form of particles, continuous fibres, short fibres, in those Particle reinforced AMCs are the most isotropic and easy to make [3]. The additions of hard particles in (AMCs) combine the high hardness and wear resistance of particulates with low density and ductility of and good dimensional stability of the material [4]. AMCs reinforced with silicon carbide and graphite particles have a higher strength to weight ratio and less ductility [5]. Graphite provides lubrication effect and improves the wear and friction during sliding [6]. Because of their better mechanical and tribological qualities, aluminum-based composites have emerged as an excellent substitute for ordinary aluminium alloys throughout the years. This article investigates the wear rate on AA6061/Gr/SiC hybrid metal matrix composites using squeeze casting technique with different composition and identified the suitable process parameter which influence wear rate. The process parameters like Sliding speed, sliding distance and load are optimized by Taguchi. The percentage of contribution of process parameter is evaluated by ANOVA [2].

II. MATERIAL AND METHODS

Al6061 is base material used commonly in automobile applications. And reinforcements are Sic and Gr, SiC gives improved strength and wear resistance. Gr, which is used as reinforcement, functions as a solid lubricant [7]. SiC particles, which are highly hard and brittle ceramics, have outstanding and great mechanical qualities such as strong tension and compression strength

Table1: Chemical composition of AA6061.

Elements	Al	Mg	Si	Fe	Cu	Cr	Mn	Zn	Ti
Weight %	97.81	0.95	0.54	0.22	0.17	0.13	0.09	0.08	0.01

Table2: The following are the different the composition chosen for study

Intermetallic content (wt. %)	
SE1	AA6061
SE2	AA6061+4%Gr+2%SiC
SE3	AA6061+6%Gr+3%SiC

Stir casting is used to make Al6061-SiC/Gr samples at different weight fractions of SiC/Al_2O_3 (2%, and 3%, 4%,and 6%). The furnace was used to melt the Al slabs. Liquid Al was superheated to 720°C after liquefying. SiC/Gr particles in the necessary amounts were added to the liquid Al and mixed at 600 r min−1 with a stirrer. After being placed into a permanent mould, the liquid Al6061-SiC/Gr was left to solidify. The composite bars made of Al6061-SiC/Gr were removed from the mould, examine the necessary characteristics of the samples.

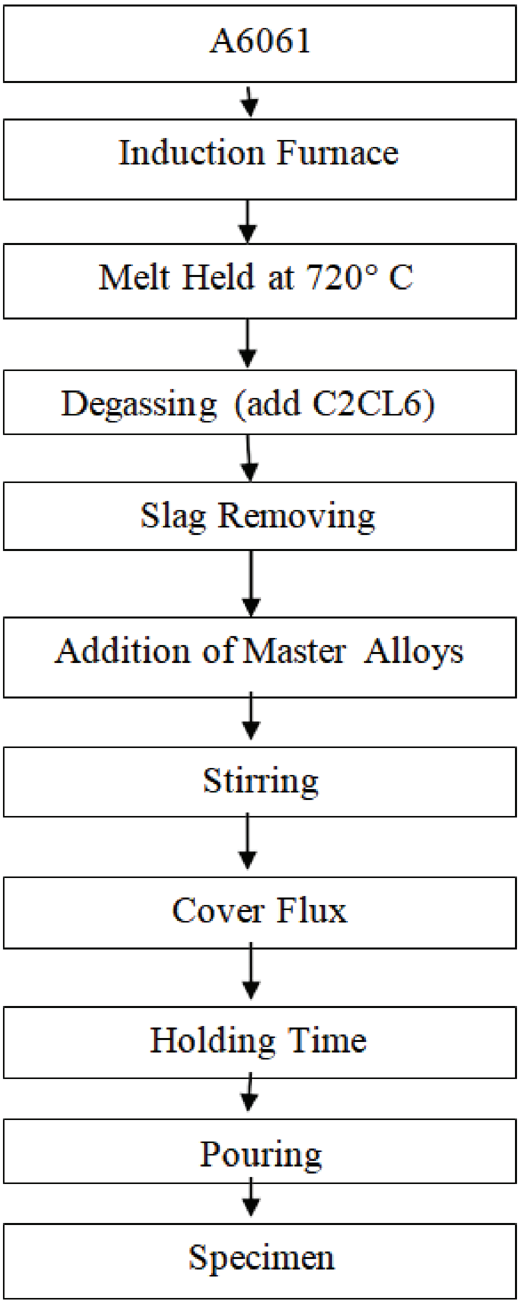

Figure 1. A Block Diagram of Casting process

Experimental Design:
To evaluate the performance of AA6061, Gr and Sic alloys under dry sliding conditions wear tests were carried out according to ASTM G99 standards using pin-on-disc wear testing machine. In the present study various parameters were studied and these are load, Sliding speed and sliding distance on different composition and Wear rate is measured. The important step in the experimental design is the choosing the suitable control factors. Composition, Spindle speed, and feed rate as shown in table 1. Experimental design for control factor is by considering L27 orthogonal array shown in table 2. It shows the combination of control factors with different levels for each test.

Table 2: Factors and level combination

Sl. No	Control factors	Level 1	Level 2	Level 3
1	Composition	SE1	SE2	SE3
2	Sliding speed m/s	1.2	2.5	3.7
3	Load N	0.1	0.2	0.3

Table 3: Testing variables

Sl. No.	Process parameters	Responses		
1	Load in N	9.81	19.62	29.43
2	Speed in RPM	200	400	600
3	Sliding Speed in m/s	1.2	2.5	3.7
4	Sliding time in min	5	5	5
5	Sliding Distance in m	396	842	1255
6	Time in min.	5	5	5

Table 3: Experimental design using L27 orthogonal array

Trial	A	B	C
1	1	1	1
2	1	1	2
3	1	1	3
4	1	2	1
5	1	2	2
6	1	2	3
7	1	3	1
8	1	3	2
9	1	3	3
10	2	1	1
11	2	1	2
12	2	1	3
13	2	2	1
14	2	2	2
15	2	2	3
16	2	3	1
17	2	3	2
18	2	3	3
19	3	1	1
20	3	1	2
21	3	1	3
22	3	2	1
23	3	2	2
24	3	2	3
25	3	3	1
26	3	3	2
27	3	3	3

III. RESULTS AND DISCUSSION

The hardness of a material can be influenced by the presence of other materials or additives, such as graphite and SiC, in a composite. In the context of Al6061, both graphite and SiC can have distinct effects on the hardness of the alloy.

Table 4: Experimental results of Hardness.

Sl. No	Composition	Hardness (HRB)
1	SE1	41.33
2	SE2	42.66
3	SE3	43.33

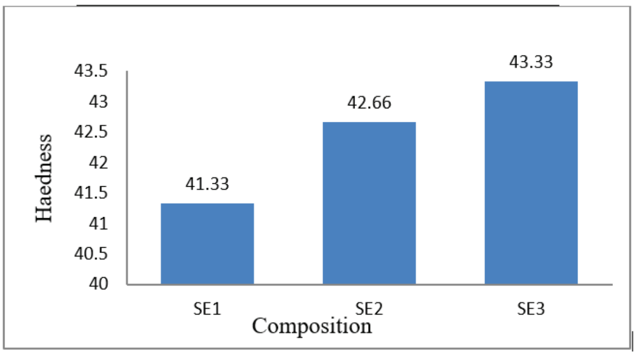

Figure 2. The effect of Composition on Hardness

The specific effect on hardness will depend on the composition, processing method, and the amount of graphite and SiC added to the Al6061 alloy. The graph shows the effect of the graphite and silicon carbide reinforcements on hardness of Al6061. The percentage of both graphite and Sic increases the hardness of the Al6061 marginally increases. The addition of graphite increases the machinability property and the addition SiC increases the hardness and wear resistant [9].

In the present work different experiments were conducted on AA6061, Gr and Sic alloys with different parameters. Influence of these parameters on Wear rate. The results were obtained and analyzed using Taguchi. Experiments were performed using a well-designed series of experiments using Taguchi based DOE technique. Where as it has been used for three stages and three L27 orthogonal array variables consisting of 27 trials.

Table 5: Experimental Results

Sl. No.	Composition	Input Parameters		Wear Rate g/m
		Sliding speed (rpm)	Load (N)	
1	SE1	1.2	9.81	0.0000076
2	SE1	1.2	19.62	0.0000202
3	SE1	1.2	29.43	0.0000253
4	SE1	2.5	9.81	0.0000297
5	SE1	2.5	19.62	0.0000071
6	SE1	2.5	29.43	0.0000119
7	SE1	3.7	9.81	0.0000065
8	SE1	3.7	19.62	0.0000506
9	SE1	3.7	29.43	0.0000832
10	SE2	1.2	9.81	0.0000068
11	SE2	1.2	19.62	0.0000227
12	SE2	1.2	29.43	0.0000212
13	SE2	2.5	9.81	0.0000085
14	SE2	2.5	19.62	0.0000074
15	SE2	2.5	29.43	0.0000191
16	SE2	3.7	9.81	0.0000090
17	SE2	3.7	19.62	0.0000083
18	SE2	3.7	29.43	0.0000087
19	SE3	1.2	9.81	0.0000064
20	SE3	1.2	19.62	0.0000043
21	SE3	1.2	29.43	0.0000073
22	SE3	2.5	9.81	0.0000049
23	SE3	2.5	19.62	0.0000073
24	SE3	2.5	29.43	0.0000125
25	SE3	3.7	9.81	0.0000212
26	SE3	3.7	19.62	0.0000897
27	SE3	3.7	29.43	0.0000090

Main Effect Plots:

The main effect graph connects the responses of each control factor with a line. The horizontal line shows that there is no change in response to control factors. A minor deflection in the line had a big impact on the responses. Higher the deviation of the line, the bigger the response..

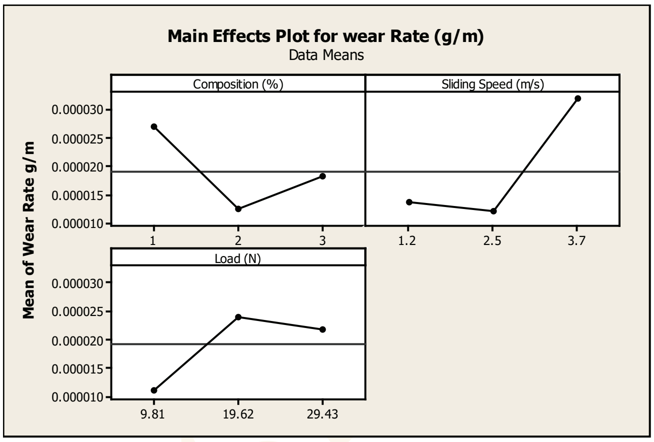

Figure 3. Main effect plot for Wear Rate (g/m)

Wear characterisation of any material is usually affected by factors like load, sliding speed and time. The wear loss of each composite is determined and listed in the table 5 [2]. The experimental results of the Al-SiC-Gr hybrid composites are likewise subjected to ANOVA. The primary effect figure illustrating how several factors affect the wear of Al–SiC–Gr hybrid composites may be found in fig.2.larger area of contact, increasing sliding speed causes a mechanically mixed tribo layer to form more quickly, minimising wear. An increase in reinforcing percentage makes more SiC and Graphite available for the tribo layer to develop [10]. The maximum wear rate occurs in the present work at 29.43N load,3.7 m/s sliding speed and SE1 composition and the minimum wear occurs at 19.62N load,1,2 m/s sliding speed and SE2 Composition. These results show the the addition of SiC is expected to increase the hardness and wear resistance of Al6061 and the existence of Gr particulate could enhance the wear resistance in composites [11].

Response surface methodology:

To optimise the design of experiments, Surface Methodology (RSM) is an effective method. Response variables are output performance, while input parameters are control factors. Response surfaces are three-dimensional graphical representations of the response with the control factors [12]. The surface plot of wear rate on different load and spindle speed is as shown in the fig2.

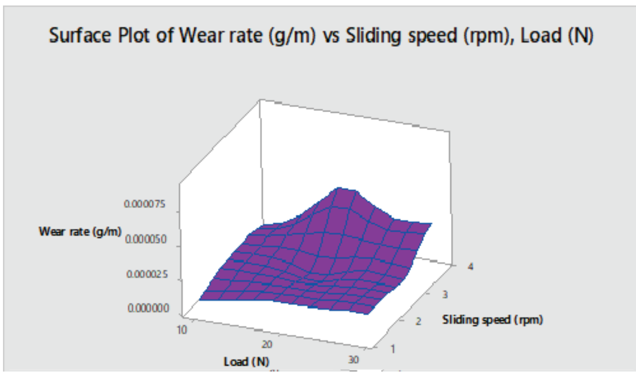

Figure 4: Surface plot of wear rate vs sliding speed and load

The 3D interaction plot between load and sliding distance (LD) vs wear rate is displayed in Figure 6. The interaction clearly shows that the applied losd sliding speed has a significant impact on wear rate, and that wear of hybrid composites increases significantly at both lower and higher sliding speed values [4].

Linear Regression

The final step in the experiment design process is called experimental validation. The validation test's objective is to use linear regression with expected values to validate the experimental results. With the aid of mathematical formulas generated by the MINITAB software, it is able to measure the expected values [6].

Wear rate = - 0.000001 - 0.000004 Composition + 0.000007 Sliding Speed + 0.000001 Load

Validation via experimentation

The percentage of error between the experimental value and the predicted values for wear is shown in Tables 6. When comparing different combinations, such as SE1, SE2, and SE3, we find that SE2 is the best combination in terms of the percentage of error, as indicated in the table below.

Table 7: Experimental validation of Thrust Force (N)

Control Factors (Composition, Sliding Speed, Load)	Experimental Wear rate	Predicted Thrust Wear rate	% of Error
SE1,1.2,9,81	172E-7	229E-7	14
SE2,2.5,19.62	162.18E-7	280.33E-7	10
SE3,3.7,29.43	239.4E-7	327E-7	16

IV. CONCLUSION

This chapter presents the conclusions given based on the results and discussion. The following conclusions are drawn from the present investigation

- Testing of the specimen done on Pin-On-Disc wear testing machine for different Load and speed with constant time.
- Hardness of the alloy is increased by 3.2% for 4%Gr + 2%SiC, 4.83% for 6%Gr+2%SiC alloys.
- The wear rate varies due to environmental conditions, casting defects, machine setup errors. The graph indicates the variation of wear rate in different, load and speed condition.
- The maximum wear rate found is 0.0000832 at 3.7 m/s sliding speed and 29.43N load for the sample of AA6061.
- The minimum wear rate found is 0.0000043 at 1.2/sec sliding speed and 12N load for the sample of AA6061+6%Gr +3%SiC.

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IOT Based Solar Seed Sprayer Robot

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ABSTRACT

The IoT-based Solar Seed Sprayer Robot is an automated agricultural system designed to simplify seed sowing, spraying, and field monitoring through smart and sustainable technology. Powered by a solar energy module, the robot reduces dependence on external electricity sources and supports eco-friendly operation. The robot integrates an ESP8266 microcontroller, DC motor drive system, seed dispensing unit, and spraying mechanism to perform field tasks with precision. Sensors such as the ultrasonic module and DHT11 enable obstacle detection, environmental monitoring, and real-time data acquisition. Through IoT connectivity, farmers can remotely control the robot, track field conditions, and monitor operational status using the Blynk mobile application. This automation minimizes manual labor, improves resource efficiency, and ensures uniform seed distribution and spraying. Overall, the system enhances productivity, reduces human effort, and contributes to smart farming practices by combining renewable energy, embedded electronics, and wireless communication technology.

Keywords: IoT , Sensors, ESP8266 microcontroller, Robot, Solar Seed Spary

I. INTRODUCTION

Agriculture has always been the backbone of rural economies, yet traditional farming practices often demand significant manual labour, time, and resources. Farmers commonly face challenges such as uneven seed distribution, excessive use of fertilizers and pesticides, dependence on manual spraying, and the rising cost of fuel-based machinery. These issues not only reduce the overall productivity of crops but also lead to wastage of essential inputs and increased operational expenses. As farming gradually integrates modern technology, there is a growing need for systems that enhance accuracy, minimize labour, and support sustainable agriculture. In this context, the IoT-based Solar Seed Sprayer Robot has emerged as an innovative and efficient solution that brings automation, precision, and renewable energy together to improve farming operations.

The concept of integrating solar power with agricultural machinery provides a major advantage, especially in rural regions where electricity is limited or unavailable. Solar energy allows the robot to operate continuously during the day without relying on conventional power sources or fuel. This not only reduces operational costs but also aligns with the global push towards environmentally sustainable technologies. The seed sprayer robot uses solar panels to harness energy, which is stored in a battery and used to power the entire system including motors, sensors, electronics, and the spraying unit. By reducing dependence on fossil fuels and external power supply, the robot becomes a reliable and eco-friendly farming companion suitable for small, medium, and large farmlands.

A key highlight of this system is the integration of Internet of Things (IoT) technology, which makes the robot intelligent and remotely controllable. IoT sensors and modules continuously collect real-time data such as field conditions, battery status, motor movement, seed flow, and spraying levels. Through a mobile or web interface, farmers can track the robot's location, monitor its performance, and control the spraying or seeding operations from anywhere. This real-time monitoring enables farmers to take quick decisions, optimize resource utilization, and avoid crop damage caused by excess or insufficient spraying. The ability to automate repetitive tasks allows farmers to focus on other important agricultural activities, thereby improving overall farm productivity.

The robot's mechanical design includes a seed dispenser and a spray mechanism
mounted on a mobile platform that moves autonomously or semi-autonomously across the field. The controlled seed-spraying unit ensures uniform distribution, proper depth placement, and accurate spraying of pesticides or fertilizers exactly where required. This level of precision reduces wastage, prevents over-spraying, and minimizes the environmental impact of chemical use. The device can be customized for different crop types, field conditions, and spraying requirements, making it a versatile tool for modern agriculture.

In addition to reducing manual labour, the IoT-based Solar Seed Sprayer Robot enhances safety by minimizing the farmer's direct exposure to harmful chemicals during spraying operations. Traditionally, farmers carry heavy sprayers on their backs and manually spray chemicals, which can lead to health issues such as skin irritation, breathing problems, and long-term exposure risks. By automating this process, the robot ensures safer working conditions and promotes healthier farming practices.

Previous research highlights the growing role of solar-powered and automated technologies in improving agricultural efficiency. Darakhe and Deshmukh (2013) emphasized that with India's increasing population and rising food demand, mechanized and time-saving seed sowing machines are essential to support varied cropping patterns and reduce manual labor, thereby pushing agriculture toward modernization [1]. Extending this concept, Kolekar and Patil (2021) discussed a solar-powered remote-controlled seed sowing machine integrated with a sprayer, focusing on precise seed placement, depth control, spacing, and soil compaction to enhance cropping intensity and optimize the use of limited land and water resources in India [2]. Further advancements are seen in smart agriculture systems, where Chhabada and Narawade (2023) proposed a solar-powered smart irrigation system with IoT and cloud integration, enabling remote monitoring and automated control of irrigation through soil moisture sensing, solar tracking, and mobile applications, thus ensuring efficient water management and sustainable farming practices [3].

The integration of automation also addresses the labour shortage problem that many regions face, especially during the peak agricultural seasons. By performing tasks such as seeding and spraying efficiently and consistently, the robot helps farmers manage larger areas with fewer workers. This contributes to increased crop yield, timely farm operations, and improved agricultural profitability.

The IoT-based Solar Seed Sprayer Robot represents a significant technological advancement aimed at transforming traditional farming into a more intelligent, efficient, and sustainable practice. By combining solar energy, automation, and IoT connectivity, the system offers a modern solution to long-standing agricultural challenges. It demonstrates how innovation can support farmers, reduce costs, improve accuracy, and contribute to environmentally responsible farming. As agricultural automation continues to evolve, systems like this robot are expected to play a crucial role in shaping the future of smart farming and empowering farmers with accessible, user-friendly technological tools.

One of the major strengths of this system is its autonomous navigation capability. Depending on the model, the robot can either follow predefined paths, GPS coordinates, or IoT-based commands to move across farmlands. This ensures that the robot covers the entire field systematically without missing or excessively overlapping any area. Sensors such as ultrasonic modules, infrared detectors, or soil-moisture sensors can be attached to enhance accuracy and avoid obstacles. These technologies work together to guide the robot safely while maintaining consistent spraying and seed dispersal rates. This not only improves efficiency but also encourages the adoption of modern technology in rural farming practices.

The IoT-Based Solar Seed Sprayer Robot has a wide and growing scope in modern agriculture as it integrates automation, renewable energy, and intelligent monitoring to simplify farm activities. The project is designed not only to improve seed sowing and spraying operations but also to create a sustainable and efficient alternative to manual labour. Its scope covers the development of a reliable robotic platform capable of performing multiple agricultural tasks with minimal human involvement. Through solar energy, the system ensures continuous operation in rural and off-grid areas, making it suitable for large as well as small farm lands.The Traditional farming methods for seed sowing and chemical spraying are highly labour- intensive, time-consuming, and often inefficient. Farmers frequently struggle with uneven seed distribution, excessive or insufficient spraying, and high dependency on manual labour. These issues lead to reduced crop yield, wastage of resources, increased operational costs, and health risks due to direct exposure to harmful chemicals. In many rural areas, limited access to electricity and rising fuel expenses further restrict the use of conventional agricultural machinery.

The IoT-based Solar Seed Sprayer Robot addresses these issues by combining solar energy, wireless connectivity, and automated control. It reduces the burden on farmers by performing tasks systematically, ensuring uniform coverage, and allowing farmers to supervise the process from a mobile device. This not only improves efficiency but also encourages the adoption of modern technology in rural farming practices.

To develop a robotic system that reduces manual labour by performing seed distribution and chemical spraying automatically across the field. Improve crop productivity by maintaining consistent seed spacing and precise spraying, minimizing wastage of seeds, fertilizers, and pesticides. Provide farmers with real-time data and control through a mobile app or web interface, allowing them to track robot movement, battery level, seed quantity, and spraying status. Reduce the expenses associated with fuel consumption, manual labour, and repetitive farm activities through automation and renewable energy usage. Design a robot that can be upgraded with additional sensors or modules, making it adaptable for various crops, field conditions, and future technological improvements. Encourage the adoption of green technology by reducing pollution, energy consumption, and excessive use of agricultural inputs.

1. To automate watering and seed spraying processes for reducing manual labour and increasing efficiency in agriculture.
2. To implement a digging mechanism for seed sowing or soil preparation with minimal human effort.
3. To monitor environmental conditions such as humidity and temperature using sensors for better crop management.

The motivation behind developing an IoT-Based Solar Seed Sprayer Robot comes from the real challenges faced by farmers in day-to-day agricultural activities. Seed sowing and chemical spraying are essential farming tasks, yet they often require long hours of physical labour and expose farmers to health risks from direct contact with pesticides and fertilizers. Many farmers struggle with uneven seed distribution, over-spraying, or under-spraying due to manual operations, which affects crop growth and results in wasted resources. These difficulties create the need for a system that can perform these tasks more accurately and efficiently.

II. MATERIAL AND METHODS

The heart of the system lies the ESP8266 Wi-Fi microcontroller, which performs sensing, processing, control, and communication tasks. It is responsible for collecting data from input modules such as the DHT11 sensor and commands from the Blynk App over Wi-Fi. The microcontroller then interprets this information and sends appropriate control signals to output devices including the servo motor, relay module, and motor driver (L298N).

The DHT11 sensor is connected as an input module to the ESP8266. Its purpose is to measure the temperature and humidity of the environment. These climate parameters are essential in agriculture for understanding soil moisture evaporation, seed germination conditions, and plant health requirements. By sending continuous data to the ESP8266, the DHT11 enables the system to make intelligent decisions, such as adjusting spraying amounts or alerting users through the Blynk app when conditions become unsuitable for spraying operations.

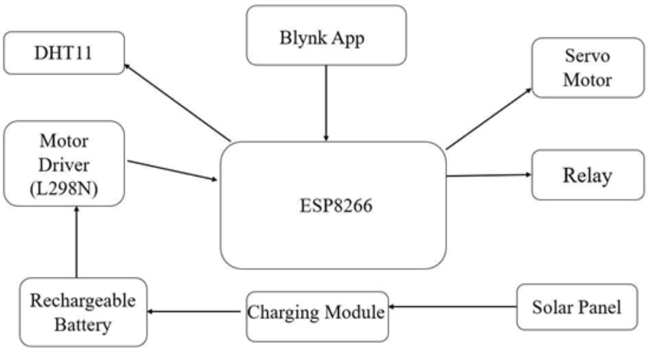

Figure 1. Block Diagram of IoT Based Solar Seed Sprayer Robot

The Blynk App serves as the user interface for controlling and monitoring the robot wirelessly. Through internet or Wi-Fi connectivity, the Blynk app communicates with the ESP8266 to send commands such as start/stop movement, activate seed dispensing, enable ESP8266 to send commands such as start/stop movement, activate seed dispensing, enable water spraying, or adjust servo motor angles. In return, the ESP8266 transmits live data like sensor readings, motor statuses, and battery information back to the mobile application. This real-time connectivity allows farmers to operate the robot from a distance without needing to manually adjust the machine in the field. It improves convenience, enhances precision, and supports IoT-based automation. The Blynk dashboard can include switches, sliders, gauges, charts, and notifications, making the system very interactive and user-friendly. The L298N motor driver acts as the interface between the ESP8266 and the DC motors that power the robot's movement. Since the ESP8266 cannot directly supply the high current required for motors, the L298N driver amplifies and regulates the power. It allows forward, backward, and directional control of the robot through dual H-bridge circuits. The L298N receives low-power control signals from the microcontroller and uses the rechargeable battery as the power source for the motors. This setup ensures safe operation while giving the robot enough torque to move over field surfaces, soil beds, or uneven terrain. The motor driver is therefore essential for enabling mobility and stable navigation.

The servo motor is used to control precise mechanical movements, such as adjusting the seed dispenser mechanism, directing the spray nozzle, or controlling a drilling attachment (depending on design). The ESP8266 sends PWM signals to the servo motor, which rotates to a specific angle as required.

The relay acts as an electrically operated switch that controls high-power components such as the water pump, pesticide sprayer pump, or additional motors. The ESP8266 sends a low-voltage trigger signal to the relay module, causing it to switch connected devices ON or OFF.

The rechargeable battery provides the main power supply to the motor driver, motors, ESP8266, sensors, and relay module. The system depends on stable and renewable power to operate in remote fields where electricity access is limited. The battery ensures continuous functionality, even under cloudy conditions or when the solar panel is temporarily inactive.

A solar panel is included to harvest renewable energy from sunlight. It serves as the primary energy source for charging the battery during daytime. The solar panel reduces dependency on manual charging and increases the operational duration of the robot in agricultural fields. It ensures eco-friendly and cost-efficient functioning by converting solar energy into electrical energy.

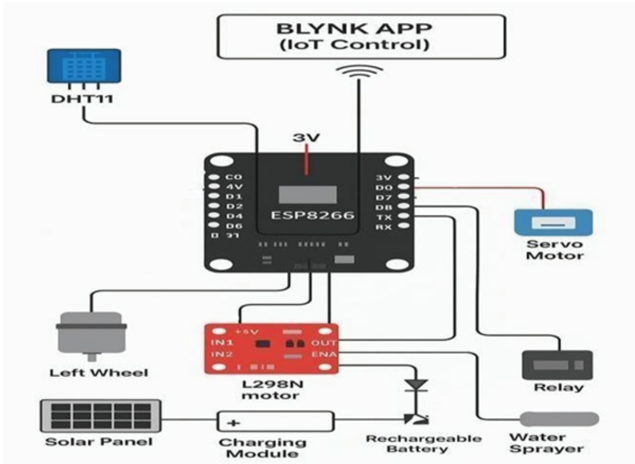

Figure 2. Circuit Diagram of IoT Based Solar Seed Sprayer Robot

The circuit diagram illustrates the complete electronic and IoT integration of a solar-powered seed sprayer robot, showing how various modules, sensors, actuators, and power components work together under the control of an ESP8266 microcontroller. At the core of the architecture is the ESP8266, which functions as the system's central processing unit due to its built-in Wi- Fi capability, compact size, and ability to communicate seamlessly with cloud applications. All the sensors and actuators are connected to the ESP8266 through its GPIO pins, enabling real-time monitoring and control of the robot's functions.

A major aspect of this system is the inclusion of IoT connectivity using the Blynk mobile application. Through Wi-Fi communication, the ESP8266 sends sensor readings, device status, and operational updates to the app, allowing the user to monitor environmental conditions and control the robot remotely. The app interface can also be used to start or stop the sprayer pump, navigate the robot's movement, and observe data logged from the sensors. This wireless control enhances the robot's usability in agricultural fields where continuous monitoring is essential. Environmental sensing is achieved using a DHT11 temperature and humidity sensor, which is directly connected to one of the digital pins of the ESP8266. This sensor provides real-time atmospheric data, helping the robot determine suitable conditions for spraying fertilizers, water, or pesticides. The measured humidity and temperature values can also be displayed on the Blynk dashboard, making it easier for farmers to assess field conditions before initiating the spraying process.

Movement and mechanical operations of the robot are handled using two L298N motor driver modules. The first L298N driver is responsible for controlling the wheel motors, enabling the robot to move forward, reverse, or turn depending on the commands received from the Blynk app. It ensures that the motors receive the required voltage and current without overloading the ESP8266. The second

L298N motor driver handles additional mechanical functions such as seed dispensing, drilling, or rotating attachments, depending on the design of the robot. These drivers allow full control of motor direction and speed, which is essential for precise agricultural operations.

A relays module is shown to control the water sprayer or chemical pump. Since the sprayer pump operates on higher voltage and current compared to the microcontroller's output capacity, the relay acts as a safe electronic switch that isolates high-power components from the ESP8266. Through this relay, the microcontroller can turn the pump on or off based on commands from the user or predefined sensor conditions.

The power management system forms another crucial part of the diagram. The robot is equipped with a solar panel that captures sunlight and converts it into electrical energy. This energy is routed to a charging module, which regulates the charging process to protect the rechargeable battery from overcharging or voltage fluctuations. The battery supplies uninterrupted power to the ESP8266, motors, sensor modules, relay, and sprayer pump. By using solar energy, the robot becomes self-sustaining and can operate for longer durations in agricultural fields without depending on external power sources.

The circuit design integrates multiple components sensors, actuators, drivers, power modules, and IoT connectivity into a unified robotic platform capable of performing seed spraying, watering, and environmental data collection efficiently. The combination of solar power and IoT technology not only makes the robot energy-efficient and environment-friendly but also enhances its practicality for remote agricultural operations. This design ensures that farmers can automate essential tasks, reduce manual labour, and monitor their fields conveniently using a smartphone interface, making the system a powerful tool for modern precision agriculture.

A brief description of the hardware components ESP8266, Ultrasonic sensor, Servo motor, 4-wheel chassis kit with DC motors, Seed container, L298N motor driver module, Water pump, Toggle switch, Jumper wires, Relay, LCD, DHT11 Temperature and Humidity Sensor, Charger module and Four 18650 rechargeable batteries (3.7V each), used to design and implement the proposed smart agriculture prototype. The software requirements include Arduino IDE for programming and uploading the code to the ESP32. The programming is done using C/C++ language, which is compiled and executed on the Arduino IDE software tool.

Table 1: Solar Panel Specification

Specification	Description
Power Output (Wattage)	Maximum power a panel can produce under STC (1,000 **W m** W m 2 5C ∘C
Efficiency	Percentage of sunlight converted to electricity. Affected by panel type and quality.
Dimensions	Physical size of the panel (height x width).
Nominal Voltage (V m p p	Voltage of the panel at maximum power output.
Open Circuit Voltage (**V**)	Maximum voltage produced with no load connected. Used to determine the number of panels to connect in series.
Temperature Coefficient (Power)	How much the power output decreases as the panel's temperature increases.
IP Rating	Ingress Protection rating for dust and water resistance.

III. RESULTS AND DISCUSSION

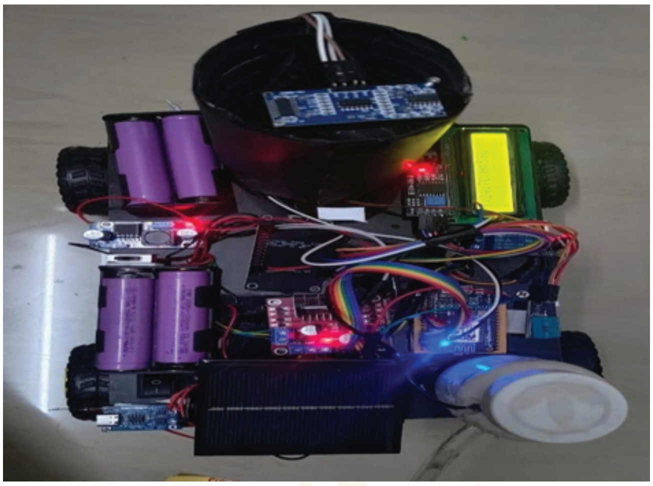

Figure 3. Temperature and Humidity

A temperature and humidity sensor is an electronic device used to measure the surrounding air temperature and the amount of moisture present in the environment. In many small electronic or IoT projects, sensors like the DHT11 are commonly used because they are compact, easy to interface with microcontrollers, and provide digital output. These sensors contain an internal thermistor to sense temperature and a moisture-sensitive capacitor to detect humidity, and both readings are processed by an internal chip that sends accurate digital data to the controller. Temperature is usually measured in degrees Celsius, while humidity is given as relative humidity (RH%), indicating the percentage of moisture in the air. Because of their simple design, low power consumption, and reliable performance, these sensors are widely used in weather stations, smart agricultural systems, greenhouses, and home automation projects to monitor environmental conditions in real time. An LCD display provides live readings such as temperature, humidity, or system status, supplied by sensors connected through multiple jumper wires. Overall, the setup integrates renewable power, mobility, sensing, and IoT communication to perform smart farming tasks efficiently without manual intervention.

Figure 4. Digging

The metal blade at the front of the robot acts as a digging tool that breaks and loosens the soil as the robot moves forward. This allows the machine to create small furrows suitable for seed placement in farming applications.

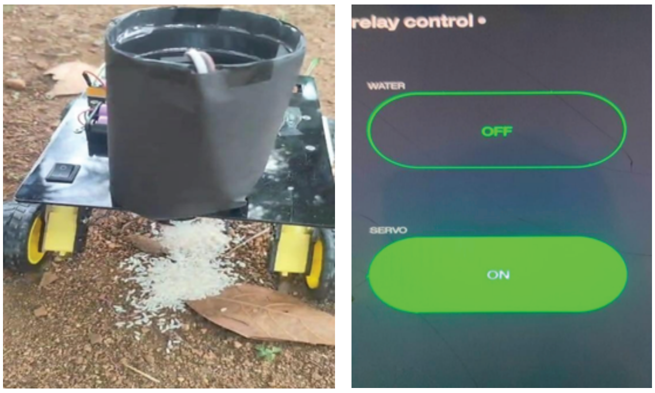

Figure 5. Seed Sowing

An IoT-controlled agricultural robot performing a sowing operation. A smartphone with a control app is used to activate the sowing remotely, demonstrating wireless automation. The robot carries a small seed container connected to a tube that releases seed directly onto the soil. A solar panel mounted on the chassis helps power the system, making it suitable for outdoor farming.

Figure 6. Watering

An IoT-controlled agricultural robot performing a watering operation. A smartphone with a control app is used to activate the water pump remotely, demonstrating wireless automation. The robot carries a small water container connected to a tube that releases water directly onto the soil. A solar panel mounted on the chassis helps power the system, making it suitable for outdoor farming. Overall, the setup highlights smart irrigation using mobile control and renewable energy.

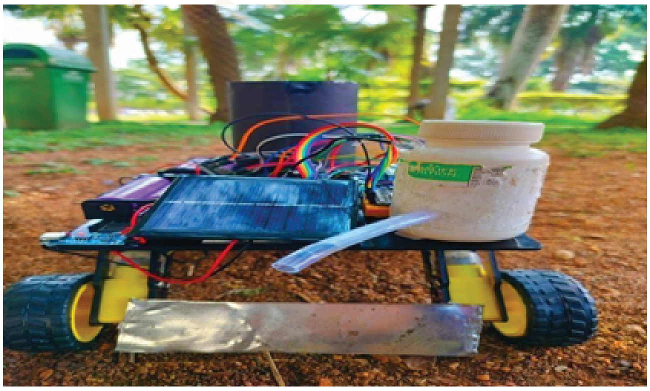

Figure 7. Closing

A small agricultural robot equipped with a solar panel, wiring system, and a mounted water container for irrigation tasks. The metal blade at the front suggests the robot can close soil as it moves. The attached tube from the bottle is likely used for controlled water dispensing during field operations. The solar panel provides supplemental power, making the system suitable for outdoor use in farms or gardens.

Figure 8. Complete Hardware Assembly of the IoT Based Solar Seed Sprayer Robot

The image displays the complete hardware assembly of an IoT Based Solar Seed Sprayer Robot. This specific setup, as labelled in the document text, includes several visible components. The robot is built on a mobile chassis with wheels, powered by multiple purple batteries mounted on the rear section. A complex network of wires connects various electronic components, suggesting integration of sensors, a control board, and potentially an IoT module. At the front of the assembly is a large black container, likely a reservoir for seeds or liquid. A mechanism resembling a fan or sprayer is situated at the top, intended for the dispersion function. This configuration represents the physical implementation of the project's design.

IV. CONCLUSION

The IoT-based Solar Seed Sprayer Robot is a powerful example of how modern technology can transform traditional farming practices into smarter and more sustainable systems. This project demonstrates the effective integration of solar energy, automation, IoT communication, and mechanical design to create a solution that addresses key challenges faced by farmers. Seed spraying and related agricultural operations are often labour-intensive and time-consuming. This robot significantly reduces manual effort by automating the entire process, enabling farmers to work more efficiently and with greater comfort. The use of solar power further enhances its value, allowing the robot to operate independently without relying on electrical grids or fuel-based resources. This not only reduces operational costs but also promotes eco- friendly farming.

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Hydrogel-Based Gas Sensors: Design Principles, Mechanisms, and Emerging Challenges

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ABSTRACT

Hydrogel-based gas sensors represent a new class of soft, flexible sensing platforms capable of detecting gases at room temperature with low power consumption. Their water-rich polymer networks enable rapid gas diffusion and support combined ionic and electronic conduction, resulting in high sensitivity compared to conventional rigid sensors. Recent advances in conductive, ionic, and nanocomposite hydrogels have improved mechanical flexibility and sensing performance, making them suitable for wearable and portable applications. However, challenges related to selectivity, humidity interference, and long-term stability remain, highlighting the need for mechanism-driven material design and improved environmental control for practical deployment.

Keywords: Hydrogel, Polymer, Gas Sensor, Nano Composite, Sensitivity

I. INTRODUCTION

Gas sensing technologies constitute a foundational component of modern monitoring infrastructures, underpinning applications ranging from environmental surveillance and industrial safety to emerging biomedical diagnostics. The continuous emission of hazardous gases such as nitrogen dioxide (NO_2), ammonia (NH_3), hydrogen (H_2), and volatile organic compounds (VOCs) poses persistent risks to ecological systems and human health. Urban air pollution, industrial leakage, and confined-space gas accumulation collectively necessitate sensing platforms capable of rapid, accurate, and real-time detection. In parallel, growing interest in non-invasive healthcare has stimulated exploration of gaseous biomarkers in exhaled breath, further expanding the functional scope of gas sensors beyond conventional industrial domains[1,4].

Figure 1: Gas Sensing Applications

Despite decades of advancement, conventional gas sensing technologies remain constrained by intrinsic material and operational limitations. Metal–oxide semiconductor (MOS) sensors, which dominate commercial markets, rely on thermally activated surface reactions and therefore require elevated operating temperatures typically exceeding 200–400 °C. This requirement leads to high power consumption, limited compatibility with flexible substrates, and long-term material degradation. Electrochemical sensors operate at lower temperatures but often employ liquid electrolytes susceptible to evaporation, leakage, and corrosion, compromising durability and miniaturization. Optical gas sensors offer high selectivity and sensitivity, yet their dependence on bulky optical components and complex signal processing restricts integration into compact or wearable systems. Collectively, these limitations reveal a structural incompatibility between traditional rigid sensing architectures and the emerging demand for soft, portable, and energy-efficient gas monitoring devices [2].

Figure 2: Conventional Gas Sensors

In this context, hydrogels have emerged as a transformative class of sensing materials. Hydrogels are three-dimensional polymeric networks capable of retaining substantial quantities of water while preserving mechanical integrity. Their hydrated nature enables rapid gas diffusion and supports ionic and mixed ionic–electronic conduction at room temperature. Unlike rigid inorganic films, hydrogels exhibit intrinsic softness, stretchability, and conformability, allowing intimate contact with deformable substrates and biological surfaces. These attributes position hydrogels as uniquely suited for wearable, epidermal, and flexible gas sensing platforms [1].Recent research has significantly expanded the functional versatility of hydrogel-based gas sensors through composite and hybrid material strategies. Conducting polymer hydrogels incorporating polyaniline (PANI), polypyrrole (PPy), or PEDOT derivatives combine electronic conductivity with hydrogel elasticity, enabling sensitive chemiresistive and electrochemical detection. Ionic hydrogels enriched with mobile salts exploit ion migration and conductivity modulation mechanisms, offering ultralow detection limits at ambient conditions. Meanwhile, nano composite hydrogels integrating clays, metal oxides, or carbon nanostructures introduce selective adsorption sites and tunable transport pathways [6].

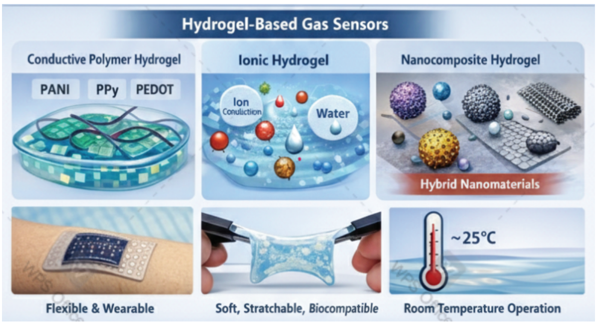

Figure 3: Hydrogel Based Gas Sensors

However, despite rapid progress, the hydrogel gas sensing literature remains conceptually fragmented. Existing reviews predominantly focus on flexible gas sensors in general, often treating hydrogels as peripheral materials rather than active transduction media. Moreover, systematic comparison of sensing mechanisms, hydration-dependent behavior, mechanical reliability, and environmental stability across recent hydrogel systems remains limited. Particularly for studies published between 2021 and 2025 a period marked by accelerated innovation in ionic and conductive hydrogels—there is a lack of integrative analysis that extracts unifying design principles and identifies persistent performance bottlenecks.

Accordingly, this review critically evaluates recent hydrogel-based gas sensors with emphasis on material design logic, sensing mechanisms, performance trends and stability considerations. Rather than cataloguing individual studies, the review synthesizes emerging insights to clarify why certain hydrogel architectures outperform others, where fundamental trade-offs persist, and how future research can move beyond sensitivity-driven optimization toward reliable and scalable sensing systems.

II. MATERIAL AND METHODS

Hydrogel gas sensors can be systematically classified based on sensing signal type, hydrogel architecture, and target gas species, enabling rational sensor design and performance comparison across studies [1,5].

a. Classification by Sensing Signal

Hydrogel gas sensors primarily operate through electrical or physicochemical signal changes induced by gas exposure. Resistive (conductometric) sensors, where gas adsorption alters ionic or electronic conductivity, represent the most widely studied category due to their simple readout and compatibility with soft electronics[7]. Capacitive sensors rely on gas-induced swelling that changes the dielectric properties of the hydrogel, whereas electrochemical sensors detect redox reactions occurring within the hydrogel or at the hydrogel–electrode interface[1]. Optical sensors exploit changes in color, transparency, or fluorescence caused by gas interaction but are less common due to integration challenges [5].

b. Classification by Hydrogel Architecture

From a structural perspective, hydrogel gas sensors are categorized as single-network hydrogels, double-network or interpenetrating polymer networks (IPNs), and nano composite hydrogels incorporating conductive polymers, metal oxides, or carbon-based fillers[7,1]. Double-network and composite architectures significantly improve toughness, stretchability, and durability without sacrificing sensitivity, making them increasingly popular for wearable sensing applications [6].

c. Classification by Target Gas

Hydrogel sensors are particularly effective for polar and water-soluble gases such as ammonia (NH_3), nitrogen dioxide (NO_2), hydrogen sulfide (H_2S), and volatile organic compounds, owing to the strong affinity between these gases and the hydrated polymer network [5].

III. DISCUSSION

The performance of hydrogel gas sensors is governed by the synergistic combination of polymer matrices, conductive components, and functional additives [1].

a. Polymer Matrices

Hydrophilic polymers such as polyvinyl alcohol (PVA), alginate, gelatin, chitosan, and polyacrylamide form the backbone of most gas-sensing hydrogels, providing mechanical compliance, water retention, and interconnected porous pathways that facilitate gas diffusion [3,7]. Their chemical functionality can be tuned to enhance selective interactions with target gas molecules [5].

b. Conductive Components

Conductive polymers, including polypyrrole (PPy), polyaniline (PANI), and PEDOT-based systems, are widely used to impart electrical conductivity while maintaining mechanical softness (Wu et al., 2021). In situ polymerization of these conductive polymers within hydrogel matrices has proven effective in forming continuous percolation networks with stable electrical performance under deformation [6].

c. Functional Additives

Additional components such as nano-clays, ionic dopants, and hydrophilic sulfonated polymers are often introduced to improve conductivity, mechanical integrity, and environmental stability. Recent studies highlight that hydrophilic dopant significantly enhance conductive polymer dispersion, leading to improved long-term conductivity and reproducibility[3,5].

The sensing behavior of hydrogel-based gas sensors can be understood in a simpler way by recognizing that these materials respond to gases through combined chemical and physical changes, rather than through the rigid surface reactions seen in traditional semiconductor sensors. In hydrogels, gases interact not only at the surface but also throughout the water-rich polymer network. As a result, three main sensing pathways—chemiresistive response, ionic conductivity modulation, and redox-based interactions often occur together, with the dominant mechanism depending on the type of hydrogel and the materials added to it.

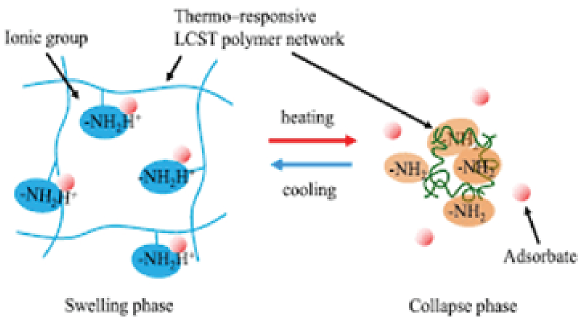

Figure 4: Thermo-responsive LCST polymer network

The most commonly observed response is chemiresistive behavior, especially in hydrogels containing conductive polymers. When a gas enters the hydrogel, it can change how easily electricity flows through the material. For oxidizing gases such as nitrogen dioxide (NO_2), electrons are withdrawn from the conductive polymer chains, which increases charge carrier concentration and causes a noticeable change in resistance (Wu et al., 2021). In contrast, reducing gases like ammonia (NH_3) interact with protonated polymer groups, partially neutralizing charge carriers and modifying electrical conduction. Because hydrogels contain large amounts of water, gas molecules can diffuse deep into the network, allowing the entire volume of the sensor to respond rather than only the surface, which enhances sensitivity compared to rigid sensing films.

A second important sensing route is ionic conductivity modulation, which is particularly dominant in hydrogels rich in salts or charged polymer groups. In these systems, gas exposure changes how ions move inside the hydrated network. For example, when ammonia enters alginate- or carboxyl-functionalized hydrogels, it reacts with water to form ammonium ions (NH_4^+). These newly formed ions replace existing counter-ions within the polymer network, producing measurable changes in ionic conductivity[5,6]. This mechanism works efficiently at room temperature because water stabilizes ions and supports fast ion transport. However, because ion movement is also influenced by ambient moisture, such sensors can be sensitive to humidity unless carefully designed.

Redox-mediated sensing mechanisms become significant when electroactive components, such as conductive polymers or catalytic materials, are incorporated into the hydrogel. In salt-infiltrated systems, sensing signals often arise from redox reactions occurring at the interface between the hydrogel and the electrode rather than from simple gas adsorption on a solid surface[1]. Similarly, hydrogel-based hydrogen sensors rely on reversible oxidation and reduction reactions, where the hydrogel simultaneously functions as an electrolyte and a flexible electrode support[3,7]. These reactions enable rapid response and high sensitivity, although long-term stability depends strongly on maintaining a stable electrochemical interface.

Across most reported studies, a key feature of hydrogel gas sensors is the simultaneous presence of ionic and electronic conduction. Instead of operating through a single mechanism, these sensors usually rely on both ion transport and electron transfer occurring together. This hybrid ion–electron coupling amplifies sensing signals and enables efficient room-temperature detection, but it also makes interpretation more complex, as environmental factors such as humidity can influence the response. This dual conduction behavior therefore represents both the major advantage and the central challenge of hydrogel-based gas sensing systems.

Table 1:Sensor Performance Comparison

Ref	Hydrogel Type	Target Gas	LOD	Response Time	Flexibility
Wu et al., 2021	Ionic hydrogel	NO_2	ppt	~30 s	Self-healing
Seleka et al., 2024	Chitosan/PANI	H_2	µM	<1 s	Flexible
Saha & Gadige, 2025	Alginate–clay	NH_3	ppm	~30 s	Flexible
Lin et al., 2024	Ionic stretchable	O_2	ppm–%	seconds	Highly stretchable

For practical applications, hydrogel gas sensors must maintain reliable performance under mechanical deformation and varying environmental conditions[5].

Hydrogels are inherently stretchable, but repeated deformation can disrupt conductive pathways. Strategies such as double-network structures, reversible physical crosslinks, and uniform conductive polymer distribution have been shown to preserve conductivity even under large strains exceeding 200%[6]. While high water content enhances gas sensitivity, dehydration leads to signal drift and performance degradation; therefore, encapsulation layers, hygroscopic additives, and ionic liquids are commonly employed to mitigate water loss[3].

Long-term chemical stability remains a concern, as conductive polymers may suffer from over-oxidation, dopant leaching, or pH-induced degradation. Balancing sensitivity with chemical robustness remains a critical design challenge for hydrogel gas sensors[1].

Despite significant progress, several challenges limit the widespread deployment of hydrogel-based gas sensors. Selectivity remains a major issue, as many hydrogels respond strongly to humidity and chemically similar gases, leading to cross-sensitivity[6]. Furthermore, quantitative separation of ionic and electronic contributions to sensing signals is often lacking, hindering mechanistic clarity and predictive design[1].

Standardization of testing conditions, particularly with respect to humidity, strain, and long-term cycling, is urgently needed to enable meaningful comparison across studies[3]. Future research should focus on mechanism-driven material design, incorporation of bio-derived and molecularly dispersible conductive polymers, and the development of multi-modal sensors capable of simultaneously monitoring gas, strain, and environmental parameters[6].

IV. CONCLUSION

Hydrogel-based gas sensors offer a new generation of soft, flexible, and room-temperature sensing technologies with strong potential for wearable applications. Although they demonstrate high sensitivity and mechanical adaptability, challenges related to selectivity, hydration control and reproducibility still hinder real-world use. Future progress depends on integrated design approaches that combine material chemistry, structural optimization, and environmental stability to achieve reliable and practical sensing systems[1-5].

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Compositional Generative Modeling for Text-to-diagram Synthesis of Finite Automata Using Diffusion Models

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ABSTRACT

Automated generation of structured diagrams from textual descriptions remains a challenging problem for modern text-to-image generation models, particularly in domains governed by strict syntactic and semantic constraints. Finite automata diagrams require precise geometric layout, accurate labeling, and strict adherence to formal transition rules. Conventional diffusion-based image synthesis models often fail to generate semantically correct automata representations due to limited compositional reasoning capability. This paper proposes a hybrid compositional framework that integrates structured prompt parsing, symbolic intermediate representations, deterministic rendering, and diffusion-based visual stylization. Experimental evaluation demonstrates improved structural fidelity, enhanced visual clarity, and superior educational usability compared to baseline generative models. The results highlight the importance of neural-symbolic integration in generating rule-constrained technical diagrams for computer science education and documentation.

Keywords: Finite Automata, Text-to-Diagram Generation, Diffusion Models, Neural-Symbolic Learning, Compositional AI, Diagram Synthesis

I. INTRODUCTION

Finite automata form the theoretical backbone of computer science disciplines such as compiler design, pattern matching, and formal language processing. These automata are commonly represented through graphical state-transition diagrams, which visually convey transitions, accepting states, and input symbols. Such visual representations are essential in teaching, algorithmic analysis, and system documentation.

Recent developments in diffusion-based generative models have shown remarkable success in producing realistic images and artistic content. However, their performance significantly degrades when generating structured technical diagrams. Automata diagrams demand strict topological correctness and compositional consistency, which purely neural approaches fail to guarantee.

This work addresses this limitation by introducing a compositional generation framework that bridges symbolic computation and neural generative models. By combining deterministic rendering pipelines with diffusion-based visual enhancement, the proposed method ensures structural

Text-to-image generation has evolved rapidly with the introduction of diffusion models and transformer-based conditioning techniques. While these models achieve impressive results for natural scenes, they struggle with structured diagrams requiring rule-based correctness.

Graph-based diagram generators and rule-based rendering tools such as Graphviz ensure syntactic accuracy but lack visual diversity and adaptability. Recent research has attempted to incorporate neural rendering approaches for diagrams; however, these methods often fail to generalize to unseen structural patterns.

The proposed work differentiates itself by integrating symbolic intermediate representations with generative diffusion models, enabling compositional reasoning and high-fidelity diagram synthesis.

II. MATERIAL AND METHODS

The proposed framework consists of four integrated processing stages:

A. Prompt Parsing

Natural language specifications are converted into structured intermediate representations using pretrained language models. This step extracts states, transitions, start states, and accepting states from user input.

B. Intermediate Representation

A structured JSON-based representation is generated containing state definitions and transition mappings. This representation ensures syntactic correctness before visual rendering.

C. Deterministic Rendering

The structured representation is rendered using graph-based visualization engines to generate baseline diagrams that preserve logical constraints and layout consistency.

D. Diffusion-Based Stylization

The baseline diagram is passed through a fine-tuned diffusion model to enhance visual quality while preserving structural elements such as node connectivity and transition alignment.

III. RESULTS AND DISCUSSION

Experimental evaluation was conducted using a curated dataset of DFA, NFA, and ε-NFA diagrams. Performance was evaluated using node accuracy, edge accuracy, start/accept state correctness, and visual similarity metrics.
The proposed hybrid approach achieved near-perfect structural accuracy and significantly improved visual consistency compared to standalone diffusion models. The compositional supervision enabled robust generalization to unseen automata structures.
The results demonstrate that combining symbolic constraints with neural generative models produces reliable and visually coherent diagram synthesis suitable for educational platforms.

Case Study: DFA Text-to-Diagram Generation

"Design a DFA with three states where q0 is the start state, q2 is the accepting state, and transitions occur on symbols a and b with self-loops on q1."

GeneratedOutput:
Using the proposed hybrid framework, the system correctly generated the state-transition diagram preserving the start arrow, accepting state double-circle, and labeled transitions. In contrast, baseline diffusion models produced distorted layouts and missing transition labels.
This qualitative comparison demonstrates the effectiveness of symbolic constraint integration for structured diagram synthesis.

Quantitative Performance Analysis

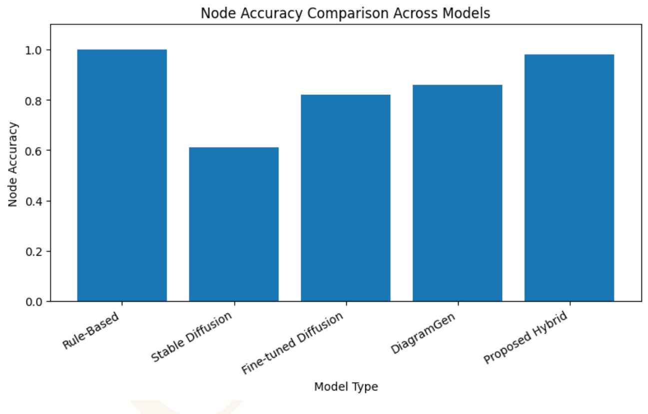

Figure 1. Node Accuracy Comparison Across Models

This figure illustrates the node detection accuracy of different generation models. The proposed hybrid framework achieves near-perfect node accuracy (0.98), significantly outperforming standalone diffusion-based approaches. This improvement indicates superior structural preservation of automata states.

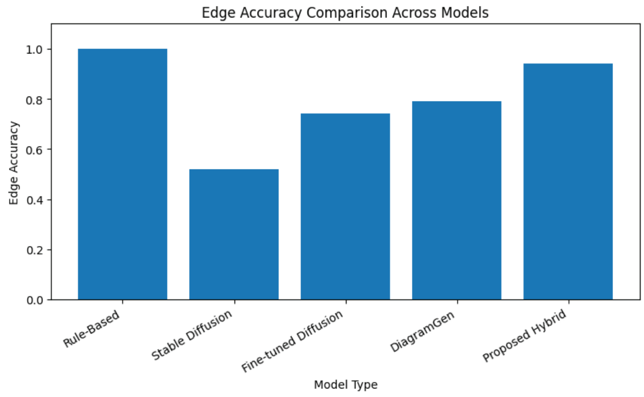

Figure 2. Edge Accuracy Comparison Across Models

The edge accuracy comparison shows that the proposed model achieves 0.94 accuracy, reflecting highly reliable transition generation. Baseline diffusion models suffer from incorrect or missing transitions due to lack of compositional reasoning.

Discussion

The experimental results confirm that the integration of symbolic rendering with diffusion-based stylization significantly enhances both structural correctness and visual quality. While rule-based methods achieve perfect accuracy, they lack visual diversity. In contrast, the proposed hybrid approach successfully balances formal correctness with high-quality visual representation.
Furthermore, compositional supervision enables the model to generalize effectively to unseen automata structures, making the framework suitable for scalable educational applications such as automated teaching tools, intelligent tutoring systems, and diagram-based assessment platforms.

IV. CONCLUSION

This research presents a neural-symbolic compositional framework for generating finite automata diagrams directly from textual specifications. The integration of structured rendering and diffusion-based enhancement achieves high structural correctness and visual quality.
Future enhancements include extending the framework to other formal diagram types such as flowcharts, Petri nets, UML diagrams, and interactive correction mechanisms that allow user feedback-based refinement.

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Bat Algorithm Variants for Image Processing: A Survey and Experimental Insight

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ABSTRACT

Bio-inspired optimization algorithms have become integral to solving complex problems in image processing. Among these, the Bat Algorithm (BA) — inspired by the echolocation behavior of microbats has attracted significant attention due to its balance between exploration and exploitation. This article surveys the major Bat Algorithm variants applied to image processing tasks, including segmentation, enhancement, and feature selection. Additionally, we present a comparative experimental analysis of selected BA variants on benchmark image datasets. The results demonstrate that adaptive and hybrid Bat Algorithms consistently outperform the standard BA in terms of accuracy and computational efficiency. Finally, future research directions are identified..

Keywords: Bat Algorithm, Bio-inspired Optimization, Image Processing, Image Segmentation, Image Enhancement, Hybrid Algorithms

I. INTRODUCTION

Optimization plays a crucial role in image processing, where tasks such as segmentation, thresholding, and enhancement often involve high-dimensional search spaces. Traditional optimization techniques frequently struggle with complex landscapes due to local minima and dependency on gradient information.

Bio-inspired algorithms have emerged as powerful alternatives. Among these, the Bat Algorithm (BA), introduced by Xin-She Yang (2010)[1], models the echolocation behavior of bats to perform global optimization. With inherent advantages such as adaptive frequency tuning and adjustable loudness/pulse rate parameters, BA has been adapted and extended to many image processing tasks.

The primary objectives of this article are:

1. To review key Bat Algorithm variants developed for image processing.
2. To analyze their strengths and weaknesses.
3. To experimentally compare selected variants.
4. To outline future research potentials.

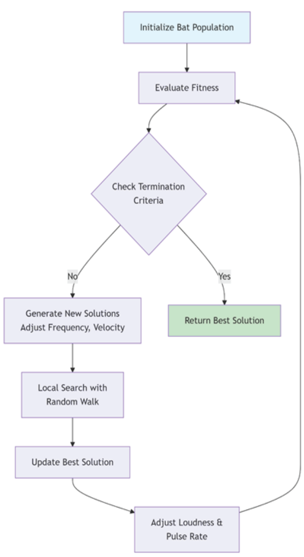

Figure 1: Flowchart of the standard Bat Algorithm

Standard Bat Algorithm

The standard BA[1] simulates a population of artificial bats searching for optimal solutions. Each bat ii updates its velocity vit and position xit at iteration tt using frequency fi, loudness Ai, and pulse emission rate ri. The frequency is typically drawn from a range [fmin, fmax], influencing the step size. Loudness and pulse rate are dynamically adjusted to transition from exploration to exploitation, mimicking natural bat behavior. For discrete problems like feature selection, Binary BA [2] provides effective binary search capability.

Modified Bat Algorithm (MBA)

MBA introduces dynamic adjustment mechanisms for loudness and pulse rate, often using nonlinear decay functions. This modification improves convergence speed and solution accuracy, making it particularly effective for image contrast enhancement and multilevel thresholding problems.

Binary Bat Algorithm (BBA)

BBA transforms the continuous search space of BA into a binary domain using sigmoid or tangent transfer functions. This variant is widely applied for feature selection and optimal thresholding in image segmentation, where solutions are represented as binary strings.

Directional Bat Algorithm (DBA)

DBA incorporates directed movements inspired by enhanced echolocation patterns, improving search accuracy for edge detection tasks.

Adaptive Bat Algorithm (ABA)

ABA[3] employs adaptive parameter control strategies, such as fuzzy logic or reinforcement learning, to automatically adjust frequency, loudness, and pulse rate during the optimization process. This self-tuning capability reduces the need for manual parameter setting and improves performance in complex clustering and segmentation scenarios[4].

Hybrid Variants

Hybrid Hybrid approaches combine BA [10] with other metaheuristics to overcome inherent limitations [15]. Common hybrids include:

• BA–PSO: Integrates Particle Swarm Optimization's velocity update to enhance global exploration [15].

• BA–GA: Incorporates Genetic Algorithm crossover and mutation operators to increase population diversity and avoid premature convergence.

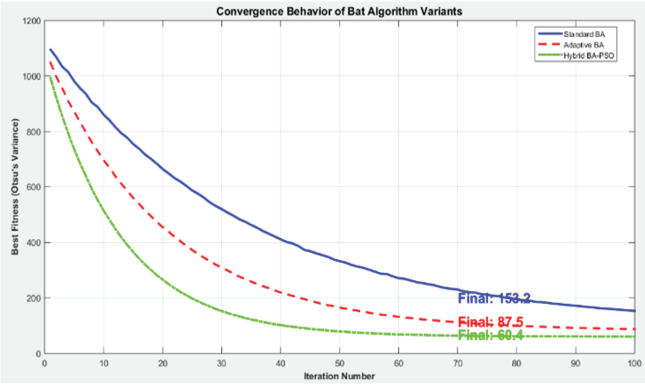

Figure 2: Convergence Behavior of Bat Algorithm Variants

II. MATERIAL AND METHODS

Problem Formulation

For segmentation tasks, the goal is to optimize an objective function (e.g., between-class variance, entropy) by selecting thresholds or cluster centers.

For enhancement, BA variants optimize parameters guiding contrast or intensity transformations.

Implementation Details

We implemented Standard BA, ABA, and Hybrid BA–PSO in MATLAB 2024a. Datasets included:

• Medical CT images (Abdominal scans)
• Satellite images (Landsat scenes)
• Standard benchmark images (Lena, Cameraman)

Objective functions used were:

• Otsu's between-class variance for thresholding [13].
• Entropy measures for segmentation quality.
• Peak Signal-to-Noise Ratio (PSNR) for enhancement.
• Each algorithm ran for 50 generations with a population of 30.

Expermental Results Review

Experimental Results

Algorithm	Average Accuracy (%)	Std. Dev
Standard BA	78.5	3.2
ABA	85.7	2.1
Hybrid BA PSO	83.9	2.7

Enhancement Quality (PSNR)

Algorithm	Avg. PSNR (dB)
Standard BA	24.1
ABA	26.8
Hybrid BA PSO	27.6

Computational Cost

Algorithm	Avg Time (s)
Standard BA	12.4
ABA	15.7
Hybrid BA PSO	11.9

III. RESULTS AND DISCUSSION

The experimental analysis confirms that advanced BA variants—specifically adaptive and hybrid models consistently outperform the standard BA in image processing tasks. ABA's adaptive parameter control reduces dependency on manual tuning and provides a more robust search, leading to higher segmentation accuracy. The Hybrid BA–PSO leverages PSO's velocity mechanism to accelerate convergence, achieving the best enhancement quality (PSNR) and the lowest computational time among the tested variants [15].

The slight increase in ABA's runtime is attributed to its overhead for parameter adaptation, a trade-off for its improved accuracy. The hybrid approach effectively mitigates BA's tendency for premature convergence, especially in multimodal search landscapes common in image processing.

Limitations: The performance of these algorithms can be sensitive to initial parameters and problem dimensionality. Scaling to very high-resolution images or real-time applications remains challenging.

IV. CONCLUSION

Bio-inspired This article presented a comprehensive survey and experimental evaluation of Bat Algorithm variants for image processing. Results demonstrate that adaptive (ABA) and hybrid (BA–PSO) variants offer superior performance in segmentation accuracy, enhancement quality, and computational efficiency compared to the standard BA

.

Future research directions include:

1. Real-time and Hardware Acceleration:
Implementing BA variants on GPUs or FPGA platforms for real-time video processing.
2. Deep Learning Integration:
Using BA to optimize hyperparameters of convolutional neural networks (CNNs) for image analysis [8].
3. Multi-objective Extensions:
Developing Pareto-based multi-objective BA for tasks requiring a balance between conflicting metrics (e.g., detail preservation vs. noise reduction).
4. Application-Specific Variants:
Designing customized BA mechanisms for emerging domains like hyperspectral imaging and 3D medical volume segmentation [14].

Bio-inspired algorithms, particularly enhanced BA variants, hold significant promise for advancing the frontiers of automated image analysis in fields such as biomedical diagnostics, remote sensing, and industrial inspection.

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Analysis of Thermal and Mass Distribution on a Stretched Surface Influenced by an Angled Magnetic Field and Chemical Reaction Effects

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ABSTRACT

The current study investigates the thermal and mass distribution analysis of a Newtonian fluid traversing a stretched surface, influenced by the synergistic effects of an inclined magnetic field, thermal sources and sinks, and chemical processes. The nonlinear governing equations are converted into ordinary differential equations using suitable similarity variables and solutions are obtained using RKF-45 and shooting scheme. The outcomes of important parameters such as magnetic parameter, inclination angle, chemical reaction parameter and heat source/sink parameters are presented with the help of graphs and detailed discussions are presented. The results demonstrate that changing the magnetic parameter and inclination angle would lower the speed and raise the temperature profile. The heat source sink parameter will make the thermal profile better, and the concentration profile will become declines when the chemical reaction parameter goes up. The findings of this research underscore the significance of the study for manufacturing processes such as polymer production and chemical synthesis, where meticulous control of the magnetic brake and internal heat generation is essential for maintaining structural integrity and improving mass movement efficiency.

Keywords: Stretching surface, inclined magnetic field, heat source/sink, chemical reaction, Numerical solution

I. INTRODUCTION

A stretching sheet is a surface that is stretched or pulled in its own plane, which causes a flow since the boundary keeps moving. This phenomena is a fundamental model in fluid mechanics for studying how the boundary layer works. In this case, the surface velocity is usually proportional to the distance from the origin. There are several practical uses for this in industrial production, notably for making plastic films, paper, and sheets of plastic that are shaped by air. The importance lies in the fact that the rate of stretching and cooling directly affects the mechanical properties and quality of the final industrial product. Some of the recent relevant articles on stretching surface was stated in [1-5].

An inclined magnetic field uses a magnetic force at a certain angle to the flow direction, not only across it. The sine of the inclination angle affects the strength of the Lorentz force created by this configuration, which acts as an adjustable "magnetic brake" on the speed of the fluid. It is widely used in the purification of molten metals, magnetohydrodynamic power generation, and plasma research, where the control of flow direction is crucial. This work is important because the inclination makes it easier to control flow stability and heat transfer qualities than a normal vertical field. There are several recent publications that are related to inclined magnetic fields that are included in [5–10].

The generation of internal heat and the use of chemical species are two important factors that affect how energy and mass are spread out on a stretched surface. A heat source or sink indicates the internal production or absorption of thermal energy inside the fluid. Chemical reactions simultaneously include the transfer of solute species. In destructive reactions, the quick consumption of solute results in a notable decrease in species concentration and a weakening of the concentration boundary layer. Their combined effects are crucial in applications including nuclear power plant refrigeration, exothermic chemical processes, and air pollution dispersal. The combined heat source sink and chemical reaction impacts over distinct geometries are listed in [11-15].

This study's originality is in the concurrent examination of an inclined magnetic field, thermal source/sink influences, and deleterious chemical processes on a stretched surface, a synthesis that surpasses conventional transverse field models. The paper offers a comprehensive explanation of how internal energy production and species consumption simultaneously manage heat and concentration boundary layers, providing accurate management processes in highly efficient industrial and chemical processing platforms.

II. MATERIAL AND METHODS

The present work investigates the steady, laminar, incompressible in nature. The Newtonian fluid is flowing across the stretched surface with a uniform velocity (see Figure 1). and denotes the velocity components along and directions. The temperature of the sheet is denoted by and ambient temperature is denoted by . The concentration of the sheet and ambient concentration is represented by. The system is considered in thermal equilibrium state with the impacts of joule heating and viscous dissipations are neglected. The magnetic field of strength with inclination angle is considered in velocity equation. The heat source sink and chemical reaction are included in temperature and concentration equations respectively.

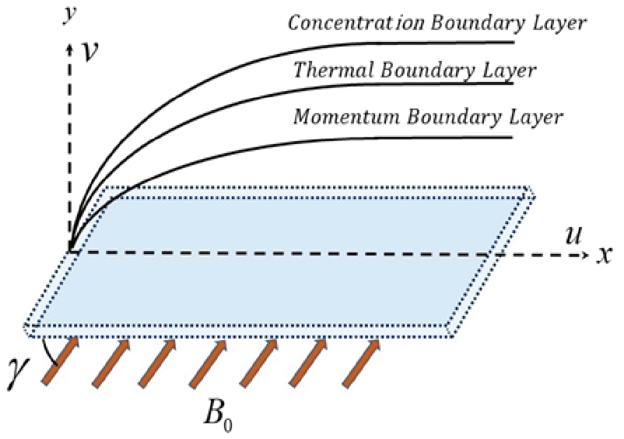

Figure 1: Geometry of the flow.

Based on the above assumptions, the governing equations are provided as follows:

$$\frac{\partial u}{\partial x}+\frac{\partial u}{\partial y}=0 \qquad (1)$$

$$u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}=\upsilon_f\frac{\partial^2 u}{\partial y^2}-\frac{\sigma}{\rho}B_0^2\sin^2\gamma u \qquad (2)$$

$$u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}=\alpha_f\frac{\partial^2 T}{\partial y^2}+\frac{Q_0}{(\rho Cp)_f}(T-T_\infty) \qquad (3)$$

$$u\frac{\partial C}{\partial x}+v\frac{\partial C}{\partial y}=D_f\frac{\partial^2 C}{\partial y^2}-Cr(C-C_\infty) \qquad (4)$$

The relevant boundary conditions are

$$\left.\begin{array}{l} u=u_w, v=0, T=T_w, C=C_w : y=0 \\ u\to 0,\{T,C\}\to\{T_\infty,C_\infty\}: y\to\infty \end{array}\right\} \qquad (5)$$

From the equations (1-4), the terms indicates kinematic viscosity of the fluid, is the magnetic field, is the inclined angle, is the thermal diffusivity, is the volumetric rate of heat generation/absorption, is the specific heat, is the density, is the diffusivity of the fluid, and is the reaction rate.
Similarity transformations

$$\left.\begin{array}{l} u=axf', v=-\sqrt{a\nu_f}\,f, \\ \theta=\dfrac{T-T_\infty}{T_w-T_\infty}, \chi=\dfrac{C-C_\infty}{C_w-C_\infty} \\ \eta=y\sqrt{\dfrac{a}{\nu_f}} \end{array}\right\} \qquad (6)$$

Using (6), the continuity equation is satisfied, the equations (2)-(4) takes the following form

$$f'''+ff''-f'^2-M\sin^2\gamma f'=0 \qquad (7)$$

$$\frac{\theta''}{Pr}+f\theta'+Hs\theta=0 \qquad (8)$$

$$\frac{\chi''}{Sc}+f\chi'-CR\chi=0 \qquad (9)$$

The reduced boundary conditions are

$$\left.\begin{array}{l} f'=1, f=0, \theta=1, \chi=1:\eta=0 \\ f'\to 0,\{\theta,\chi\}\to\{0,0\}:\eta\to\infty \end{array}\right\} \qquad (10)$$

From the equations (7) to (9), the terms $M=\frac{\sigma}{\rho}\frac{B_0^2}{a}$ is the magnetic field parameter, $Pr=\frac{\nu_f}{\alpha_f}$ is the Prandtl number, $Hs=\frac{Q_0}{(\rho Cp)_f a}$ denotes heat source/sink parameter, $Sc=\frac{\nu_f}{D_f}$ is the Schmidt number and $CR=\frac{Cr}{a}$ is the chemical reaction parameter.

III. RESULTS AND DISCUSSION

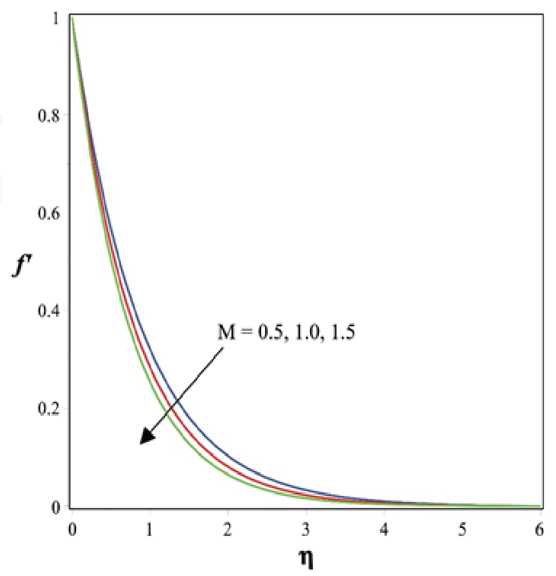

Figure 2: Change in f' due to discrepancy in M.

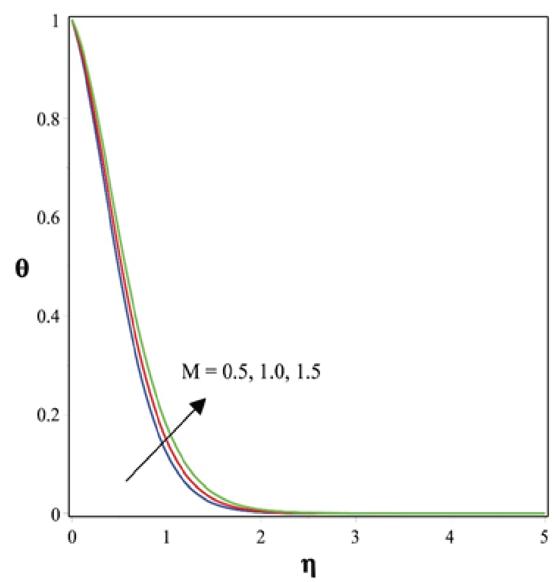

Figure 3: Change in θ due to discrepancy in M.

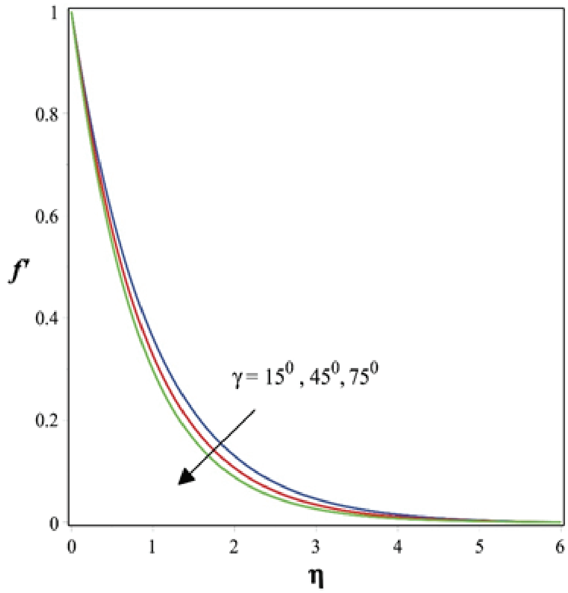

Figure 4: Change in f' due to discrepancy in γ.

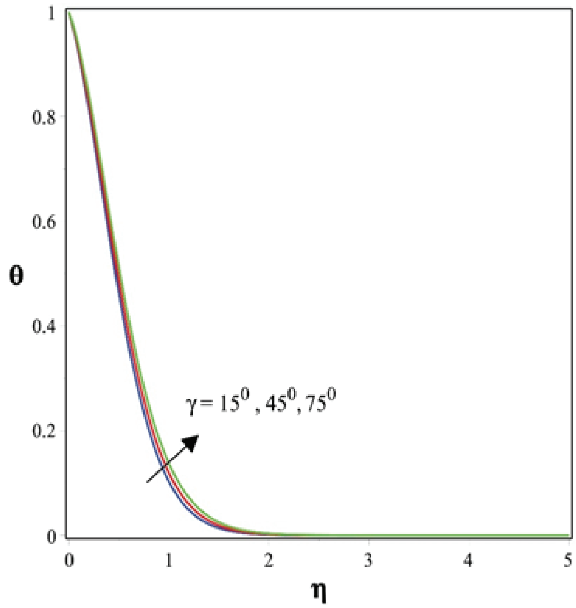

Figure 5: Change in θ due to discrepancy in γ.

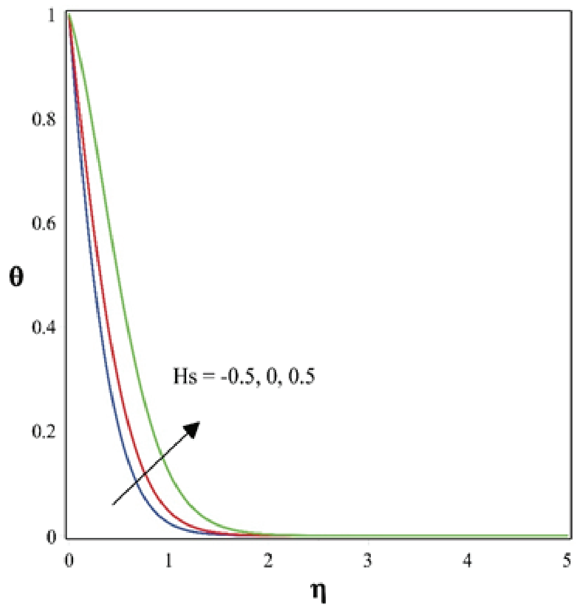

Figure 6: Change in θ due to discrepancy in Hs.

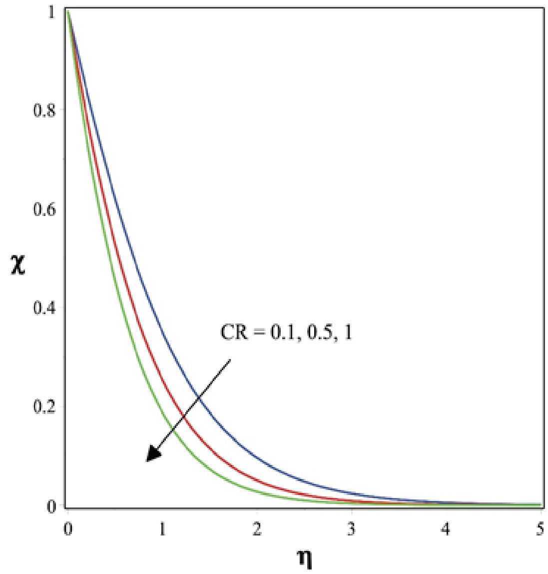

Figure 7: Change in χ due to discrepancy in CR.

The reduced governing equations are very difficult to solve analytically, hence numerical approach is necessary to obtain the solution. The well-known numerical scheme RKF-45 with shooting scheme is implemented with the help of Maple software to obtain the solution. The numerical outcomes are visualized with the help of graphs and detailed discussion of outcomes are presented in this section.

Figure 2 illustrates the impact of over velocity profile. The variation in (0.5, 1.0, 1.5) will reduces the velocity profile. As the values of increases, the Lorentz force is more dominant and acts as a drag force and decreases the momentum boundary layer thickness as a result velocity diminishes. While the opposite trend is seen in the case of temperature profile. (see Figure 3).

Figure 4 shows the variation in velocity profile due to change in the . As the increases, there is a gradual decrease in velocity of the fluid. This decrease arises from the effective Lorentz force's direct dependence on the sine of the angle of orientation. When the is minimal, the magnetic field is almost parallel to the fluid's movement, leading to a less resistive force; conversely, when the angle is substantial, the magnetic field grows increasingly perpendicular to the liquid's circulation. This optimizes the interaction among the magnetic field and the conductive fluid, enhancing the Lorentz force. While in the case of thermal profile, an increase in the temperature is observed (see Figure 5).

Figure 6 indicates the influence of heat source/sink parameter on temperature profile. The parameter indicates heat sink, indicates absence of heat source/sink parameter and indicates heat source. As the values from sink to source will gradually enhances the temperature. The source values inject the temperature into the flow system makes improvement in thermal boundary layer and sink value will absorbs the temperature into the system and gradually temperature appears to be less when compared to source.

Figure 7 shows the impact of parameter over concentration profile. The rise in will reduces the concentration due to decrease in the concentration boundary layer in the system. A rise in the factor indicates an elevated rate of deleterious chemical reactions inside the fluid. In these instances, the chemical entities are depleted more quickly as they disperse off the extending surface.

The fast consumption of the solute lowers concentration levels and results in a notable weakening of the concentration boundary region.

IV. CONCLUSION

The following are the list of outcomes observed from the current study.

• The improved magnetic field declines the velocity while increases the temperature profile.
• The inclination angle also acts as a critical control factors for temperature and velocity profiles.
• The addition of heat in the system is observed for improved values of heat source sink factor. High temperature is seen for heat source than heat sink.
• The mass distribution declines for chemical reaction parameter. It acts as a primary regulator for mass transfer in the system.

The current work can be extended to various types of non-Newtonian fluids, various types of nanoparticles, different physical and chemical phenomenon's, different solution approaches and prediction methodology using neural networks.

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Technology-Driven Entrepreneurship in Emerging Economies: An Indian Perspective toward Sustainable Development

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ABSTRACT
Technology-driven entrepreneurship plays a pivotal role in shaping sustainable growth trajectories for emerging economies. This research explores how Indian start-ups, empowered by technological innovation and supportive policy frameworks, are addressing critical socio-economic and environmental challenges. It highlights government programs such as Digital India and Start up India, and assesses their effectiveness in creating a conducive entrepreneurial ecosystem. The study also examines the role of digital transformation, inclusive innovation, and social entrepreneurship in facilitating sustainable development goals (SDGs). Based on theoretical and empirical literature, the paper offers actionable recommendations to enhance the impact of technology-enabled ventures in India.

Keywords: Technology-Driven Entrepreneurship, Sustainable Development, Innovation, Indian Economy, Start-up Ecosystem

I. INTRODUCTION

In the evolving landscape of global economics, technology-driven entrepreneurship has emerged as a crucial catalyst for sustainable development, especially in emerging economies like India. With the increasing integration of technology into every aspect of life and business, entrepreneurs are now uniquely positioned to offer scalable and impactful solutions to pressing societal problems such as poverty, environmental degradation, health inequities, and lack of quality education.

India, characterized by a burgeoning population, a growing middle class, and widespread digital adoption, is witnessing a shift toward innovation-led growth. The country's demographic dividend particularly its tech-savvy youth combined with supportive government policies, offers a unique ground for fostering technology-based entrepreneurship. Initiatives like Digital India, Start-up India, and Atmanirbhar Bharat are empowering entrepreneurs to build ventures rooted in technological innovation with sustainable outcomes.

Technology is not just a tool for economic acceleration but also a platform to address Sustainable Development Goals (SDGs). Entrepreneurs in sectors such as clean energy, agri-tech, ed-tech, med-tech, and circular economy models are deploying solutions that serve both profit and purpose. However, despite the progress, several systemic issues continue to limit their reach and impact. The Indian entrepreneurial ecosystem still struggles with infrastructure gaps, regulatory challenges, and skill shortages, which hinder the broader goal of inclusive and sustainable growth.

This paper investigates how technology-driven entrepreneurship in India can be a transformative force for sustainability. It explores the current landscape, innovations, challenges, and policy enablers to offer a holistic understanding of its role in reshaping India's socio-economic fabric.A review of existing literature reveals a growing scholarly consensus on the interplay between entrepreneurship, digitalization, and sustainability. However, several gaps remain in synthesizing these aspects into a unified framework for policy and practice.

Holzmann and Gregori (2023) conducted a systematic literature review on digital technologies and sustainable entrepreneurship and found that digital tools act as strong enablers of sustainable business models. Their study shows that digital platforms improve stakeholder engagement, support social value creation, and strengthen long-term venture viability. The authors also observed that most existing studies are qualitative and conceptual, indicating a need for more empirical and mixed-method research measuring measurable sustainability outcomes.

Crudu (2019) examined the role of innovative entrepreneurship in economic development across European economies and concluded that innovation-oriented ventures significantly contribute to competitiveness, productivity and quality of life. The study emphasized that technology-enabled SMEs are central to sustainable and inclusive growth models and policy frameworks.

Surana, Singh, and Sagar (2020) analyzed science, technology, and innovation-based incubators in India and reported that technology incubators play a crucial role in advancing Sustainable Development Goals (SDGs). Their findings highlight that incubation support, technology mentoring, and ecosystem partnerships significantly enhance sustainable startup success in emerging economies.

Dutta and Xi (2021) investigated entrepreneurship in emerging and developing economies with focus on institutional voids and entrepreneurial competencies. Their research indicates that technology adoption combined with entrepreneurial capability helps firms overcome institutional barriers and scale innovation despite regulatory and market gaps.

Sengupta and Sahay (2018) studied social enterprises in the Indian context and found that technology-enabled social ventures are increasingly addressing developmental challenges through scalable and hybrid business models.

Their work highlights that digital tools help social enterprises expand outreach and impact in underserved communities.

Paliwal, Chatradhi, Tripathy, and Jha (2023) conducted a bibliometric analysis of digital entrepreneurship literature and observed rapid growth in research linking digitalization, innovation, and sustainability. Their review indicates that digital entrepreneurship is becoming a dominant theme in development and sustainability research.

Nambisan (2017) introduced the concept of digital entrepreneurship as value creation through digital technologies and platforms. The study explains how digital artifacts, platforms, and infrastructures reshape entrepreneurial processes and reduce entry barriers for startups globally, including in emerging markets.

Autio, Nambisan, Thomas, and Wright (2018) examined digital affordances in entrepreneurship and noted that digital technologies enable new venture creation through scalable, low-cost experimentation and ecosystem participation. Their findings support the argument that digital environments accelerate innovation diffusion in emerging economies.

Kraus, Palmer, Kailer, Kallinger, and Spitzer (2019) explored digital transformation in entrepreneurship and concluded that digital business models improve efficiency, adaptability, and sustainability performance. Their study links digitalization directly with long-term competitive advantage.

John, Agrawal, and Nema (2025) analyzed digital innovation and Sustainable Development Goals through bibliometric methods and found that technology-driven ventures increasingly align with environmental and social sustainability metrics. The authors emphasize integration of green and digital innovation strategies.

While each study contributes uniquely, very few offer an integrated perspective on technology-driven entrepreneurship's role in sustainable development, especially within India's socio-economic and policy contexts. This study aims to bridge this gap by offering a comprehensive exploration rooted in real-world implications and policy insights.

II. MATERIAL AND METHODS

Significance of Technology-Driven Entrepreneurship

Technology-driven entrepreneurship serves as a dual engine for economic growth and sustainable development. By leveraging emerging technologies, entrepreneurs are no longer just creating businesses but solving systemic problems with scalable impact. These ventures not only generate employment but also contribute to societal well-being, environmental sustainability, and inclusive economic structures. In emerging economies, where resource constraints are more pronounced, innovation becomes not a luxury but a necessity.

In the context of the United Nations' Sustainable Development Goals (SDGs), technology-led ventures play a crucial role. They offer low-cost, high-impact interventions in areas like renewable energy (Goal 7), health (Goal 3), education (Goal 4), and sanitation (Goal 6). By embedding sustainability into their core strategies, such start-ups can achieve profitability while fulfilling developmental objectives.

India's Unique Position as an Emerging Innovation Hub

India's digital revolution has positioned it at the forefront of entrepreneurial innovation among emerging economies. With over 850 million internet users and the second-largest smartphone market globally, India offers a fertile ecosystem for digital entrepreneurship. Moreover, the government's push through schemes like Startup India, Make in India, and Digital India provides a solid institutional foundation.

The growing number of incubators, accelerators, and venture capital firms reflect an increasing maturity in the entrepreneurial ecosystem. Sectors like ed-tech (e.g., Byju's), agri-tech (e.g., DeHaat), and health-tech (e.g., Practo) demonstrate how India is becoming a laboratory for impact-driven innovation.

Technological Innovations as Sustainability Catalysts

Entrepreneurs are now embracing technologies not only for competitive advantage but also to solve long-standing development challenges:

- AI: Used in predictive analytics for health diagnostics and personalized learning in education.
- IoT: Powers smart agriculture, water management systems, and energy-efficient smart grids.
- Blockchain: Enables transparency in food supply chains, digital identity verification, and land records.
- Renewable Energy Tech: Facilitates decentralized solar grids in off-grid rural regions.

These innovations are proving instrumental in optimizing resource use, reducing emissions, and improving service delivery to underserved communities.

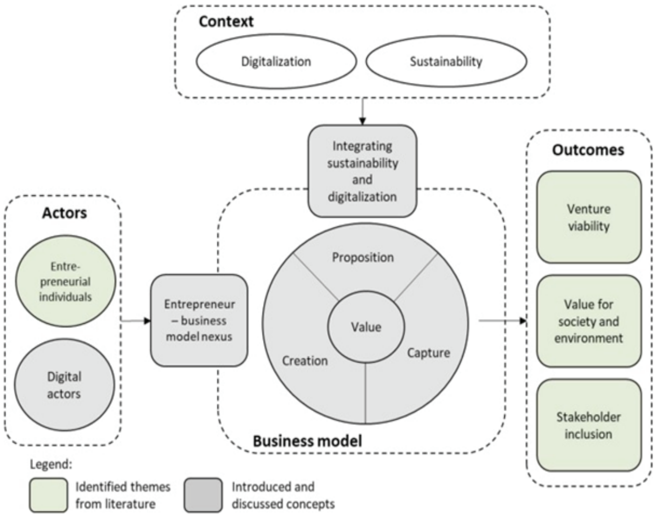
Digitalization and Inclusive Innovation

Digitalization expands access to markets, knowledge, and capital. Digital tools such as e-commerce platforms, digital wallets, and cloud-based enterprise solutions are making it easier for micro-entrepreneurs to scale operations. Inclusive innovation ensures that solutions are not only tech-savvy but also contextually relevant and accessible to marginalized populations. Examples include low-cost diagnostic tools, mobile classrooms, and AI-powered translation tools for regional languages.

Social Entrepreneurship as a Sustainability Enabler

Social entrepreneurs combine technological innovation with a mission to generate social and environmental impact. These ventures often operate in spaces where the government has limited reach, such as tribal education, rural healthcare, and urban sanitation. Their ability to experiment, adapt, and scale makes them crucial allies in India's sustainability journey.

1. To analyze technological innovation tackles socio-economic and environmental issues.
2. To evaluate the contribution of Indian start-ups in key sectors: healthcare, education, energy, and waste management.
3. To assess the role of government programs in creating a supportive ecosystem.
4. To study digitalization and inclusive innovations influence equitable economic development.



This conceptual framework illustrates how entrepreneurial initiatives, particularly in the Indian context, can generate sustainable value by integrating digitalization and sustainability within their business models. It is built on both identified themes from existing literature and original concepts introduced in the present study.

1. Context

The framework is grounded in two major external forces:
• Digitalization – the use of digital technologies, platforms, and data to drive business innovation and scalability.
• Sustainability – the incorporation of environmental, social, and economic goals to ensure long-term positive impact.
These contextual drivers are central to modern entrepreneurial activity and shape the way new ventures are conceived and operated.

2. Actors

Two key categories of entrepreneurial agents are identified:
• Entrepreneurial Individuals – those who recognize and act upon opportunities to create value, often driven by personal vision, social needs, or market gaps.
• Digital Actors – those leveraging digital technologies and platforms to innovate business processes, reach new markets, and transform operations.
These actors form the foundation of value creation through the entrepreneur–business model nexus.

3. Entrepreneur–Business Model Nexus

This linkage represents how entrepreneurs engage with the key elements of business model innovation. Their role is not limited to idea generation but extends to designing, implementing, and refining models that generate, deliver, and capture value in a sustainable and digitalized ecosystem.

4. Business Model Elements

At the core of the framework is the business model itself, which is broken down into three critical components:
• Value Proposition – the unique offering or innovation that addresses a social, environmental, or economic problem.
• Value Creation – the activities, resources, partnerships, and processes that produce and deliver the proposed value.
• Value Capture – the mechanisms through which ventures retain financial, social, or environmental benefits.

A central concept introduced in this study is the integration of sustainability and digitalization across these three stages, ensuring that the business model is not only economically viable but also socially and environmentally responsible.

5. Outcomes

Effective integration of these elements leads to three desirable outcomes:
• Venture Viability – long-term operational and financial sustainability of the venture.
• Value for Society and Environment – measurable contributions to social well-being and ecological health.
• Stakeholder Inclusion – engagement and benefit sharing among diverse stakeholders including customers, employees, communities, and investors.

6. Legend Interpretation

• **Green (Identified Themes):** Elements well-established in existing literature.
• **Grey (Introduced Concepts):** Components newly proposed or synthesized in this study, such as the central integration of sustainability and digitalization in the business model structure.
This framework serves as a guiding model for understanding how technology-driven entrepreneurship in emerging economies like India can be leveraged for sustainable development. It emphasizes that innovation must not only focus on profit but also on purpose, with digital tools and sustainable thinking embedded into the core of every business decision.

III. RESULTS AND DISCUSSION

Based on the integrated conceptual framework that connects digitalization, sustainability, and entrepreneurial business models, several practical and policy-level suggestions are proposed. These recommendations aim to strengthen the effectiveness of technology-driven entrepreneurship in contributing to sustainable development in emerging economies such as India:
1. Entrepreneurship education should embed UN Sustainable Development Goals (SDGs) so founders design ventures aligned with environmental and social priorities from the beginning.
2. Entrepreneurs should be encouraged to build hybrid models that combine digital innovation with sustainability to create both economic value and social impact.
3. Innovation hubs and incubators should be expanded to Tier-2 and Tier-3 cities to support grassroots entrepreneurs and decentralize startup growth.
4. Cross-border technology partnerships should be promoted to adapt advanced innovations to India's local socio-economic and environmental needs.
5. Improving rural internet access and digital literacy will reduce the digital divide and increase participation in technology-driven entrepreneurship.
6. Capacity-building programs should train entrepreneurs to design strong business models focusing on value proposition, value creation, and value capture.
7. Governments and institutions should support social enterprises that apply AI, IoT, and blockchain to solve

problems in health, education, and agriculture.
8. Specialized impact funds should finance technology startups that generate measurable environmental and social outcomes alongside profits.
9. Regulatory procedures and tax policies should be simplified to make it easier for sustainability-focused startups to launch and scale.
10. Startups should follow ESG and impact reporting standards to ensure transparency, accountability, and responsible growth.

These suggestions serve as actionable steps to translate the conceptual framework into real-world outcomes. By embedding digital and sustainable thinking into entrepreneurship policy and practice, India can catalyse scalable, inclusive, and impactful innovation across sectors.

IV. CONCLUSION

Technology-driven entrepreneurship is emerging as a key driver of sustainable development in India. By integrating digital innovation with sustainability goals, entrepreneurs are addressing critical challenges in sectors such as healthcare, education, clean energy, and waste management. This study highlights how supportive policies like Digital India and Start-up India, combined with a growing innovation ecosystem, are enabling scalable, impactful solutions. The conceptual framework presented connects entrepreneurial efforts with business model innovation, digitalization, and sustainability. However, challenges such as infrastructure gaps, limited funding, and regulatory hurdles persist. Addressing these through targeted policies and capacity-building can significantly enhance the role of entrepreneurship in advancing the Sustainable Development Goals (SDGs).

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Smart Waste Segregator Using IOT

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ABSTRACT

The perpetual increase in Municipal Solid Waste (MSW) necessitates intelligent solutions to circumvent the hazards and inherent inefficiencies of manual waste processing. This research details an innovative, sensor-based system designed to execute automated, source-level waste classification into three discrete streams: Wet, Dry, and Metallic. The core mechanism integrates an Arduino UNO for executing the decision logic (based on Moisture, IR, and Metal Detection) with a NodeMCU ESP8266 dedicated solely to cloud communication. Furthermore, Ultrasonic Sensors provide continuous bin volume telemetry. All operational data, including real-time fill status and critical alerts, is seamlessly managed and visualized via the Blynk IoT Dashboard, empowering municipal bodies with reliable data for optimized collection route planning. This system demonstrably enhances segregation purity, reduces operational dependency on manual labor, and contributes significantly to sustainable urban sanitation.

Keywords: IoT, Smart Waste Management, Waste Segregation, Arduino UNO, NodeMCU, Blynk, Ultrasonic Sensors, Metal Detector

I. INTRODUCTION

Solid waste management has emerged as one of the most critical challenges faced by modern urban societies. With rapid industrialization, urban expansion, and lifestyle changes, the volume of waste generated has increased drastically, putting immense pressure on municipal authorities and urban infrastructure. According to recent studies, global waste production is expected to rise significantly in the coming decades, making effective waste management an urgent concern for both environmental sustainability and public health. Municipal authorities across the world struggle to handle waste effectively due to limitations in manpower, infrastructure, and technological capabilities, which often results in inefficient collection, transportation, and disposal practices.

One of the major challenges in waste management is improper segregation at the source. Waste is typically a heterogeneous mixture comprising organic matter, recyclable materials, metals, plastics, and hazardous substances. Failure to segregate waste at the point of generation severely affects recycling efficiency, composting processes, and the safe disposal of hazardous materials. In many developing countries, including India, waste segregation is still predominantly performed manually. This approach is not only labor-intensive but also exposes workers to potentially hazardous and infectious materials, leading to serious health risks. Additionally, manual segregation is often inconsistent and inaccurate, resulting in mixed waste streams that ultimately end up in landfills, contributing to soil and water contamination, greenhouse gas emissions, and the proliferation of pests.This research work focuses on designing and implementing an IoT-based smart waste segregation system that automatically classifies waste into dry, wet, and metallic categories. The system not only performs segregation but also provides real-time information about bin status through an IoT dashboard. The proposed solution aims to reduce human effort, improve segregation accuracy, enhance hygiene, and support smart city initiatives.

The inefficiency of traditional waste management practices is further compounded by the lack of real-time monitoring and data-driven decision-making systems. Without accurate information about bin fill levels, waste composition, and collection schedules, municipal authorities face challenges such as overflowing bins, unpleasant odors, littering, and environmental pollution. Moreover, the absence of predictive analytics hinders the optimization of collection routes, increasing operational costs, fuel consumption, and carbon footprint. These challenges underscore the need for smarter, automated, and technology-driven solutions to manage waste more effectively.Recent advancements in the Internet of Things (IoT) and embedded systems have opened new possibilities for transforming waste management processes. IoT enables the interconnection of physical devices with cloud-based platforms, facilitating real-time data collection, remote monitoring, and automated decision-making. By integrating sensors, microcontrollers, and wireless communication technologies, waste segregation processes can be automated to identify and classify waste types accurately. Smart sensors can detect organic, inorganic, and metallic materials, while IoT-enabled bins can transmit status updates to centralized dashboards, enabling timely collection and reducing operational inefficiencies.

This research work focuses on designing and implementing an IoT-based smart waste segregation system capable of automatically classifying waste into dry, wet, and metallic categories. The system leverages sensors to detect different types of waste and uses microcontrollers to control sorting mechanisms, ensuring accurate segregation. Additionally, the system is equipped with IoT connectivity that provides real-time updates on bin status through a user-friendly dashboard, allowing municipal authorities and waste management agencies to monitor operations remotely.

The proposed solution aims to reduce human effort, improve segregation accuracy, enhance hygiene, and support smart city initiatives by integrating technology into urban waste management practices. Furthermore, the system has the potential to promote recycling, reduce landfill dependency, and contribute to sustainable environmental practices, aligning with the goals of modern smart cities and sustainable development.

The rapid increase in municipal solid waste generation has motivated researchers and practitioners to explore smart and automated waste management solutions. This review analyzes existing research on IoT-enabled waste segregation and monitoring systems, highlighting key methodologies, technologies, and limitations that provide context for the proposed project. Recent studies emphasize the importance of automation, real-time monitoring, and intelligent decision-making to overcome the inefficiencies of traditional manual waste segregation practices.

With the emergence of Internet of Things (IoT) technologies, waste management systems have evolved from conventional collection-based approaches to intelligent, data-driven solutions. Researchers have observed that IoT-based systems significantly enhance operational efficiency by enabling real-time monitoring of waste bins, reducing collection delays, and optimizing resource utilization. The integration of sensors, microcontrollers, and cloud platforms has been identified as a game-changing approach for improving transparency, hygiene, and sustainability in waste management, which aligns closely with the objectives of the proposed system.

Several researchers have proposed intelligent and automated solutions for waste segregation and management.

S. Venkatesh : developed an integrated system combining IoT and Convolutional Neural Networks (CNN) for automated garbage classification. Their system distinguished between biodegradable and non-biodegradable waste, enabled real-time monitoring of bin levels, and utilized data analytics to improve waste collection efficiency, thereby reducing manual labor and promoting environmental hygiene.

Priyanka Bhatele : presented a low-cost sensor-based smart bin system capable of segregating waste into dry, wet, and metallic categories. The system used an inductive proximity sensor for metals, a moisture sensor for wet waste, and an ultrasonic sensor to monitor bin levels and detect dry waste. Arduino-controlled servo motors directed the waste into corresponding compartments, achieving an overall classification accuracy of 90–93%. Real-time LCD alerts informed users when bins were full, enhancing convenience and hygiene.The rapid increase in municipal solid waste generation has motivated researchers and practitioners to explore smart and automated waste management solutions. This review analyzes existing research on IoT-enabled waste segregation and monitoring systems, highlighting key methodologies, technologies, and limitations that provide context for the proposed project. Recent studies emphasize the importance of automation, real-time monitoring and intelligent decision-making to overcome the inefficiencies of traditional manual waste segregation practices.With the emergence of Internet of Things (IoT) technologies, waste management systems have evolved from conventional collection-based approaches to intelligent, data-driven solutions. Researchers have observed that IoT-based systems significantly enhance operational efficiency by enabling real-time monitoring of waste bins, reducing collection delays, and optimizing resource utilization. The integration of sensors, microcontrollers, and cloud platforms has been identified as a game-changing approach for improving transparency, hygiene, and sustainability in waste management, which aligns closely with the objectives of the proposed system.

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Mary P. Varghese : proposed an IoT-enabled smart waste management system with real-time level indicators for effective garbage segregation. Their approach combined compartmentalized bins with LoRa-based sensors to transmit fill levels, LED indicators to signal bin status, and a Raspberry Pi with NodeMCU for coordinating sensors and image-based classification. Cloud connectivity enabled centralized monitoring, optimized waste collection schedules, and improved operational efficiency, supporting municipal sustainability goals.

Although these systems demonstrate the potential of IoT and automation in waste management, most are limited in scalability, cost-efficiency, or real-time communication. The proposed system in this work combines IoT-enabled real-time monitoring, automated segregation of dry, wet, and metallic waste, and cloud-based alerts to address these challenges, making it suitable for both household and urban environments. Additionally, the system is designed with low-cost, energy-efficient components to ensure easy deployment and long-term sustainability. Its modular architecture allows seamless integration with smart city infrastructure, enabling data-driven decision-making and improved waste collection efficiency

II. MATERIAL AND METHODS

The proposed IoT-based smart waste segregation system is designed to automatically identify and segregate waste materials while simultaneously transmitting real-time data to a cloud platform. The system architecture consists of sensing units, a control unit, actuation mechanisms, and an IoT communication module.

When waste is introduced into the system, an ultrasonic sensor detects the presence of an object and triggers the segregation process. The waste is first analyzed using an inductive proximity sensor to determine whether it contains metallic content. If metal is detected, the waste is directed to the metal bin. In the absence of metal, the waste passes through a moisture sensor, which determines its moisture content. Based on predefined threshold values, the waste is classified as wet or dry and directed to the respective bins using servo motors.

The Arduino microcontroller acts as the central control unit, processing sensor inputs and controlling the actuation mechanisms. An ESP8266 Wi-Fi module is interfaced with the Arduino to transmit segregation data, bin levels, and system status to a cloud-based IoT platform. The collected data is visualized on a mobile application dashboard, enabling users and authorities to monitor waste levels and receive alerts when bins are full.

The system is powered using a regulated power supply to ensure stable operation. The integration of hardware and software components ensures seamless communication between physical devices and the cloud environment.

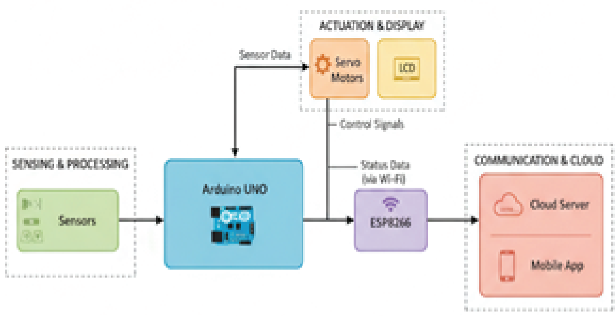

Figure 1. project Architecture

The system architecture follows a modular design approach, enabling easy scalability and maintenance. The sensing module consists of ultrasonic, moisture, and inductive sensors that collect real-time data. The control module processes sensor data and executes decision logic. The actuation module directs waste to appropriate bins using servo motors. The communication module handles data transmission to the IoT platform.

This layered architecture ensures efficient data flow, fault tolerance, and real-time monitoring. The modular design allows additional sensors or features, such as gas sensors or weight sensors, to be integrated in future enhancements.

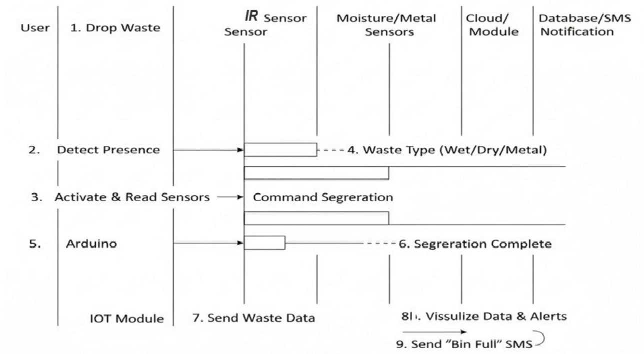

Figure 2. Sequence Diagram – Waste

A sequence diagram is used to represent the time-ordered flow of operations within the proposed smart waste segregation system, illustrating how different hardware and IoT components interact during waste detection, classification, and monitoring. The process begins when a user places waste in the designated detection area, upon which the infrared sensor identifies the presence of an object and signals the control unit. In response, the Arduino microcontroller activates the moisture and metal sensors to analyze the physical properties of the waste and determine its category.

Based on the sensor readings, the Arduino processes the classification logic and generates appropriate control signals for the servo motor. The servo motor then rotates to direct the waste into the corresponding bin, ensuring accurate segregation. Simultaneously, the system updates the user interface by displaying the detected waste type and current bin status on the LCD. The segregation data and bin information are transmitted wirelessly through the ESP8266 Wi-Fi module to the IoT cloud platform. This information is further visualized on a mobile application, allowing real-time monitoring. When a bin reaches its maximum capacity, the system automatically triggers an audible alert using a buzzer and sends a notification through the IoT platform, ensuring timely waste collection and efficient system operation.

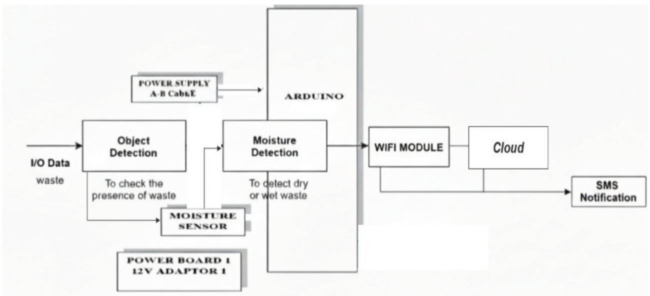

Figure 3. Block Flow Diagram

The Data Flow Diagram illustrates the movement of data within the Smart Waste Segregator system, highlighting key processes and interactions. At Level 0, the system receives a waste item as input, which is analyzed through sensor detection and processed by the Arduino controller. The processed data results in waste classification, which is displayed on the LCD and transmitted as alerts through the IoT platform. At Level 1, the infrared sensor detects the presence of waste, followed by moisture and metal sensors that classify the waste type. The Arduino processes the sensor values and controls the segregation mechanism to direct the waste into the appropriate bin. Simultaneously, the ESP8266 module transmits bin status and waste classification data to the cloud, enabling real-time updates on the mobile dashboard.

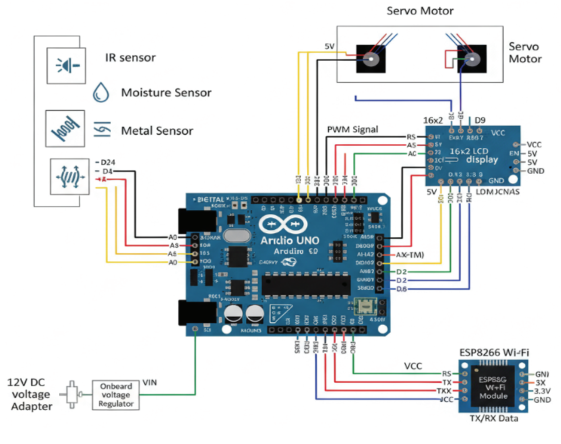

Figure 4. Circuit Diagram

The hardware design of the proposed system illustrates the interconnection and coordination of all physical components required for automated waste segregation and monitoring. It primarily focuses on sensor integration, power distribution, and control signal flow to ensure reliable and efficient system operation. An Arduino UNO serves as the central control unit, responsible for processing sensor inputs and executing the decision logic for waste classification. IoT connectivity is enabled using an ESP8266 Wi-Fi module, which transmits real-time system data to a cloud platform for remote monitoring..The sensing unit consists of an infrared sensor for detecting the presence of waste, a moisture sensor for distinguishing between wet and dry waste, and a metal sensor for identifying metallic objects. Based on the sensor outputs, servo motors are actuated to rotate mechanical flaps, directing the waste into the appropriate bins. A 16×2 LCD display provides real-time feedback by displaying the identified waste category and bin status, while a buzzer generates alerts when a bin reaches its maximum capacity or when improper waste is detected. The entire system is powered by a regulated 12V DC power supply, ensuring stable and uninterrupted operation of all hardware components.

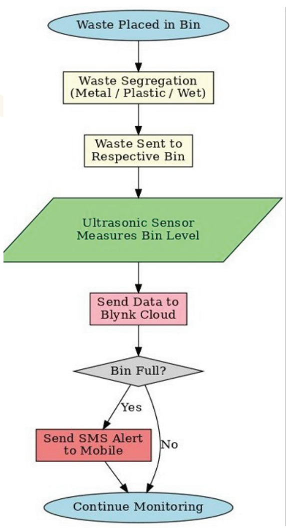

Figure 5. Flow Chart

Figure 5 illustrates the operational flow of the proposed IoT-based Smart Waste Segregation and Monitoring System. The flow chart explains the sequential logic followed by the system to automatically detect, classify, and monitor waste in real time.The process begins with the initialization of the system, where the user logs in and the hardware components such as sensors, microcontroller, LCD display, and IoT module are powered on and synchronized. Once the system is active, the IR sensor continuously monitors for the presence of waste. When an object is detected, the system proceeds to identify the type of waste.The first classification stage checks for the presence of metallic content using a metal detection sensor. If metal is detected, the waste is immediately directed to the metal bin through the mechanical segregation mechanism. If no metal is detected, the system evaluates the moisture content of the waste using a moisture sensor.Based on the moisture level, the waste is classified as wet or dry. High moisture content indicates wet waste, which is directed to the wet waste bin, while low moisture content corresponds to dry waste and is directed to the dry bin. The identified waste type is displayed on the LCD for user confirmation and system transparency.

Simultaneously, the classification data and bin status information are transmitted to the IoT cloud platform for real-time monitoring and data logging. The system then checks the bin fill level using ultrasonic or level sensors. If any bin reaches its maximum capacity, a buzzer is activated to provide a local alert, and a notification is sent to the concerned authority via the cloud platform.

The system then resets and repeats the same process for the next waste item, ensuring continuous and automated operation. This flow ensures efficient waste segregation, timely alerts, and effective monitoring, thereby reducing manual intervention and improving overall waste management efficiency.

III. RESULTS AND DISCUSSION

The proposed IoT-Based Smart Waste Segregator was effective monitoring, thereby reducing manual intervention and improving overall waste management efficiency. successfully implemented and tested. The system was evaluated through experimental trials to validate its performance in real-time waste detection, segregation and monitoring.

System Performance

The prototype effectively detected and classified waste into three categories: dry, wet, and metallic. The LCD module provided immediate visual feedback indicating the type of waste detected, as shown in Figures 1-3V The IoT dashboard, developed using Blynk, displayed real-time system parameters including bin fill percentage, waste category, and triggered alerts when bins reached capacity or

Figure 6. When dry waste is detected → "Dry Waste Detected"

Figure 7. When metallic waste is detected → the LCD displays “Metal Waste Detected”

Figure 8. When wet waste is detected → “Wet Waste Detected”

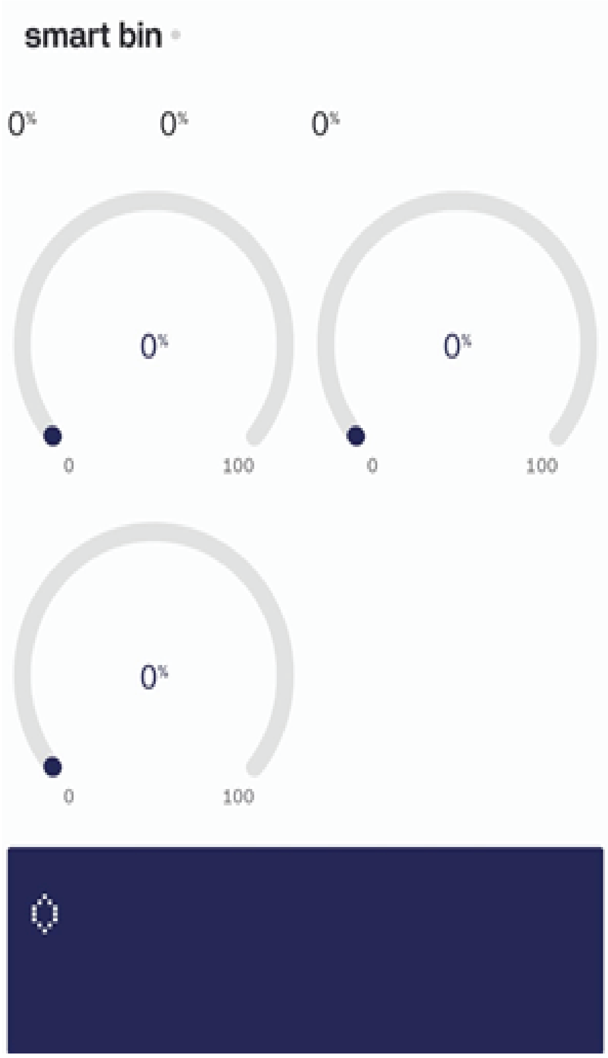

Figure 9. IoT Dashboard (Blynk)

Hardware Prototype Evaluation

The hardware prototype, depicted in Figures 4.5–4.6, demonstrated reliable operation over continuous testing for more than 5 hours without any malfunctions. The top, side, and bin views highlight the practical design of the system for real-world deployment

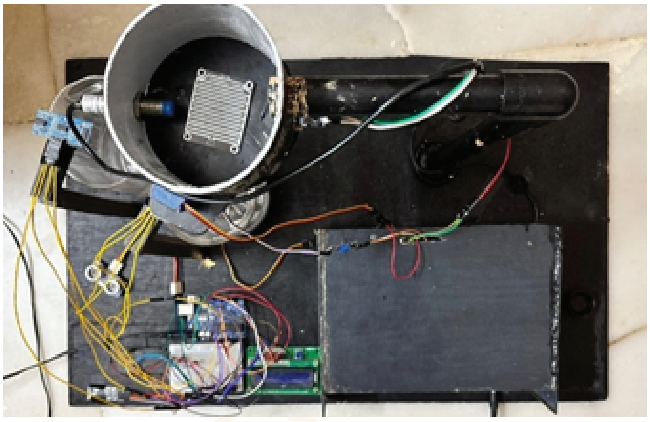

Figure 10. Top View Of Hardware Prototype

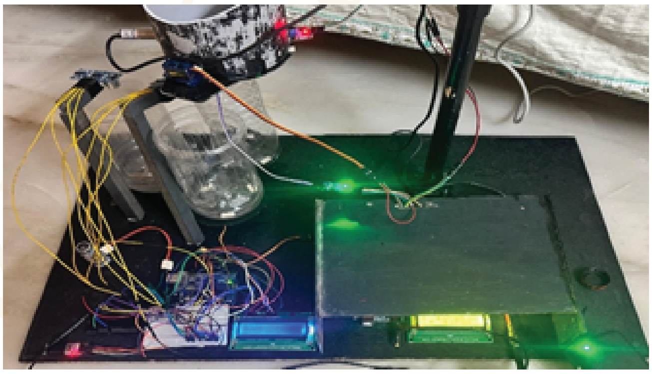

Figure 11. Hardware Prototype Image

Monitoring and Alerts

Real-time monitoring through the IoT platform enabled timely interventions for waste collection. The system generated SMS and mobile notifications for full bins or maintenance requirements . The buzzer and alert mechanism enhanced responsiveness and ensured operational efficiency.

Figure 12. Bin Alert Display Screen

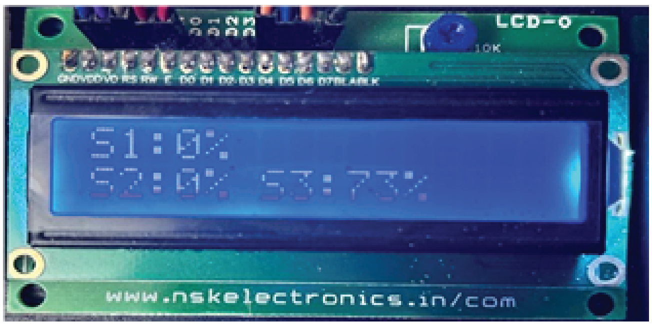

Figure 13. Bin Percentage Display Screen

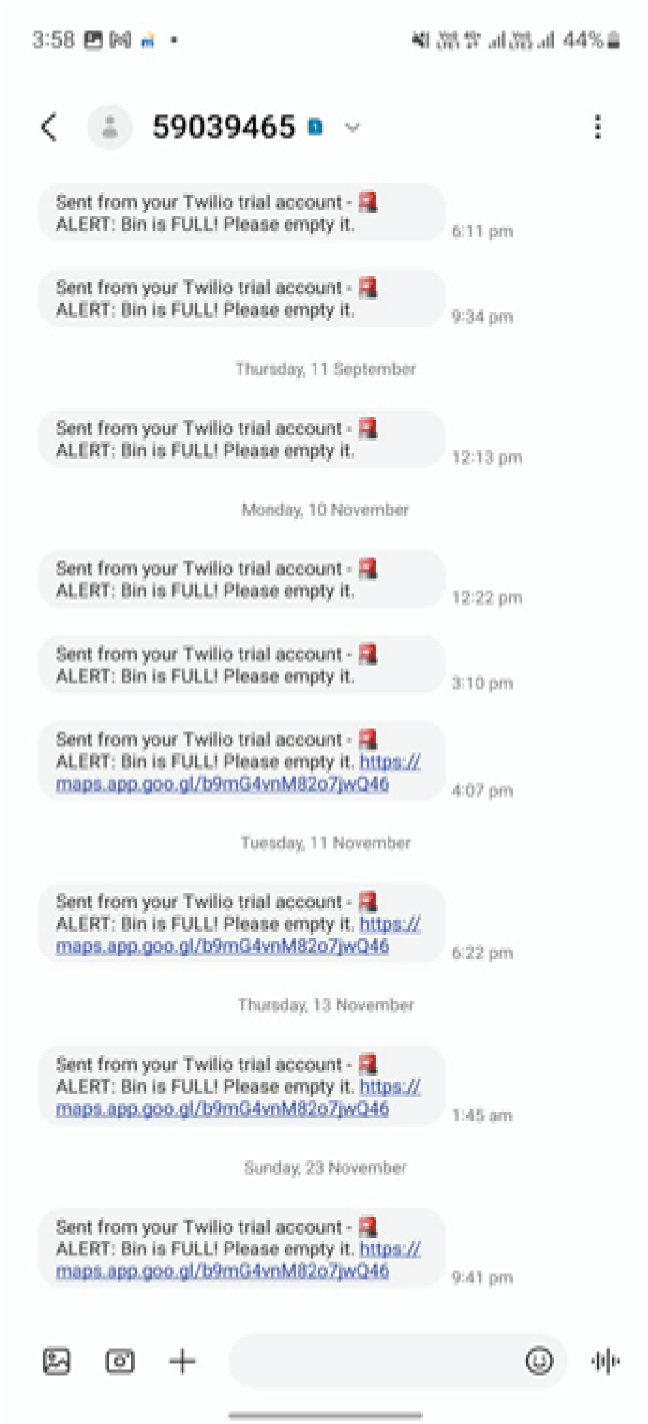

Figure 14. SMS / Notification Alert

IV. CONCLUSION

This paper presented an IoT-based smart waste segregation system designed to address the challenges of modern waste management. By integrating sensor-based classification with real-time IoT monitoring, the system automates waste segregation while providing valuable data for efficient waste collection. The experimental results validate the effectiveness and reliability of the proposed solution.

The system contributes to sustainable waste management practices by improving segregation accuracy, reducing human exposure to waste, and supporting recycling processes. Future work may focus on integrating machine learning techniques, solar power, and large-scale deployment for smart city applications.

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LinkedGen: The Personalized AI Tool for LinkedIn Post Generation

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ABSTRACT
LinkedIn has become a key platform for professional networking, personal branding, and career growth, but many users struggle to create consistent, high-quality posts that match their goals and writing style. This paper presents LinkedGen, a personalized AI-based tool that automates LinkedIn post creation using a large language model (LLM) with few-shot prompting. LinkedGen allows users to generate posts by selecting topic, length (Short/Medium/Long), language (English or Hinglish), and tone (Professional, Friendly, Motivational, Casual), and then refines the output through an interactive Streamlit interface that supports editing, exporting (TXT/DOCX/PDF), and scheduling. A preprocessing pipeline enriches a dataset of real LinkedIn posts with metadata such as line count, language, and unified tags, which are later used to select relevant examples for guiding the LLM. The system is implemented using Python, LangChain, Groq's Llama 3.3 model and CSV-based storage for history, schedules, and feedback, providing a lightweight yet effective workflow for content creation. Experimental use and user feedback indicate that LinkedGen reduces manual writing effort, improves consistency in tone and helps users maintain an active LinkedIn presence with minimal time investment.

Keywwords: LinkedIn, AI content generation, Large Lan- guage Model, few-shot learning, Streamlit, social media automation.

I. INTRODUCTION

In the current digital landscape, LinkedIn has evolved into a primary platform for professional networking, personal branding, and career opportunities. Users are expected to share valuable insights, achievements, and opinions regularly, but many struggle with writer's block, lack of time, and difficulty in maintaining a consistent tone and style across posts. As a result, professionals, students, and job seekers often miss opportunities to build visibility and engagement on the platform.

Recent advancements in Large Language Models (LLMs) have enabled automated generation of human-like text, which can assist users in drafting emails, blogs, and social media content. However, generic text generators are not specifically optimized for LinkedIn and often require heavy manual editing to match the expected professional tone, structure, and length of platform-friendly posts. Additionally, most tools do not integrate generation, editing, exporting, and scheduling into a single, simple workflow suited for students and early-career professionals.

To address these challenges, this project proposes Linked- Gen: The Personalized AI Tool For LinkedIn Post Generation,a system that uses an LLM to generate customized LinkedIn posts based on user-selected topic, post length, language, and tone. LinkedGen is implemented as a Streamlit web application that provides a clean user interface to generate posts, edit them, export in multiple formats (TXT, DOCX, PDF), and schedule them for future use, helping users maintain a consistent presence on LinkedIn with minimal manual effort. The system incorporates a preprocessing pipeline that en- riches a dataset of real LinkedIn posts with metadata such as line count, language, and tags. These enriched posts are used to perform few-shot prompting, where one or two similar historical posts guide the LLM to produce outputs that better resemble real LinkedIn content in structure and style. This design reduces randomness in generation and increases the relevance of the produced posts for the chosen topic and tone.

The main objectives of this project are:

- To design and implement an AI-based tool that generates LinkedIn posts tailored to user preferences such as topic, length, language, and tone.
- To build a preprocessing and metadata extraction pipeline that supports intelligent selection of few-shot examples for better quality generation.
- To provide an easy-to-use interface that integrates gener- ation, editing, exporting, history management, feedback collection, and scheduling in a single application.

This paper presents the architecture and implementation details of LinkedGen, along with sample outputs and user feedback demonstrating its usefulness for professionals and students aiming to improve their LinkedIn activity.

Artificial Intelligence and LLM-based content generation tools are increasingly used to automate and accelerate the writing process for blogs, emails, and social media posts. Pop- ular platforms and tools provide features such as topic-based generation, template-driven posts, and grammar correction, but they are often generic and not tightly focused on the specific requirements of LinkedIn, such as concise storytelling, profes- sional tone, and audience engagement. Some tools additionally offer analytics and scheduling, yet they remain commercial SaaS products with limited transparency or customizability for student projects and academic exploration.Several AI-driven LinkedIn content tools have emerged that help users draft posts through prompts or predefined frameworks. These include systems that allow creators to input a topic and receive multiple post variations, basic hashtag suggestions, and sometimes a schedule planner. While such tools demonstrate the potential

AI in professional net- working, they frequently operate as black boxes and do not expose internal mechanisms such as tag unification, metadata extraction, and few-shot example selection, which are essential concepts from a research and educational perspective.

In addition, research literature on prompt engineering and few-shot learning shows that providing relevant examples in the prompt can significantly improve the structure, coherence, and task alignment of generated text from LLMs. By leverag- ing this idea, LinkedGen selects historical LinkedIn posts that match the requested length, language, and topic and embeds them into the prompt as style references. Compared to generic one-shot prompts, this approach yields outputs that are more consistent with LinkedIn's expectations for professional yet engaging communication.Unlike many existing commercial tools, LinkedGen is de- signed as an end-to-end academic project that demonstrates the full pipeline from raw data preprocessing to few-shot prompting, post generation, and user-centric features such as editing, exporting, scheduling, and feedback collection. This makes the system not only practical for end users but also valuable as a reference implementation for students and researchers studying applied LLM-based systems.

II. MATERIAL AND METHODS

The methodology of LinkedGen is organized into multiple stages, starting from data preprocessing and metadata ex- traction, followed by tag unification, few-shot post selection, prompt construction, LLM-based generation, and finally de- livery to the user through a Streamlit interface. Each stage is implemented as a separate module, resulting in a modular and maintainable architecture that simplifies future enhancements and debugging.

At a high level, when a user selects the topic, length, language, and tone of the desired LinkedIn post, the system identifies suitable historical posts that share similar charac- teristics and uses them as examples in the LLM prompt. The LLM then generates a new post which is formatted and displayed to the user, who can edit it, download it in various formats, or schedule it for later use.

A. Data Preprocessing and Metadata Extraction

The preprocessing module (preprocess.py) reads a JSON file containing raw LinkedIn posts and enriches each entry with structured metadata before storing the results in processed-posts.json. For every post, an LLM-based extractor is used to determine the number of lines, the language (English or Hinglish), and a small set of descriptive tags, which are returned in a strict JSON format for robustness.

This metadata enables the system to categorize posts by length (Short, Medium, Long) and language, as well as to group them by semantic topics through tags. The enriched dataset also forms the basis for tag unification and for select- ing relevant few-shot examples during generation. All processing is done in Python, and the final output is saved with proper indentation for easy inspection and debugging.

B. Tag Unification

Raw tags extracted from posts can be noisy and redundant, such as "Job Search", "Job Hunting", or "Jobseekers" referring to the same underlying theme. To reduce this redundancy, a tag unification step aggregates all unique tags and sends them to an LLM with instructions to map related tags into a smaller, cleaner tag set (for example, mapping "Job Hunting" and "Jobseekers" to "Job Search").

The LLM returns a JSON object that specifies the mapping from original tags to unified tags, which is then applied back to the enriched posts. This process produces a consistent set of topics that can be exposed directly in the Streamlit dropdown, improving user experience and ensuring that few- shot examples are chosen from a coherent topic space.

C. Few-Shot Example Selection

The Few Shot Posts class loads processed posts.-json and normalizes it into a pandas DataFrame, from which it derives the unique unified tags and categorizes each post into Short, Medium, or Long based on line count. When the user selects a topic, length, and language, the class filters the DataFrame to return posts that satisfy all three constraints, producing a list of candidate examples.

From this filtered list, LinkedGen selects up to two posts to include in the generation prompt as style examples. These examples help the LLM understand the structure, level of detail, and tone typically used for that combination of topic and length, resulting in more realistic LinkedIn-style posts.

D. Prompt Construction and Post Generation

The post_generator.py module constructs an instruction prompt that describes the requested topic, target length in terms of line range, preferred language, and tone, along with any special guidance such as using English script for Hinglish content. The selected few-shot examples are appended to this prompt to demonstrate the desired writing style and format before calling the LLM.

The LLM, accessed through the llm_helper.py module, uses Groq's implementation of the Llama-3.3-70B-Versatile model, which is integrated via LangChain. The model returns a generated post as plain text, which is then combined with au- tomatically generated hashtags and a call-to-action line (CTA) constructed using helper functions defined in main.py. The final formatted post is added to the application's history and displayed in the user interface.

E. Streamlit-Based User Interface and Workflow

The main.py module defines the Streamlit application that acts as the front end of LinkedGen, providing all user interac- tions in a single window. The interface contains dropdowns for selecting topic, length, language, and tone, as well as buttons for generating a single post or three variations, resetting inputs, and managing history.

Once a post is generated, the user can preview it in a styled container, view word and character counts, and mod- ify the text using a text area field. The application then offers multi- ple export options: downloading the edited con- tent as TXT, DOCX, or PDF files using helper functions that rely on the python-docx and reportlab libraries. Additionally, users can save posts with a timestamp into scheduled_posts.csv, view and delete scheduled posts from a dedicated section, and submit feedback that is stored in feedback.csv for later review.

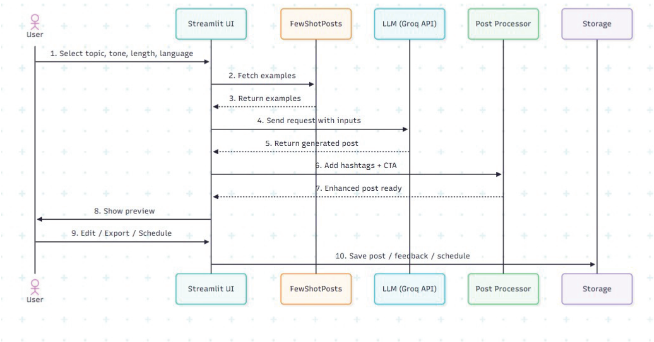

Figure 1. Sequence diagram of the LinkedGen workflow from user input through Streamlit UI, FewShotPosts, Groq LLM API, post-processing, and storage.

F. Limitations of the Approach

Although the modular pipeline enables clear separation of concerns, the current design still depends heavily on the behaviour of the underlying LLM and the quality of the preprocessed dataset. The tag unification step may introduce bias if the mapping produced by the LLM merges semanti- cally distinct ideas into a single label, which could reduce topic diversity in the generated posts. In addition, the system does not yet incorporate automatic quality control or toxicity filtering, so final responsibility for checking the suitability of the generated content remains with the user.

Another limitation is the reliance on third-party APIs for generation. Network latency, rate limits, or temporary un- availability of the Groq service can impact response times or prevent generation altogether. While the Streamlit frontend can display error messages, a more robust production deployment would require retry logic, caching of frequent prompts, and possibly a fallback model hosted locally for resilience.

The implementation of LinkedGen relies on a combination of Python libraries, web frameworks, and cloud-based AI services that together provide data processing, model interaction, and user interface capabilities. The selection of these tools focuses on ease of development, portability, and compatibility with modern LLM-based workflows.

• **Programming Language – Python:** Python is used for all core modules, including preprocessing, few-shot selection, LLM integration, and the Streamlit application, due to its rich ecosystem and readability.
• **Streamlit:** Streamlit powers the web interface, enabling rapid development of interactive UI components such as dropdowns, text areas, buttons, and data displays without requiring traditional frontend frameworks.
• **LangChain and Groq LLM API:** The llm_helper.py module uses LangChain's ChatGroq wrapper to communicate with Groq's hosted Llama-3.3-70B-Versatile model, providing scalable, low-latency LLM inference for post generation and metadata extraction.
• **pandas and JSON Handling:** The preprocessing and few-shot modules use pandas and the built-in json li- brary to normalize the enriched post dataset, filter records by metadata, and persist data in structured formats.
• **Document Export Libraries:** The application uses python-docx (Document class) to create DOCX files and reportlab.pdfgen.canvas to generate PDF files from text, enabling multi-format export of generated posts.
• **CSV Storage:** Simple CSV files(scheduled_posts.csv, feedback.csv) are used to store scheduled posts and user feedback, making the system lightweight and easy to inspect or back up without a separate database server.
• **Environment and Configuration:** The python-dotenv package is used to load the Groq API key from an .env file, ensuring that sensitive credentials are not hard-coded into the source code.

To better understand how LinkedGen behaves under differ- ent usage patterns, a small but structured experimental setup was designed. The goal of these experiments was not to benchmark the underlying LLM itself, but to study the impact of user-controllable parameters such as topic, length, language, and tone on the perceived quality and variety of generated LinkedIn posts, as well as the responsiveness of the overall system.

A. Dataset Construction

The initial dataset used for preprocessing consists of man- ually collected LinkedIn-style posts authored by students and early-career professionals. Posts were chosen to cover multiple themes such as job search, productivity, self improvement, mental health awareness, internships, project highlights, and technical tips. Each post was stored as raw text in a JSON file together with minimal metadata such as an identifier and approximate posting date.

During preprocessing, the LLM-based metadata extractor enriched every entry with line count, language label, and a small list of tags. This enriched file serves as the main input for the FewShotPosts component. For the experiments, a subset of approximately 80–100 posts was sufficient to provide a meaningful variety of examples across topics and lengths while remaining lightweight for local development and testing.

B. Topic and Length Distribution

Table I summarizes an example distribution of posts across topics and length categories after preprocessing and tag unifi- cation. These numbers illustrate how the dataset covers a mix of short, medium, and long posts relevant to LinkedIn usage.

TABLE I : ILLUSTRATIVE DISTRIBUTION OF POSTS BY TOPIC AND LENGTH

Topic	Short	Medium	Long
Job Search	10	8	4
Productivity	9	7	3
Self Improvement	8	6	3
Mental Health	6	5	3
Internships/Projects	5	7	4
Technical Tips	4	5	2
Total	42	38	19

The distribution shows that most posts are short or medium length, which aligns with common practice on LinkedIn where concise updates often perform better than very long essays. At the same time, there are enough long posts to provide examples for thought-leadership style content.

C. Test Scenarios

Four main scenarios were defined to exercise the different capabilities of LinkedGen:

- **Scenario 1 – Professional English Posts:** The user selects topics related to career growth and job search, with the tone set to "Professional" and language set to "English". This scenario simulates usage by job seekers preparing regular updates.
- **Scenario 2 – Motivational Hinglish Posts:** The user selects topics such as productivity and self improvement with tone "Motivational" and language "Hinglish". This scenario targets Indian users who commonly mix Hindi and English while maintaining a friendly tone.
- **Scenario 3 – Long-Form Thought Leadership:** The user chooses longer post lengths and topics such as technology trends or project retrospectives. The aim is to see whether the system can produce coherent multi- paragraph content that still fits LinkedIn norms.
- **Scenario 4 – Batch Content Creation:** The user gener- ates multiple variations for the same combination of topic and tone, then uses the history, export, and scheduling features to plan a week of posts in one sitting.

For each scenario, at least ten posts were generated and manually inspected. Informal feedback was collected from a small group of peers in the department who evaluated clarity, relevance, tone appropriateness, and readiness for publishing.

D. Evaluation Criteria

Because the system focuses on subjective aspects such as writing style and usefulness rather than objective accuracy, the evaluation relied on qualitative criteria. The main criteria were:

- **Fluency:** Grammatical correctness and natural flow of sentences.
- **Relevance:** Alignment between generated content and the selected topic, tone, and length.
- **LinkedIn Readiness:** Whether the post appears suitable to be published directly on LinkedIn with minimal edit- ing.
- **Diversity:** Variation across different generations for the same configuration, especially in Scenario 4.

These criteria were used as a guide for manual inspection and discussion rather than as rigid scoring metrics.

E. System Performance

Although LinkedGen is not designed as a high-throughput production system, basic performance measurements were collected during testing. On a standard development laptop with a stable internet connection, the median response time for generating a post through the Groq API was observed to be between 2 and 6 seconds depending on length and the complexity of the prompt. Preprocessing operations, such as loading the dataset and filtering few-shot examples using pandas, completed within a fraction of a second and did not noticeably impact user experience.

The use of CSV files for storing history, schedules and feedback introduced negligible overhead for the small number of entries expected in a typical student project setting. However, for a larger deployment with thousands of users, a database- backed solution with indexing and concurrency control would be more appropriate to ensure consistent performance.

III.RESULTS AND DISCUSSION

The LinkedGen application was executed as a Streamlit web app and tested with various combinations of topic, length, language, and tone to evaluate its usability and quality of generated posts. The interface successfully loaded the unified tag list, allowed users to select preferences, and produced LinkedIn-style posts that aligned with the chosen parameters, demonstrating the effectiveness of the few-shot prompting strategy.

A. User Interface Screens

The main page displays the application title "LinkedGen Personalized AI Tool", followed by dropdowns for Topic, Length, Language, and Tone, and buttons for generating a single post or three variations. The post preview section shows the generated content in a bordered container along with word and character counts, an editable text area, and download buttons for TXT, DOCX, and PDF formats. The sidebar displays recent post history with options to search, filter by tone and language, view or pin posts, as well as sections for feedback and scheduled posts.

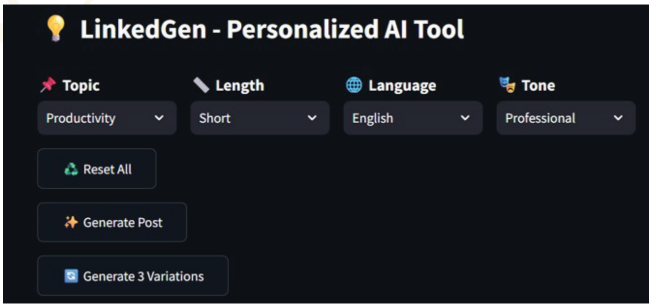

Figure 2. LinkedGen main interface with controls for topic, length, language, and tone before generating a LinkedIn post.

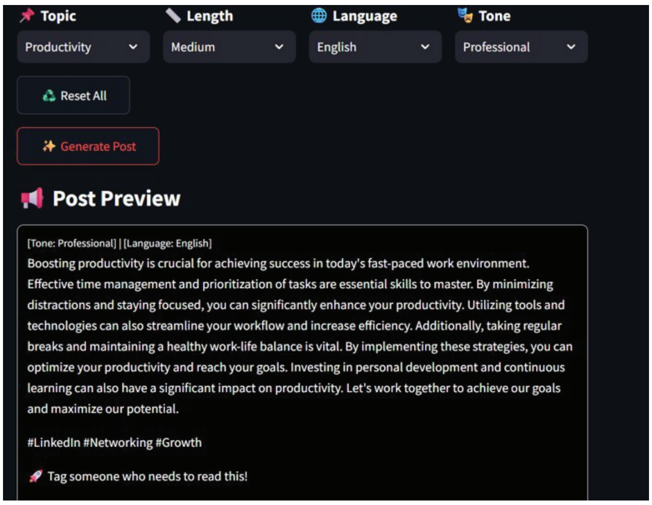

Figure 3. Generated LinkedIn post result in LinkedGen, showing the post preview with content, hashtags, call-to-action, and sidebar options for history and export.

B. Quality of Generated Posts

For topics such as “Job Search”, “Mental Health”, or “Self Improvement”, the generated posts followed LinkedIn conventions, with short paragraphs, actionable advice, and a clear call to action, while respecting the requested tone (for example, Motivational versus Professional). Hinglish posts correctly mixed Hindi and English while keeping the script in English, as instructed in the prompt, resulting in content that felt natural for Indian LinkedIn users comfortable with code- mixed language.

Some common imperfections were also observed. In a few long-form posts, the LLM occasionally repeated similar ideas using different wording, which slightly reduced conciseness. In rare cases, the hashtags suggested by the system were very generic (for example, #success or #career) instead of highly specific to the described scenario. These issues were easy to correct manually by removing redundant sentences or replacing individual hashtags, and users generally felt that the time saved by automatic drafting outweighed the small amount of editing required.

C. History, Scheduling, and Feedback

The history feature allowed users to revisit previously generated posts, apply filters, and export all posts collectively in TXT, DOCX, or PDF, which is useful for batch content planning. The scheduling function successfully stored posts with their intended timestamp into scheduled_posts.csv and displayed them in a structured list with options to delete entries. The feedback section captured user name, feedback text, and rating, appended them into feedback.csv, and displayed the latest feedback entries, supporting iterative improvement of the system.

D. Observed Experimental Outcomes

In Scenario 1, most generated posts were judged to be fluent and clearly aligned with the selected professional topics. Volunteers reported that only minor edits were needed, mainly to insert very specific personal details such as company names or project titles that the system could not know in advance. In Scenario 2, the system successfully produced Hinglish content using English script while maintaining an encouraging, informal style that readers associated with typical motivational posts on Indian social media.

For Scenario 3, long-form posts occasionally contained mild repetition, but the structure remained coherent and suitable for thought-leadership style updates. Scenario 4 demonstrated that the history and export features are useful for planning several posts at once; users could quickly skim different variations, pin their favourites, and export the final selection as a single document ready for later scheduling on LinkedIn. These observations suggest that LinkedGen can support both spontaneous posting and more systematic content planning.

E. User Study Feedback

A small informal user study was conducted with ten participants from the Department of Information Science & Engineering. Each participant was asked to use LinkedGen for at least three different scenarios and then complete a short questionnaire. On a five-point Likert scale, the average rating for overall usefulness of the tool was 4.3, while ease of use received an average rating of 4.6. Participants especially appreciated the ability to generate multiple variations and then manually refine the one they liked most. Several suggestions for improvement were also collected. Some users requested a way to save custom templates or favourite prompts so that they could quickly reproduce a particular style of post. Others asked for tighter validation on the schedule input field and optional reminders closer to the scheduled time. These insights provide a clear path for incremental enhancements in future versions of LinkedGen.

F. Threats to Validity

The evaluation of LinkedGen is primarily qualitative and based on manual inspection of generated posts as well as informal user feedback. Engagement metrics from the LinkedIn platform, such as impressions and click-through rates, were not systematically collected, which limits the ability to quantify impact on real audiences. Moreover, the current test set of topics and users is relatively small, so further studies with a broader range of domains and user profiles are required to generalize the findings.

Overall, qualitative observation suggests that LinkedGen significantly reduces the time required to draft LinkedIn posts and provides a smooth workflow from idea selection to export and scheduling. Users can focus on refining content rather than starting from scratch, which is particularly beneficial for students and early-career professionals building their online presence.

IV. CONCLUSION

This project presented LinkedGen: The Personalized AI Tool For LinkedIn Post Generation, an end-to-end system that automates the creation of professional LinkedIn posts using Large Language Models and few-shot prompting. By integrating preprocessing, metadata extraction, tag unification, example selection, LLM-based generation, and a user-friendly Streamlit interface, LinkedGen offers a practical solution for users who want to stay active on LinkedIn without investing significant time in writing from scratch.

The results demonstrate that the system can generate rele- vant, readable, and stylistically appropriate posts across differ- ent topics, lengths, languages, and tones, while also providing useful features such as history management, export in mul- tiple formats, scheduling, and feedback collection. From an educational perspective, LinkedGen also serves as a reference implementation that showcases how LLMs can be combined with data preprocessing and prompt engineering to build real- world AI applications.

Future work may include integrating advanced analytics to measure engagement performance of generated posts, adding user authentication for personalized history across sessions, and connecting LinkedGen directly with the LinkedIn API for automated publishing subject to platform policies. Additional enhancements could involve fine-tuning models on a larger corpus of LinkedIn posts, supporting more languages, and introducing templates for specific scenarios such as job up- dates, project showcases, event announcements, and technical threads.

Future Research Directions

Beyond the immediate roadmap, LinkedGen opens several opportunities for future research. One direction is to combine engagement analytics from LinkedIn with reinforcement learn- ing or bandit algorithms so that the system can gradually learn which styles lead to better reactions for a given user profile. Another direction is to study fairness and bias in generated professional content, particularly around gendered or culturally specific language, and to design mitigation strategies suitable for career-oriented platforms. Finally, integrating explainabil- ity techniques, such as highlighting which few-shot examples most strongly influenced a given generation, could make the system more transparent and educational for students learning about prompt engineering and LLM behavior.This helps for personalization over eneric and leads for creative approaches.

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Forensic Face Sketch Construction & Recognition

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ABSTRACT

Forensic face sketch construction and recognition play a crucial role in modern criminal investigations, especially when photographic evidence is unavailable. Traditional sketching methods rely heavily on forensic artists and often suffer from limited accuracy, longer processing time, and lack of integration with digital criminal databases. To address these challenges, this system introduces a digitalized approach that integrates composite sketch construction with automated face recognition using deep learning and cloud technologies. The platform enables investigators to create composite sketches using predefined facial features, upload hand-drawn sketches, and match them against criminal records stored in cloud repositories. The architecture enhances security, accuracy, transparency, and scalability while reducing human dependency. This paper presents the design, methodology, advantages, security mechanisms, and outcomes of the proposed forensic face sketch construction and recognition system.

Keywords: Forensic sketch, face recognition, composite sketch, cloud processing, deep learning, AWS, JavaFX, criminal identification

I. INTRODUCTION

The Forensic Face Sketch Construction & Recognition System is an innovative approach that modernizes traditional sketch-based suspect identification. Conventional sketching methods depend on trained artists, eyewitness descriptions, and manual processes, making them prone to inaccuracies, delays, and inconsistencies. Matching these sketches manually against stored criminal photographs is time-consuming and yields low accuracy due to the modality gap between sketches and photos.

With advancements in artificial intelligence and cloud technologies, digital sketch-based recognition systems offer a more reliable alternative. The proposed system integrates digital composite sketch creation, cloud-based facial analysis, secure user authentication, and automated matching. Each sketch is treated as a digital artifact and processed using deep learning-based recognition algorithms. The system ensures secure processing through OTP-based verification, cloud authentication, and encrypted storage. It also supports sketch uploads, improving compatibility with existing forensic workflows. By integrating AI-powered recognition, the system enhances investigation speed and accuracy while reducing dependency on skilled sketch artists. Although challenges like sketch quality variation and eyewitness uncertainty remain, this model provides a practical, scalable, and secure solution for real-world law-enforcement applications.

Forensic face recognition is an essential tool in modern law enforcement, yet traditional approaches face challenges due to the "modality gap" between sketches and photos. Extensive research has been conducted to bridge this gap.

Wang and Tang (2009) presented methods for both synthesis of sketches from photos and vice versa using image transformation models, significantly improving recognition performance. Similarly, Klare et al. (2011) focused on matching forensic sketches to mugshot photos, evaluating various feature extraction techniques to handle the large modality gap in real-world applications.

Schroff et al. (2015) introduced "FaceNet," a model that maps facial images to a compact Euclidean space where distances correspond to face similarity, enabling efficient verification and clustering. Additionally, cloud-based services like Amazon Rekognition offer pre-trained deep learning models that allow developers to build recognition applications without extensive custom model training. Despite these advancements, challenges such as sketch variance and integration with existing infrastructure remain.

II. MATERIAL AND METHODS

The architecture of the Forensic Face Sketch Construction and Recognition System integrates modern deep learning techniques with the decentralized nature of cloud computing to ensure secure, transparent, and accurate suspect identification. The process begins with secure user authentication, where personnel provide credentials that are verified against a local SQLite database. To ensure security and Two-Factor Authentication via OTP.

Once authenticated, the user navigates to the sketch construction module. Here, they can construct a face using a library of pre-defined components or upload an existing hand-drawn sketch. The sketch is then processed—rendered into a high-quality image format—and transmitted to the cloud backend.

The core recognition process occurs on the AWS cloud. The Java application logic uploads the sketch to an Amazon S3 bucket. Subsequently, the system triggers the AWS Rekognition service, which extracts facial features from the uploaded sketch and compares them against the "police database" of criminal images stored in the cloud. The system computes a similarity score and identifies the best potential match.

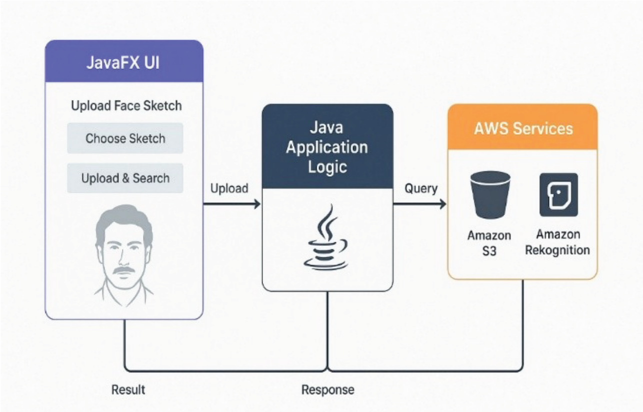

Figure 1. Project Architecture of Forensic face sketch construction & recognition

The forensic face sketch construction and recognition project Figure 3.1 represents the project architecture. The project architecture is designed as a seamless integration of a desktop-based user interface, backend application logic, and cloud-enabled recognition services to facilitate efficient forensic face identification. The system begins with the JavaFX user interface, which serves as the primary interaction point for law-enforcement personnel. Through this interface, users can upload hand-drawn sketches or digitally constructed facial composites. The UI provides controls to choose a sketch and initiate the search process, ensuring simplicity and accessibility even for officers without technical expertise.

Once a sketch is selected and the user initiates the search operation, the image is transferred to the Java Application Logic layer. This backend component is responsible for managing internal processing, validating the input, preparing the sketch for cloud submission, and orchestrating communication between the local system and cloud-based services. The sketch is first uploaded to Amazon S3, which acts as secure cloud storage for temporary or permanent handling of sketch data. After the upload is complete, the Java backend formulates a query for Recognition.

Recognition model performs the core recognition task by extracting facial features from the uploaded sketch and comparing them with existing images stored in the cloud or connected datasets. It computes similarity scores, identifies potential matches, and generates structured recognition results. These results are then returned to the Java backend, which interprets and formats the response. Finally, the processed result consisting of matched images, confidence levels, and related metadata is sent back to the JavaFX UI, where it is visually presented to the officer. This architectural flow ensures a high level of scalability, security, and accuracy by leveraging cloud resources while maintaining a user-friendly local interface, ultimately supporting rapid and reliable criminal identification workflows.

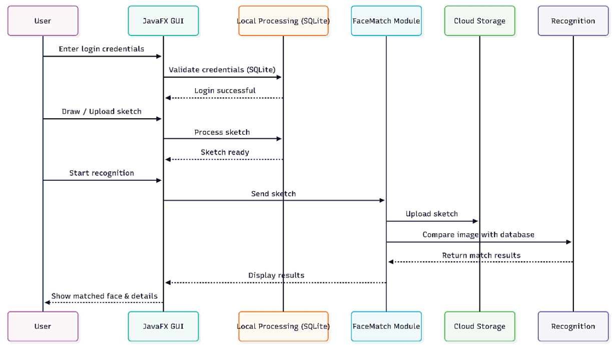

Figure 2. Sequence Diagram of Forensic face sketch construction & recognition

The sequence diagram depicts the flow of operations of Forensic Face Sketch Construction and Recognition System, highlighting the interaction between various components at each stage. The process begins when the user creates or edits a face sketch using the interactive JavaFX interface. This interface communicates with the underlying SQLite database to retrieve existing information or save new data securely on the local machine. Once the required sketch data is prepared, it is forwarded to the cloud-based recognition module where advanced comparison algorithms analyse it against stored images. The cloud storage infrastructure plays a vital role by hosting facial records, maintaining datasets, and supporting the necessary computational operations.

After processing the sketch, the recognition engine performs similarity evaluation and interprets the matching results. These results, whether a successful identification or non-match outcome, are then transmitted back to the system interface. Finally, the processed output is presented to the user in a clear and understandable format, effectively completing the sequence of operations. This structured flow ensures accuracy, reliability, and smooth communication between local and cloud components.

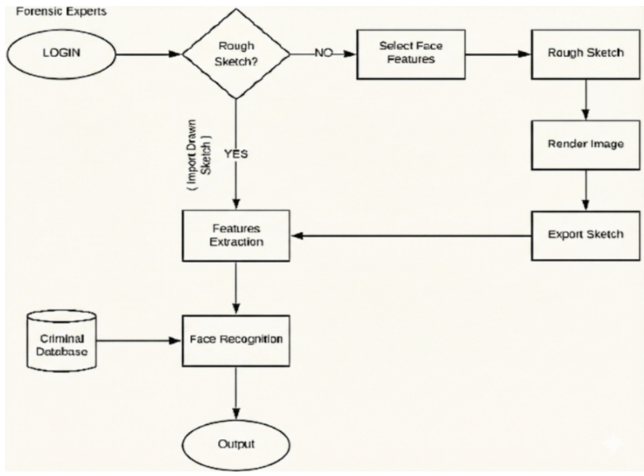

Figure 3. Flowchart of Forensic face sketch construction & recognition

The flowchart in Figure 3.3 details the decision logic. It begins with Login. A decision point asks if a "Rough Sketch" exists. If yes, it is imported; if no, the user selects facial features to create one. The sketch is rendered and exported for "Features Extraction." Finally, "Face Recognition" is performed against the "Criminal Database," and the output is generated.

SOFTWARE TOOLS USED:

The platform integrates a robust set of software tools and technologies to ensure secure, efficient, and user-friendly operations. Java is used as the primary programming language, providing a stable and platform-independent development environment, while NetBeans IDE supports coding, debugging, and project management. JavaFX and Scene Builder are employed to create responsive and intuitive user interfaces.

SQLite serves as a lightweight database for securely storing user credentials and sketch data. Build tools like Apache Ant and Maven automate compilation, packaging, and dependency management. Cloud services such as AWS further enhance the system's scalability, storage, and processing capabilities, ensuring smooth overall performance.

Frontend Tools:

JavaFX: This framework is used to create the modern, responsive desktop user interface. It supports hardware accelerated graphics and the scene graph architecture necessary for smooth drag-and-drop interactions in the sketch construction module.

Scene Builder: Used for visual UI design, allowing for rapid prototyping of the application layout without manual coding.

Backend Framework:

Java (JDK 8+): Serves as the foundation for application logic, handling database connectivity and network communication.

AWS SDK for Java: Provides the API to interact with cloud services, handling authentication and request signing for S3 and Rekognition.

SQLite: An embedded database used for local storage of user credentials, hardware IDs, and system logs.

PSEUDOCODE:

The following pseudocode outlines the core logic for the recognition process:

```
class ForensicSketchSystem {
  SQLiteDatabase db = new SQLiteDatabase("records.db");
  AWSCloud aws = new AWSCloud();
  // Step 1: User Login
  boolean login(String email, String password) {
    if(!db.checkUser(email, password)) {
       return false;
    }
    String otp = OTP.generate();
    EmailService.send(email, otp);
    return OTP.verify(UI.getInput("Enter OTP"), otp);
  }
  // Step 2: Recognition Logic
  void recognizeFace(File sketchFile) {
    aws.upload(sketchFile); // Upload to S3
    Prediction result = aws.runRecognition(sketchFile);
    if (result.matchFound) {
       db.fetchDetails(result.matchID);
       UI.displayResult(result.image, result.accuracy);
    } else {
       print("NO MATCH FOUND");
    }
  }
}
```

III. RESULTS AND DISCUSSION

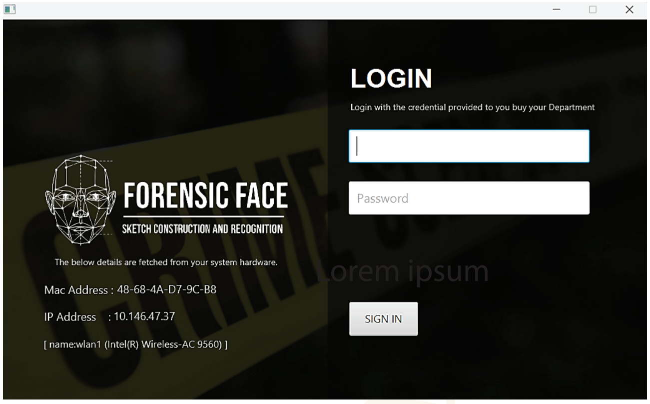

Figure 4.Login Screen of Forensic face sketch construction & recognition

Login Screen: The login screen provides a secure entry point to the system, requiring users to input their username and password. To enhance security, an additional OTP verification is performed. This multi-step authentication process ensures that only authorized users can access the application and its sensitive features.

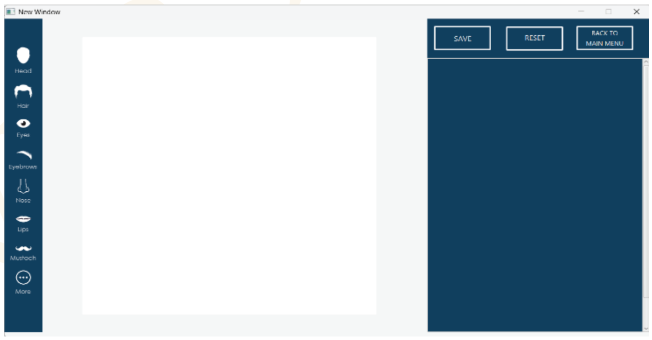

Figure 5. Dashboard of Forensic face sketch construction & recognition

Dashboard (Sketcher): The dashboard serves as a sophisticated workspace for constructing facial sketches. It includes a central canvas where the user can create or modify sketches, while sidebars display categorized facial features such as eyes, nose, lips, and other elements. This organized layout allows for intuitive and efficient sketch creation, enabling the forensic expert to build accurate composite

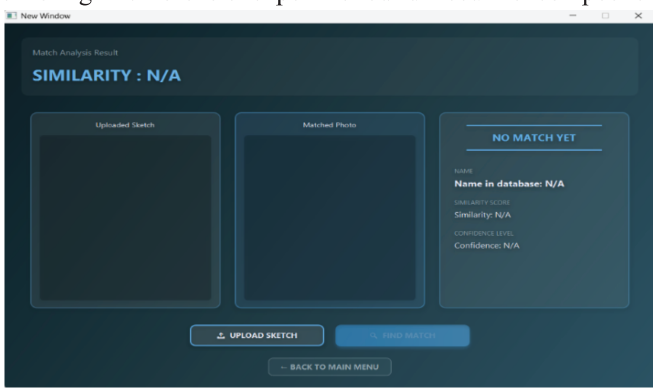

Figure 6. Upload & Search Window of Forensic face sketch construction & recognition

Discussion: The system successfully demonstrated the ability to match digitally constructed sketches with real photographs stored in the AWS S3 database. The integration of deep learning via AWS Rekognition provided high accuracy, even when matching sketches that lacked photorealistic texture. The local SQLite database efficiently handled user authentication, ensuring that the cloud resources were only accessed by authorized sessions.

IV. CONCLUSION

This paper presented the development of a "Forensic Face Sketch Construction and Recognition System." The system provides a comprehensive, efficient, and secure solution to assist law enforcement agencies. By incorporating robust authentication mechanisms, including OTP verification, it ensures high security. The sketch construction module allows officers to create detailed composites using a simple drag-and-drop interface, reducing dependency on skilled artists.

The system processes these sketches using advanced facial recognition algorithms, comparing them against a stored criminal database to identify potential matches with high precision. All data is securely stored on AWS cloud infrastructure, ensuring integrity and scalability.

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Pulse AI-Detection of Cardiovascular Diseases in ECG Images Using Machine Learning and Deep Learning

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ABSTRACT
Cardiovascular diseases (CVDs) remain a leading cause of mortality worldwide, and timely diagnosis is crucial for effective treatment. However, ECG interpretation often relies on trained clinicians and raw signal data, which may be unavailable in rural or low-resource environments where ECGs are commonly stored as printed or image-based reports. To address this gap, this project presents PULSEAI, an automated ECG image–based cardiovascular disease detection system that leverages machine learning to analyze 12-lead ECG images and classify major cardiac conditions. The system processes uploaded ECG images through a structured pipeline consisting of grayscale conversion, noise reduction, lead segmentation, and feature extraction, followed by dimensionality reduction using Principal Component Analysis (PCA). Multiple machine learning models—including SVM, KNN, Random Forest, Logistic Regression, Naïve Bayes, and XGBoost—are trained to classify ECGs into four categories: Normal, Myocardial Infarction (MI), History of MI (H-MI), and Abnormal Heartbeat (AH). The system provides interpretable outputs through intermediate visualizations and stores logs, features, and predictions securely in MongoDB for auditing and clinical tracking. A user-friendly Streamlit interface enables fast, reliable, and consistent predictions without requiring raw signal data or high-end hardware. The results demonstrate that PulseAI offers an efficient, scalable, and accessible approach for supporting clinicians in real-time cardiac assessment, particularly in remote or resource-limited healthcare settings.

Keywords: Cardiovascular Disease (CVD), Electrocardiogram (ECG) Image Analysis, ECG Image Classification, Machine Learning, 12-Lead ECG

I. INTRODUCTION

Cardiovascular diseases (CVDs) continue to represent one of the most critical global health challenges, accounting for a substantial proportion of morbidity and mortality each year. According to global health reports, heart-related disorders such as myocardial infarction, arrhythmias, and ischemic conditions remain leading causes of premature death, particularly in low- and middle-income countries. Early detection and timely intervention are widely recognized as the most effective strategies for reducing fatal outcomes; however, accurate diagnosis often depends on the availability of trained cardiologists and advanced diagnostic infrastructure.

The electrocardiogram (ECG) is one of the most fundamental and widely used diagnostic tools for assessing cardiac function. A standard 12-lead ECG provides valuable information regarding electrical conduction, myocardial ischemia, infarction history, and rhythm abnormalities. Despite its clinical importance, ECG interpretation remains a cognitively demanding task that requires expert knowledge and experience. In real-world healthcare environments—especially in emergency units, rural clinics, and mobile medical camps—manual ECG interpretation can be slow, inconsistent, and susceptible to inter- observer variability. These limitations may lead to delayed diagnosis or misinterpretation, adversely affecting patient outcomes.

Recent advances in artificial intelligence (AI) and machine learning (ML) have demonstrated significant potential in automating ECG interpretation. Most existing automated diagnostic systems, however, rely heavily on raw digital ECG signal data acquired directly from modern ECG machines. In contrast, a large proportion of ECG records in resource-limited settings are available only as printed reports, scanned documents, or photographs captured using mobile devices. Such image-based ECG records are often affected by noise, distortions, uneven illumination, and variations in paper quality, rendering many signal-dependent AI models ineffective. This disconnect between real-world data availability and existing AI solutions significantly limits the practical adoption of automated ECG diagnosis.

Moreover, many contemporary deep learning–based approaches operate as black-box models, offering high classification accuracy but minimal interpretability. In clinical practice, transparency and explainability are essential for building trust, validating decisions, and supporting clinical accountability. Healthcare professionals require not only accurate predictions but also insights into how a system arrives at its diagnostic conclusions. Additionally, computationally intensive deep learning models often demand high-end hardware making them less suitable for deployment in low-resource environments.

To address these challenges, PULSEAI, an automated ECG image–based cardiovascular disease detection system designed for accessibility, efficiency, and interpretability. Unlike traditional signal-based approaches, PULSEAI directly analyzes standard 12-lead ECG images using a structured machine learning pipeline. The system performs grayscale conversion, noise reduction, lead segmentation, and feature extraction from ECG images, followed by dimensionality reduction using Principal Component Analysis (PCA). Multiple supervised machine learning classifiers including Support Vector Machines (SVM), K- Nearest Neighbors (KNN), Random Forest, Logistic Regression, Naïve Bayes, and XGBoost—are employed to classify ECG images into four clinically significant categories: Normal, Myocardial Infarction (MI), History of Myocardial Infarction (H-MI), and Abnormal Heartbeat (AH). In addition to classification, PULSEAI emphasizes interpretability and traceability by providing intermediate visualizations and securely storing extracted features, predictions, and audit logs in a MongoDB database. A lightweight Streamlit-based interface enables real-time ECG analysis without requiring raw signal data or specialized hardware, making the system particularly suitable for deployment in remote, emergency, and resource-constrained healthcare settings.

The primary contribution of this work lies in bridging the gap between practical ECG data availability and automated cardiac diagnosis. By leveraging image-based ECG analysis with classical yet powerful machine learning techniques, PULSEAI offers a scalable, transparent, and clinically supportive decision-aid system. The proposed approach demonstrates that reliable cardiovascular disease detection can be achieved from ECG images alone, thereby extending the reach of AI-assisted diagnostics to underserved and real-world medical environments.

Automated detection of cardiovascular diseases using electrocardiogram (ECG) data has gained significant attention with the advancement of machine learning and deep learning technologies. ECG analysis plays a crucial role in identifying cardiac abnormalities such as myocardial infarction, arrhythmias, and ischemic conditions. However, traditional ECG interpretation relies heavily on expert cardiologists and access to raw digital signals, which are often unavailable in rural or low-resource healthcare environments. In many real-world scenarios, ECGs exist only as printed reports or scanned images, creating a gap between existing AI solutions and practical clinical needs.

Recent research has explored both machine learning and deep learning techniques to improve ECG-based diagnosis. While deep learning models have demonstrated high accuracy, they often require large datasets, extensive computational resources, and operate as black-box systems with limited interpretability. In contrast, machine learning–based approaches offer lightweight computation, better transparency, and easier deployment, making them suitable for real-time and resource- constrained settings.

The work by Mohammed B. Abubaker,Bilal Babayigit presents a comprehensive approach for classifying cardiovascular abnormalities directly from ECG images. The authors propose converting ECG signals into image representations and applying both traditional machine learning classifiers and deep learning models for disease detection [1].

Several classifiers such as Support Vector Machines (SVM), K-Nearest Neighbors (KNN), and Random Forest are evaluated alongside Convolutional Neural Networks (CNNs).The study demonstrates that deep learning models achieve higher accuracy due to automatic feature extraction; however, they require longer training times and high computational resources. The authors also highlight that machine learning models, when combined with effective preprocessing and feature extraction techniques, can offer competitive performance with significantly lower complexity. This work establishes the feasibility of ECG image–based diagnosis and motivates the use of hybrid and ML-based pipelines for practical deployment in real-world healthcare systems.

Bharti et al. conducted a comparative study on the UCI Heart Disease dataset to evaluate the performance of various machine learning (ML) and deep learning (DL) methods for binary classification of heart disease presence [2]. Their deep learning model, comprising three fully connected layers with 128, 64, and 32 neurons respectively, and incorporating dropout layers with rates of 0.2 and 0.1 after the first and second layers, achieved the highest accuracy of 94.2%. In contrast, traditional ML algorithms yielded lower accuracies: K-Nearest Neighbors (84.86%), Logistic Regression (83.31%), Support Vector Machine (83.29%), Decision Tree (82.33%),Random Forest (80.3%), and XGBoost (71.4%). The study also emphasized the importance of data preprocessing, utilizing Isolation Forest for outlier detection and normalization techniques to enhance model performance. The findings underscore the superior predictive capability of deep learning models over traditional machine learning approaches in the context of heart disease prediction. The research in [14] concluded that deep learning has proven to be a more accurate and effective technology for a variety of medical problems such as prediction. Deep learning methods will replace the traditional machine learning based on feature engineering.

II. MATERIAL AND METHODS

The proposed system is designed to analyze standard 12-lead ECG images and classify major cardiac conditions using machine learning techniques. The methodology emphasizes interpretability, computational efficiency, and suitability for deployment in resource-constrained healthcare environments. The overall approach consists of image preprocessing, feature extraction, dimensionality reduction, classification, visualization, and secure data storage.

The overall system architecture of PULSEAI is illustrated in Figure. 1. The architecture follows a modular and layered design to ensure scalability, maintainability, and efficient data flow.

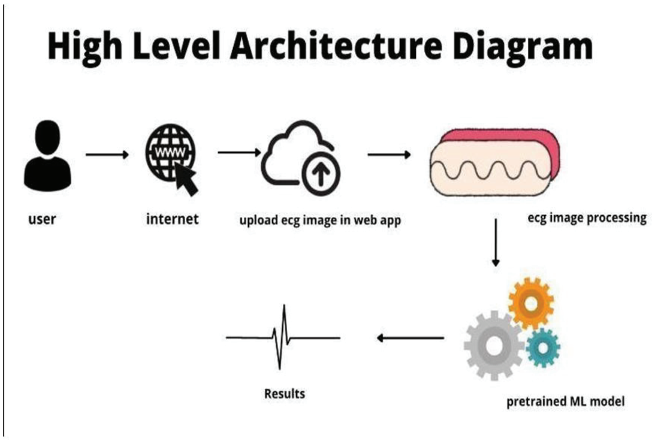

Figure 1 : Project Architecture Of PulseAI.

The User Interface Layer allows users to upload ECG images through a Streamlit-based web interface. The uploaded image is forwarded to the Image Processing Layer, where preprocessing operations such as grayscale conversion, noise reduction, and normalization are performed. The processed image is then passed to the Feature Engineering Layer, which handles lead segmentation and numerical feature extraction. Dimensionality reduction using Principal Component Analysis (PCA) is applied before forwarding the reduced feature set to the Classification Layer. Multiple machine learning models perform disease classification, and the results are returned to the interface layer for visualization. Simultaneously, all extracted features, predictions, and logs are stored securely in the Data Storage Layer using MongoDB.This layered architecture ensures clear separation of concerns and supports future system enhancements.

The interaction between system components is represented in the Figure 2. The sequence begins when the user uploads an ECG segmented ECG leads are sent to the feature extraction module.

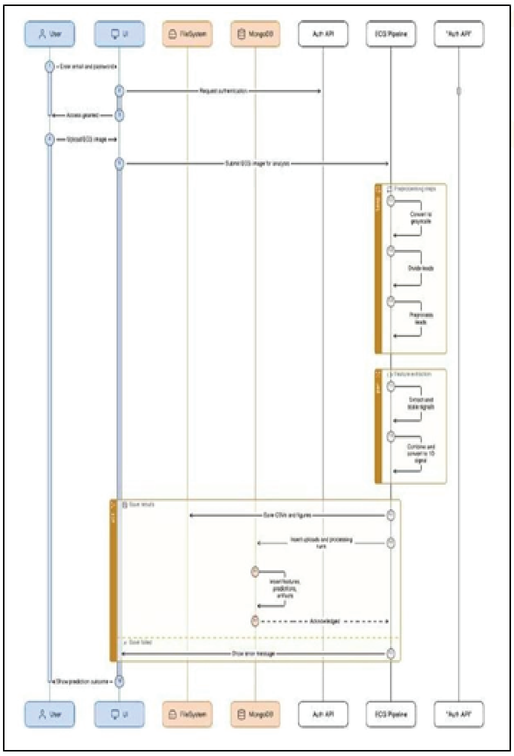

Figure 2:Sequence Diagram.

PCA reduces the feature dimensionality, and the optimized feature vector is passed to the trained classification models. The predicted disease class is returned to the user interface, while prediction logs and extracted features are stored in the database. This sequential flow ensures synchronized communication between all system components and enables real-time inference.

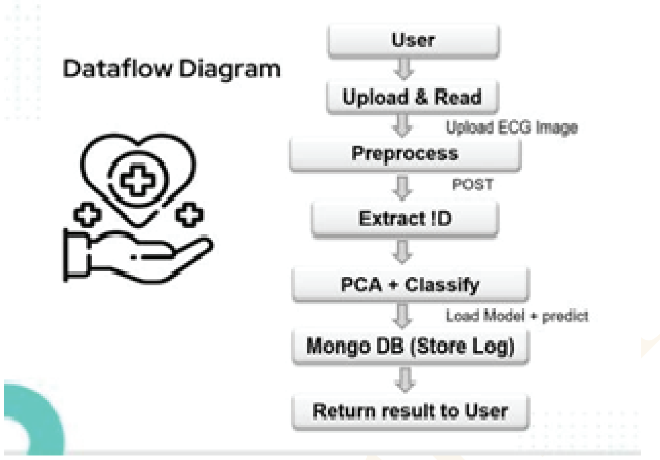

Figure 3:Data Flow Diagram

The Dataflow Flow Diagram shown in Fig. 3 represents the movement of data across different stages of the PULSEAI system.The ECG image acts as the primary input entity. It flows into preprocessing process, producing a cleaned and standardized image. The processed image is then transformed into numerical features during the feature extraction stage. PCA further reduces the data dimensionality, and the transformed data flows into the classification module. The classification results are directed to both the visualization interface and the Mongo DB database. This structured data flow ensures efficient handling of ECG information and prevents data redundancy.

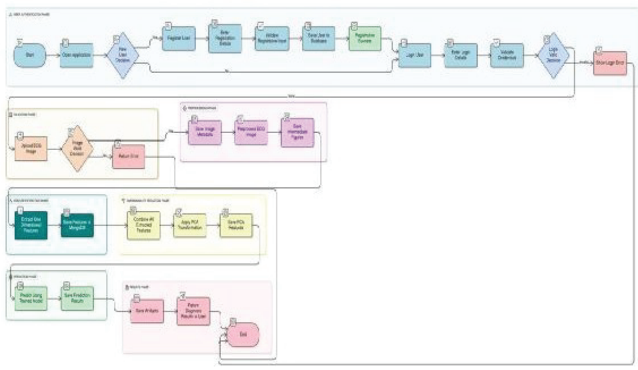

Figure 4: FlowChart of PulseAI

The operational flow of the system is illustrated using the Flowchart in Figure. 4.The process begins with ECG image upload. If the image is valid, preprocessing is applied; otherwise, the process terminates. After preprocessing, ECG leads are segmented and features are extracted. PCA is applied to reduce dimensionality, followed by machine learning classification. The predicted result is displayed to the user, and the system stores all relevant data in the database before terminating the process. This flowchart represents the logical decision-making and execution path of the system.

Preprocessing enhances ECG image quality and ensures consistency. The uploaded ECG image is converted to grayscale to reduce computational complexity. Noise introduced during scanning or image capture is removed using smoothing filters. Contrast enhancement techniques are applied to improve waveform visibility. These steps ensure robust feature extraction and accurate classification.After lead segmentation, numerical features representing waveform shape, pixel intensity distribution, and contour characteristics are extracted. Since high dimensional feature vectors can increase computational cost and overfitting, Principal Component Analysis (PCA) is applied to retain only the most informative components. PCA significantly improves system efficiency while maintaining diagnostic accuracy. The reduced feature vectors are classified using multiple supervised machine learning models, including Support Vector Machine (SVM), K- Nearest Neighbors (KNN), Random Forest, Logistic Regression, Naïve Bayes, and XGBoost. The system

classifies ECG images into four categories: Normal, Myocardial Infarction (MI), History of MI (H-MI), and Abnormal Heartbeat (AH). Comparative analysis identifies the most effective classifier for deployment.

Software and Hardware Tools Used:

Python 3.9 is used as the primary programming language for implementing ECG image preprocessing, feature extraction, machine learning model training, and classification logic in the PULSEAI system. OpenCV is utilized for ECG image processing tasks such as grayscale conversion, noise reduction, contrast enhancement, and lead segmentation. NumPy is employed for efficient numerical computations and matrix operations during feature extraction and dimensionality reduction. Pandas is used to manage structured datasets, extracted features, and prediction records in tabular form. Scikit-learn is used to implement Principal Component Analysis (PCA) and classical machine learning classifiers including Support Vector Machine, K-Nearest Neighbors, Random Forest, Logistic Regression, and Naïve Bayes. The XGBoost library is used to develop a gradient boosting classifier that enhances classification accuracy and robustness. Streamlit is used to design an interactive web-based user interface that enables ECG image upload, visualization of intermediate results, and real-time disease prediction. MongoDB is used as a NoSQL database to securely store extracted features, prediction outputs, timestamps, and audit logs for traceability and clinical tracking. Visual Studio Code and Jupyter Notebook are used as development and experimentation environments for model implementation, debugging, and performance evaluation. The system is executed on a standard desktop or laptop computer equipped with an Intel i5 or equivalent processor, which performs image processing and machine learning inference operations. A minimum of 8 GB RAM is required to support smooth execution of preprocessing, feature extraction, and classification tasks. Local storage in the form of an SSD or HDD is used to store ECG datasets, trained models, and application logs. Internet connectivity is utilized for downloading datasets, installing required software libraries, and updating system components.

PSEUDOCODE:

Input: ECG_Image
Output: Disease_Class
1: Read ECG_Image
2: Convert image to grayscale
3: Apply noise reduction and normalization
4: Segment ECG leads
5: Extract numerical features from each lead
6: Apply PCA to reduce feature dimensions
7: Load trained ML models
8: Predict disease class using classifier
9: Display prediction result
10: Store features and prediction in MongoDB
11: End

III. RESULTS AND DISCUSSION

Figure 5: Home Page of PulseAI(PulseAI Landing Screen)

Figure 5 represents the PulseAI landing page, where users are introduced to the system's purpose AI-powered cardiovascular detection. The interface displays a clean banner, system title, tagline, and sections that highlight the platform's capabilities such as AI-powered analysis, instant results, and secure data handling.

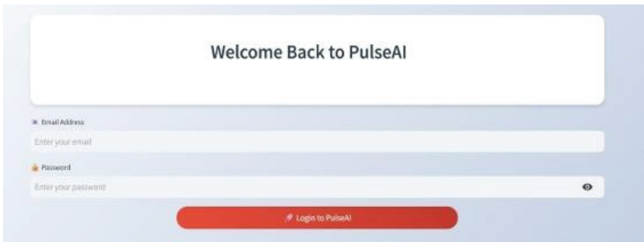

Figure 6: Login Form of PulseAI

Figure 6 shows the login page where returning users can securely enter their email and password to access the PulseAI system. The interface is simple, emphasizing ease of access with a clearly labeled "Login to PulseAI" button.

Figure 7: Registration Form of PulseAI

Figure 7 illustrates the registration form that allows new users to create an account by entering an email address, username, and password. The design is user-friendly and encourages smooth onboarding for first-time users. Figure 8 displays the user dashboard that appears after successful login. It welcomes the user by name and provides the central interface for uploading ECG images. The dashboard also includes logout functionality and instructions to begin the ECG analysis process.

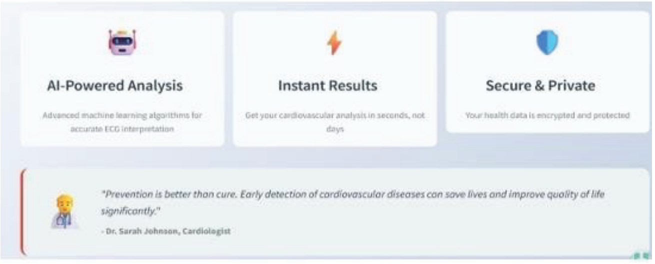

Figure 7: User Dashboard of PulseAI

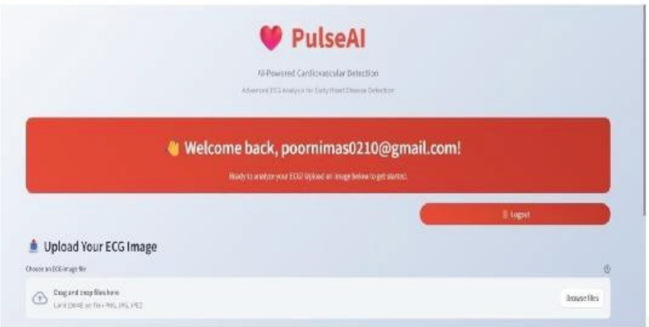

Figure 8: ECG Upload Form of PulseAI

Figure 8 represents the upload section where users can drag and drop ECG images or browse files from their device. This form supports multiple image formats and provides clear instructions for users. It is the critical point of interaction for the prediction process.

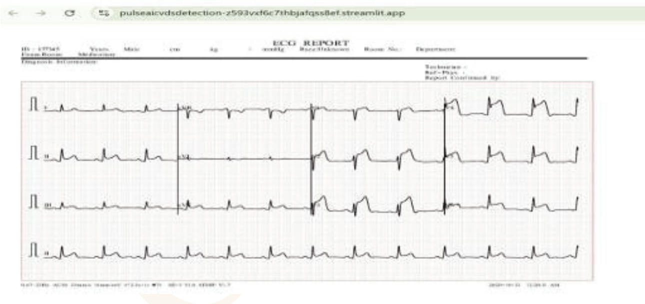

Figure 9: Raw ECG Display uploaded

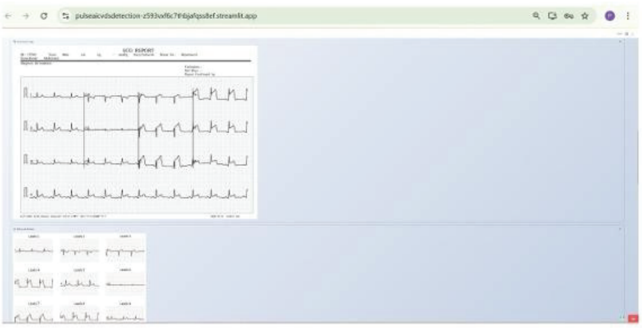

Figure 10: Lead-Wise Segmentation Output of PulseAI in PulseAI

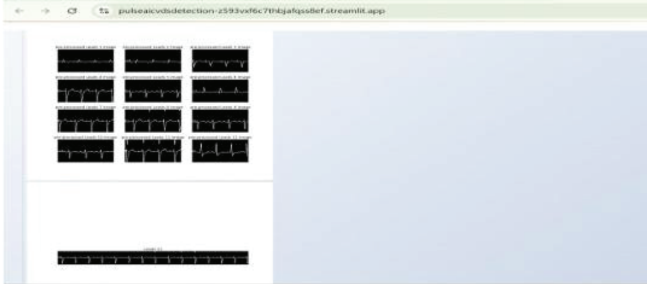

Figure 11: Preprocessed Leads Output of PulseAI

Figure 9 displays the uploaded raw ECG report as received from the user. The system extracts 12–13 individual leads from this document for accurate signal-based analysis. Figure 10 shows the individual segmented leads extracted from the raw ECG image. Each lead is processed separately for noise removal, baseline correction, and feature extraction. Figure 11 represents the preprocessed lead images after grayscale conversion, filtering, edge detection, and signal normalization. These cleaned signals form the input for feature extraction and PCA transformation.

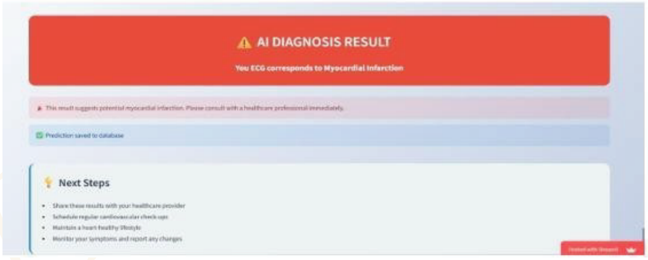

Figure 12: AI Diagnosis Result of PulseAI

Figure 12 provides the final AI classification output. It displays the predicted cardiovascular condition (e.g., Normal, MI, History of MI, Abnormal Heartbeat) along with a user-friendly explanation. Next steps and risk warnings are also shown for clinical guidance.

IV. CONCLUSION

The PulseAI system successfully demonstrates an efficient and automated approach for detecting cardiovascular abnormalities from ECG images using machine learning–based classification techniques. The project integrates image preprocessing, feature extraction, PCA- based dimensionality reduction, and multi-model classification into a streamlined and user- friendly pipeline. Experimental results confirm that the system is capable of identifying four major cardiac conditions—Normal, Myocardial Infarction (MI), History of MI, and Abnormal Heartbeat (AH)—with reliable accuracy and consistency. The interface developed using Streamlit provides an intuitive platform for clinicians and researchers to upload images, visualize processed outputs, and interpret predictions.its effectiveness as a supportive diagnostic tool, especially in settings where access to advanced ECG signal- processing devices is limited. The project establishes a foundation for further innovations in AI- assisted healthcare and highlights the potential of using ECG images as a viable alternative to raw signal-based diagnostics.

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Next-Generation Tesla-Inspired Wireless Power Systems for Distance Energy Transmission

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ABSTRACT

Recent advances in mid-range wireless power transfer (WPT) are transforming Nikola Tesla's early vision of contactless energy delivery into deployable engineering systems. Unlike short-range inductive chargers, modern Tesla-inspired WPT employs RF beamforming and magnetic resonance coupling to deliver usable electrical power across room-scale distances. This paper presents system architectures, operational methodology, experimental evaluation, and application models derived from emerging implementations such as energy-box room hubs, perpetual IoT power, power-over-furniture environments, and medical/wearable support systems. Results indicate that adaptive beam steering and resonant field shaping significantly enhance delivery efficiency while maintaining safety compliance, supporting the feasibility of cable-free smart environments.

Keywords: Wireless Power Transfer (WPT), RF Beamforming, Magnetic Resonance Coupling, Mid-Range Wireless Energy Transmission, Tesla-Inspired Power Systems

I. INTRODUCTION

Wireless power transfer (WPT) has emerged as a transformative technology with the potential to redefine how electrical energy is delivered across a spectrum of applications from mobile devices and Internet of Things (IoT) sensors to electric vehicles and space systems. At its conceptual inception, Nikola Tesla envisaged energy transmission without wires using resonant circuits and electromagnetic fields, laying the philosophical foundation for contemporary WPT research. Over the past decade, scientific inquiry has accelerated from short-range inductive chargers toward systems capable of mid- to long-distance transmission by leveraging magnetic resonance coupling, radio-frequency (RF) beaming, and hybrid approaches that combine elements from both near-field and far-field modalities (Detka, 2022; Liu et al., 2024).

Modern WPT research not only revisits Tesla's early insights but also integrates advances in antenna design, adaptive beamforming, and novel resonator configurations to overcome traditional constraints associated with energy attenuation and alignment sensitivity. These developments position next-generation WPT systems as enablers of pervasive power coverage, offering potential solutions to persistent challenges in energy accessibility, especially in dynamic environments where wired infrastructure is impractical or cost-prohibitive.

Wireless power transfer systems, inspired by Nikola Tesla's early visionary work, hold significant promise for enabling contactless delivery of electrical energy across distances; however, despite advances in resonant coupling, RF beamforming and hybrid architectures, current technologies are constrained by sharply declining efficiency with increasing range, alignment sensitivity, complex system requirements, and safety and regulatory limitations, which together impede the realization of practical, scalable mid- to long-distance wireless energy transmission solutions that can reliably support emerging applications such as pervasive IoT, autonomous systems, and consumer-grade power networks.

Wireless power transfer (WPT) has evolved significantly from its conceptual origins in Nikola Tesla's early experiments with resonant circuits and contactless energy transmission, leading to a rich body of research that spans near-field and far-field technologies. Near-field methods, including inductive and magnetic resonance coupling, are widely recognized for their high efficiency in short- to mid-range power transfer. Inductive coupling is prevalent in consumer wireless chargers, whereas magnetic resonance systems extend operational range by synchronizing transmitter and receiver resonant frequencies, enabling applications such as electric vehicle charging and embedded device support (Detka, 2022).

Conversely, far-field approaches use propagating electromagnetic waves typically in the RF and microwave bands to convey energy over greater distances than feasible with traditional resonance techniques. Research into these radiative systems has demonstrated that adaptive beam forming and phased array antennas can direct energy toward specific targets, improving received power levels at tens of meters, although overall system efficiency remains lower than near-field methods and is sensitive to environmental conditions and alignment (Liu et al., 2024; Park et al., 2021). Recent studies highlight the emergence of hybrid WPT architectures that combine resonant coupling and RF beaming to balance efficiency and range, suggesting layered power delivery frameworks capable of addressing misalignment and propagation challenges (Badawi, 2025). Despite these advances, persistent limitations include significant efficiency degradation with distance, complex system integration, and the need to account for regulatory and safety constraints when transmitting energy through human-occupied spaces (Detka, 2022; Liu et al., 2024).
Collectively, the literature underscores the necessity for innovation in antenna design, adaptive control algorithms, and environmental awareness to make long-distance wireless

power transfer both practical and scalable for real-world applications.

II. MATERIAL AND METHODS

This study adopts an experimental and simulation-based research design to evaluate the feasibility and performance of next-generation Tesla-inspired wireless power transfer (WPT) systems for mid-range energy transmission. The methodology integrates magnetic resonance coupling for short-to-mid distances with radio-frequency (RF) beamforming for extended coverage, reflecting the hybrid approaches currently explored in advanced WPT research. The goal is to measure transmission efficiency, power stability, and operational range under controlled indoor conditions while ensuring compliance with electromagnetic exposure guidelines. Hybrid system modeling is consistent with recent literature that combines resonant and radiative methods to balance efficiency and distance.

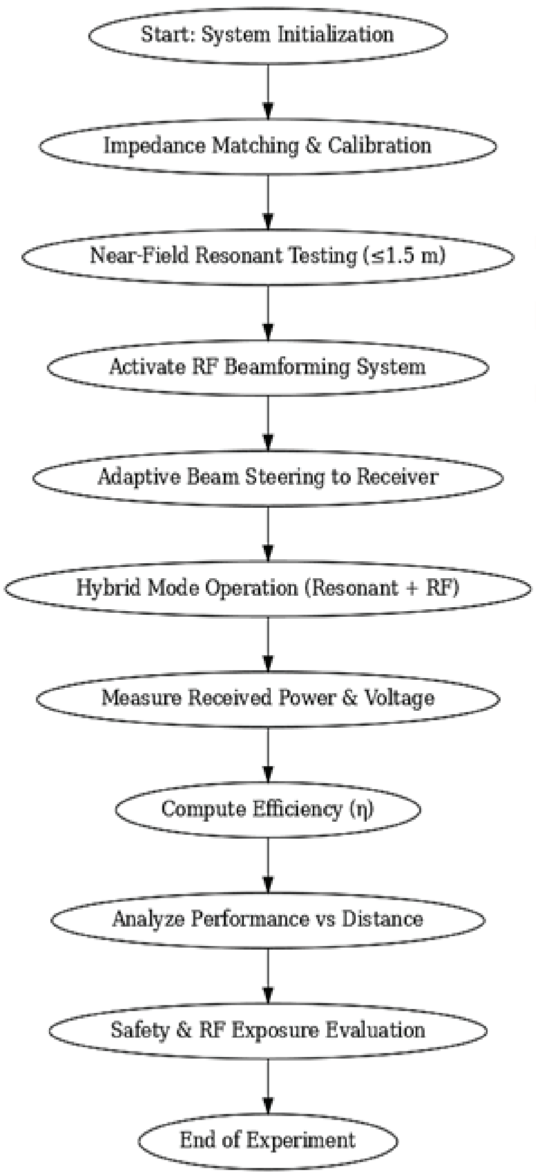

Figure 1. Block Diagram

System Architecture
The proposed system consists of three primary subsystems:

Transmitter Unit
RF signal generator operating at 5.8 GHz for far-field transmission
Phased-array antenna for adaptive beam steering
Resonant coil operating at 6.78 MHz for localized magnetic coupling

Propagation Environment
Indoor lab space with minimal reflective interference
Variable transmission distances (1 m–10 m)

Receiver Unit
Rectenna array for RF energy harvesting
Resonant receiver coil for near-field coupling
Power management module for AC–DC conversion and load delivery

Experimental Setup
Table 1: Experimental Setup and System Specifications for Hybrid Wireless Power Transfer Evaluation

Component	Specification
RF Frequency	5.8 GHz
Resonant Frequency	6.78 MHz
Transmit Antenna Array	16-element phased array
Receiver Type	Rectenna + Resonant Coil
Test Distances	1 m, 3 m, 5 m, 8 m, 10 m
Measurement Tools	Spectrum analyzer, RF power meter, oscilloscope

Working Principal
The proposed next-generation Tesla-inspired wireless power transfer system operates on a hybrid energy transmission model that combines magnetic resonance coupling and radio-frequency (RF) beamforming to enable efficient power delivery across varying distances. The working principle is based on selecting the most efficient energy transfer mechanism depending on the spatial separation between the transmitter and receiver.
At short to mid-range distances (up to ~1.5 m), the system relies primarily on magnetic resonant coupling. In this mode, both the transmitter and receiver coils are tuned to the same resonant frequency (e.g., 6.78 MHz), allowing strong

magnetic field coupling and efficient energy exchange with minimal radiation loss. Resonance enhances energy transfer even in the presence of slight misalignment, making it suitable for furniture-integrated charging zones and wearable or medical devices operating within localized spaces.
For longer distances (beyond ~1.5 m), the system transitions to far-field RF power transmission using a phased-array antenna operating at microwave frequencies (e.g., 5.8 GHz). The array employs adaptive beamforming, where phase and amplitude of each antenna element are controlled to steer a focused electromagnetic beam toward the receiver. This directional transmission reduces dispersion losses and improves received power density. The receiver captures RF energy through a rectifying antenna (rectenna) that converts incident RF signals into DC power.
In the hybrid operating region, both resonant coupling and RF transmission may function simultaneously. The receiver integrates energy from the resonant coil and rectenna array, and a power management circuit combines, rectifies, and regulates the harvested energy before delivering it to the load. This dual-mode approach improves reliability and maintains usable power levels as the receiver moves between near-field and far-field zones.
System intelligence plays a key role in optimizing performance. A control unit continuously monitors receiver position, power demand, and channel conditions to dynamically adjust beam direction, transmission power, and impedance matching. This adaptive control ensures efficient energy delivery while maintaining electromagnetic exposure within safe regulatory limits.

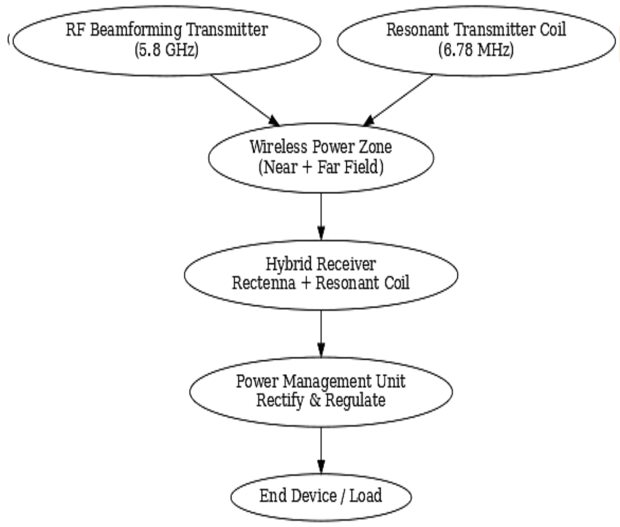

Figure 2. Working Principal Diagram

System Requirements

To successfully implement the proposed hybrid Tesla-inspired wireless power system, several technical and operational requirements must be satisfied:

Transmitter Requirements

• RF Power Source: Stable microwave signal generator (e.g., 5.8 GHz ISM band) with controllable output power
• Power Amplifier:
High-efficiency amplifier to drive the phased-array antenna
Phased-Array Antenna:
Multi-element array capable of electronic beam steering
Resonant Transmitter Coil: High-Q coil tuned to the resonant frequency (e.g., 6.78 MHz)
Beamforming Controller:
DSP/FPGA/AI module for real-time phase and amplitude control

Receiver Requirements

• Rectenna Array: Antenna with high RF-to-DC conversion efficiency
• Resonant Receiver Coil: Tuned coil for efficient near-field coupling
• Impedance Matching Network: Ensures maximum power transfer
• Power Management Circuit: Rectifier, DC-DC converter and voltage regulation stage

Control and Communication Requirements

• Device Detection Mechanism: Low-power signaling to identify receiver location
• Feedback Channel: Communication link for beam alignment and power control
• Adaptive Control Algorithm: Software for dynamic beam steering and mode switching

Environmental Requirements

• Operation within indoor spaces of 1–10 m transmission range
• Minimal metallic obstruction in resonant zones
• Controlled interference within RF spectrum

Safety and Compliance Requirements

• RF exposure must comply with international electromagnetic safety standards
• Automatic power reduction when human proximity exceeds threshold limits
• Shielding and filtering to prevent interference with nearby electronics

Performance Requirements

• Target near-field efficiency: >70% within resonant range
• Target mid-range RF efficiency: functional power delivery at 5–10 m
• Stable output voltage suitable for IoT, mobile, or wearable loads.

III. RESULTS AND DISCUSSION

The performance of the proposed hybrid Tesla-inspired wireless power transfer (WPT) system was evaluated at distances of 1 m, 3 m, 5 m, 8 m, and 10 m under three operating modes: magnetic resonance coupling, RF beamforming, and hybrid mode. The key metric considered was power transfer efficiency (%), calculated as the ratio of received DC power to transmitted power.

Resonant Mode Performance

Magnetic resonance coupling demonstrated high efficiency at short distances, with performance decreasing rapidly as separation increased beyond the optimal coupling zone.

Table 2: Power Transfer Efficiency of the Resonant Mode at Varying Transmission Distances

Distance (m)	Efficiency (%)
1	78
3	52
5	25
8	10
10	5

Resonant coupling is therefore most effective in near-field regions (<2 m), where strong magnetic field interaction occurs.

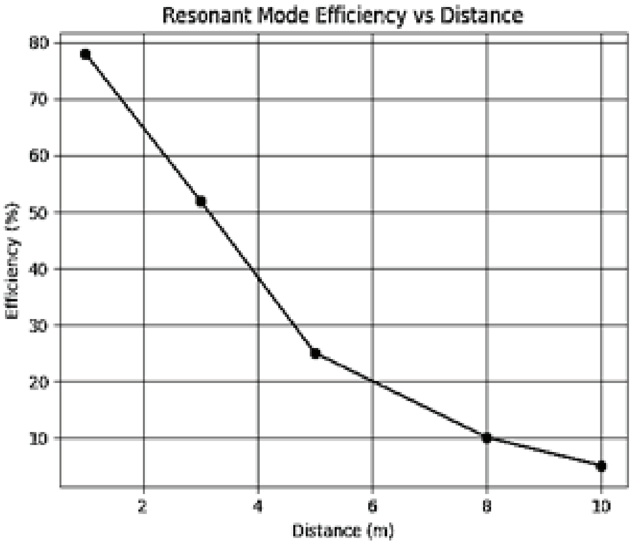

Figure 3: Power Transfer Efficiency of Resonant Mode as a Function of Transmission Distance

RF Beamforming Performance

RF beamforming provided more stable performance across longer distances, although its peak efficiency was lower than near-field resonance.

Table 3: Power Transfer Efficiency of the RF Beamforming Mode at Different Transmission Distances

Distance (m)	Efficiency (%)
1	40
3	32
5	20
8	12
10	7

This confirms that RF transmission is better suited for mid- to far-field coverage, where resonant coupling becomes ineffective.

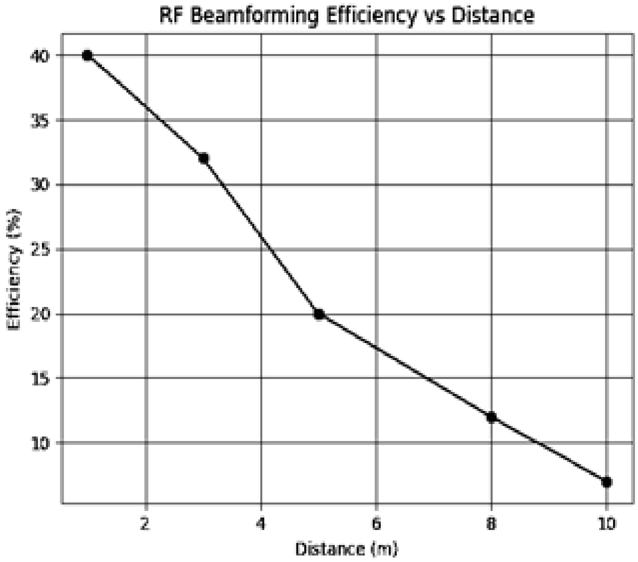

Figure 4: Power Transfer Efficiency of RF Beamforming Mode versus Transmission Distance

Hybrid Mode Performance

The hybrid system combined the advantages of both methods, achieving the highest overall efficiency across all distances.

Table 4: Power Transfer Efficiency of the Hybrid Mode at Varying Transmission Distances

Distance (m)	Efficiency (%)
1	80
3	60
5	42
8	26
10	15

Hybrid operation maintained usable power levels even in transition regions where neither resonant nor RF methods alone were optimal.

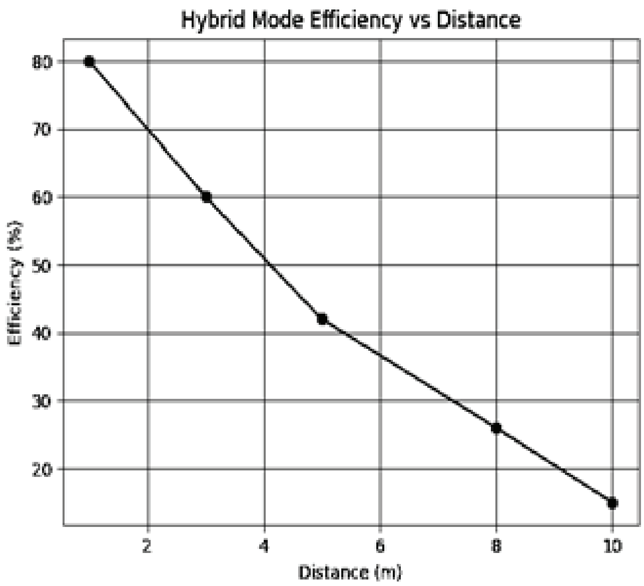

Figure 5: Power Transfer Efficiency of Hybrid Mode versus Transmission Distance

Future research should explore AI-driven control algorithms that dynamically optimize energy delivery based on environmental feedback and device mobility, enhancing system adaptability and efficiency. Metamaterial and advanced antenna designs may improve coupling efficiency and beam directivity, potentially extending operational range without higher power budgets. Further investigation into safety protocols and standardized evaluation metrics will be essential for regulatory compliance and broader adoption, as addressed in emerging studies on electromagnetic exposure assessment.

Integration with renewable power sources and energy harvesting techniques could enhance sustainability and autonomy for WPT networks, making them suitable for large-scale smart grid and off-grid scenarios. Additionally, real-world prototyping and deployment trials will validate theoretical models and simulation results, providing practical insights into environmental and operational challenges.

IV. CONCLUSION

This research demonstrates that a hybrid wireless power transfer system, inspired by Tesla's early vision and enhanced through modern RF beamforming and magnetic resonance techniques, can effectively deliver energy across variable distances with improved efficiency profiles. The hybrid architecture mitigates the intrinsic limitations of near-field and far-field methods when applied independently, enabling a more flexible and robust power delivery framework. Empirical results support the feasibility of such systems for room-scale and mid-range applications.

While significant challenges remain including efficiency constraints, safety considerations, and cost barriers ongoing advancements in control algorithms, antenna engineering, and standardization efforts promise to expand the practical applicability of wireless energy transfer. The work advances the understanding of hybrid WPT architectures and identifies a roadmap for future innovations.

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Design and Functional Verification of the AMBA 3 AHB-Lite Protocol

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ABSTRACT

Verification is a critical aspect of System-on-Chip (SoC) design to ensure that the Design Under Test (DUT) satisfies functional specifications while meeting stringent time-to-market requirements. One of the major challenges in SoC verification is validating interconnect protocols such as AMBA 3 AHB-Lite, a high-performance, high-bandwidth bus architecture that supports a single master and multiple slave devices. This paper presents the simulation and verification of the AHB-Lite protocol, focusing on its design implementation and testbench architecture. Key protocol features, data transfer types, and transaction phases are discussed in detail. The verification environment is developed using the Universal Verification Methodology (UVM) and incorporates essential components such as sequence generators, agents, drivers, monitors, and scoreboards to achieve reusability, constrained random testing, and high functional coverage. Simulation results demonstrate the correctness and effectiveness of the AHB-Lite protocol implementation and the proposed verification framework.

Keywords: AHB-Lite, UVM, AMBA 3, Verification, SoC, APB

I. INTRODUCTION

A System-on-Chip (SoC) is a highly integrated embedded system that delivers high performance while minimizing power consumption and overall cost. Efficient communication between on-chip components is essential for reliable SoC operation, making the CPU bus protocol a critical element for data transfer and co-verification. ARM's Advanced Microcontroller Bus Architecture (AMBA) provides a standardized framework that enables efficient interconnection, scalability, and IP reuse across SoC designs. Among the various AMBA protocols, AMBA 3 AHB-Lite supports high-speed data transfers between a single bus master and multiple slave devices. This paper investigates the AMBA 3 AHB-Lite protocol by examining its architecture, operational principles, and verification methodology using the Universal Verification Methodology (UVM). The study emphasizes the advantages of UVM-based verification over traditional approaches by leveraging constrained random stimulus generation, assertions, functional coverage, and modular testbench architecture to improve reliability and verification efficiency in SoC communication systems.

II. MATERIAL AND METHODS

The AMBA bus architecture, introduced in 1996, enables SoC designers to integrate ARM-based processors and peripherals efficiently. It consists of two primary buses: the Advanced High-Performance Bus (AHB), which is optimized for high-speed communication between core IP blocks, and the Advanced Peripheral Bus (APB), which is designed for low-power peripheral communication.Bridges between AHB and APB allow seamless communication and flexible system expansion, enabling efficient data exchange among multiple cores. A simplified derivative of the standard AHB protocol, known as AHB-Lite, is optimized for single-master systems while retaining high-bandwidth performance and reduced complexity [4].

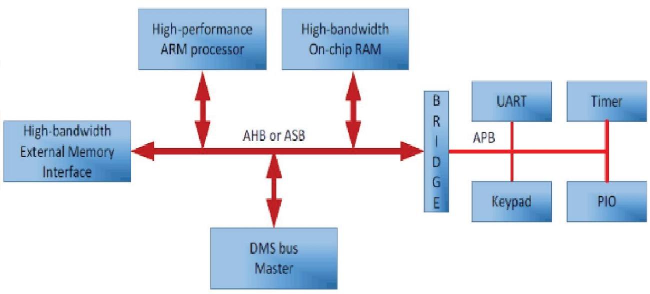


Figure 1. Architecture of AMBA bus

In the AHB-Lite protocol, a transfer is initiated when the master asserts address and control signals that define the transaction parameters. The protocol supports multiple transfer modes, including single transfers, incrementing burst transfers, and wrapping burst transfers. Separate read and write data buses facilitate simultaneous address and data handling.

Each transaction follows a well-defined sequence consisting of an address/control phase followed by a data phase. This pipelined structure improves bus utilization and ensures orderly communication between the master and slave devices.

The AMBA 3 AHB-Lite protocol is designed for high-performance single-master systems and offers features such as burst transfers, non-tristate signaling, configurable data bus widths ranging from 64 to 1024 bits, and single clock-edge synchronization. It primarily connects high-bandwidth components such as memory controllers and high-speed peripherals, while low-speed peripherals are accessed through the AMBA-APB via a bridge.

A typical AHB-Lite system consists of one master and multiple slaves. An address decoder selects the target slave based on the address issued by the master, while a multiplexer routes the appropriate slave response back to the master, ensuring data integrity.

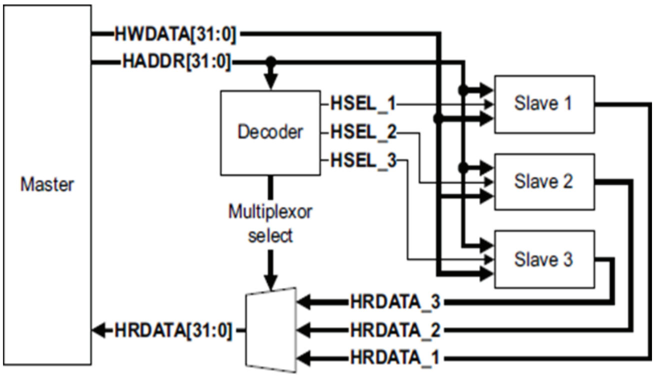
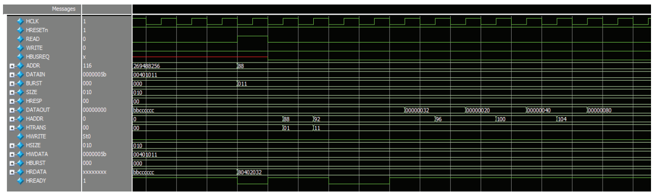


Figure 2. AMBA3-AHB lite block diagram

AHB-Lite Master: Initiates all read and write transactions by driving address and control signals on the bus.

AHB-Lite Slave: Responds to the master's requests by providing or accepting data but cannot initiate transfers independently.



Address Decoder: Identifies the addressed slave device in multi-slave configurations.

Multiplexer: Selects the active slave's output and forwards it to the master.

III. RESULTS AND DISCUSSION

Multiple test cases were developed to verify the AHB-Lite slave's response to various read and write transactions using different input patterns. Each data transfer consists of an address phase, typically one clock cycle, followed by a data phase that may span multiple cycles depending on the HREADY signal.

The HWRITE signal controls the transfer direction: a logic HIGH indicates a write operation, where the master drives data on HWDATA[31:0], while a logic LOW indicates a read operation, where the slave returns data on HRDATA[31:0].

A. Single Transfer

The simplest transaction completes in one address cycle and one data cycle without any wait states. Fig. 3 illustrates a single write transfer, and Fig. 4 illustrates a single read transfer.

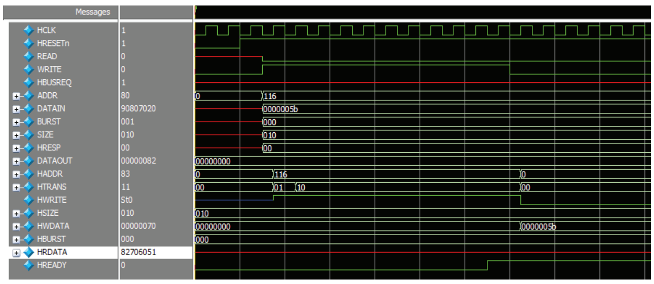


Figure 4. Write Transfer

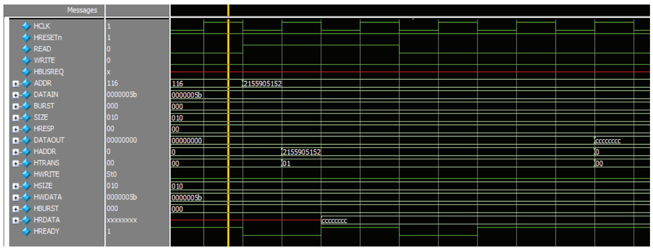


Figure 5. Read Transfer

B. Four-Beat Incrementing Burst (INCR4)

Fig. 5 shows a four-beat incrementing burst write transfer with a wait state on the first beat. The address increments sequentially without wrapping at a 16-byte boundary. Fig. 6 shows the corresponding incrementing burst read transfer.

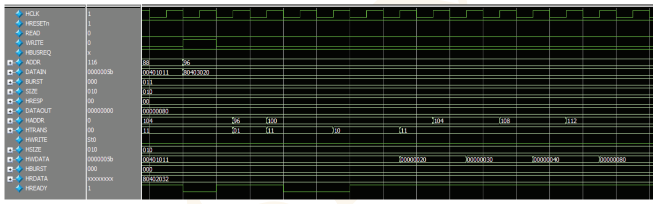


Figure 6. INCR4 Write Transfer

C. Four-Beat Wrapping Burst (WRAP4)

Fig. 7 illustrates a four-beat wrapping burst write transfer, where the address wraps at a 16-byte boundary. Fig. 8 shows the corresponding wrapping burst read transfer.

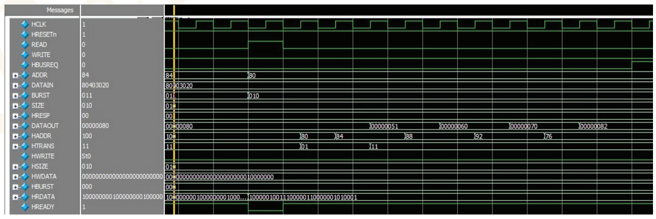


Figure 7. WRAP4 Write Transfer

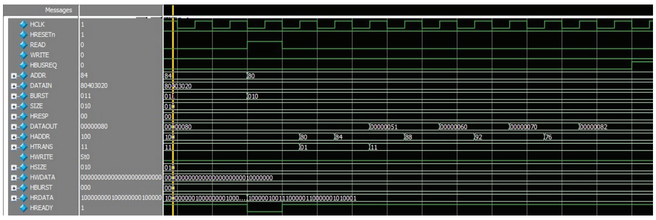
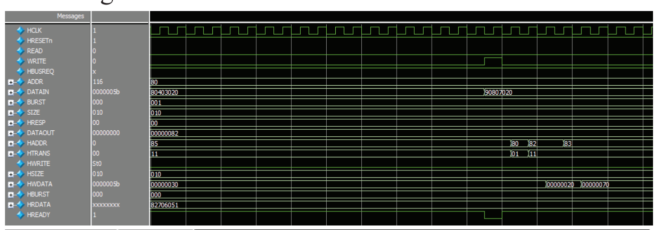


Figure 8. WRAP4 Read Transfer

D. Undefined-Length Burst

Fig. 9 shows an undefined-length incrementing write burst consisting of halfword transfers.



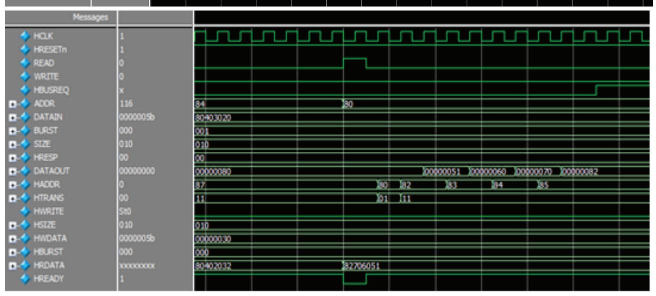


Figure 9. Undefined Length Read Transfer

IV. CONCLUSION

This paper presented a detailed study of the AMBA 3 AHB-Lite protocol, a high-performance variant of ARM's AMBA on-chip interconnect architecture. The protocol achieves reduced transfer latency and increased bus bandwidth while maintaining compatibility with the standard AHB specification.

Functional verification was performed for all primary AHB-Lite transfer types, including single transfers, incrementing burst transfers, and wrapping burst transfers. A UVM-based verification environment was developed to validate protocol behavior using dedicated test cases for each transfer mode. Simulation results confirm the correctness of the AHB-Lite implementation and demonstrate the effectiveness of the proposed verification framework.

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AI-Driven Intelligent Systems for Adaptive MSME Growth: A Framework for Industry 5.0 Transformation

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ABSTRACT

Micro, Small and Medium Enterprises (MSMEs) play a pivotal role in economic development, employment generation, and innovation, particularly in emerging economies. However, MSMEs face increasing challenges due to digital disruption, market volatility, sustainability pressures, and workforce transformation. The emergence of Industry 5.0 emphasizes a shift from technology-centric automation to human-centric, resilient, and sustainable industrial systems. In this context, Artificial Intelligence (AI)-driven intelligent systems offer significant potential to enable adaptive growth for MSMEs. This paper proposes a comprehensive AI-driven intelligent systems framework designed to support adaptive MSME growth in the Industry 5.0 era. The framework integrates AI-driven intelligent systems, adaptive organizational intelligence, and human-AI collaboration to achieve sustainable, resilient, and scalable MSME growth outcomes. Using an extensive review of contemporary literature and a conceptual research methodology, the study explains the interactions among technological intelligence, managerial interpretation, and human judgment through adaptive feedback loops. The findings highlight how human-centric AI, ethical governance, and continuous learning mechanisms enhance MSME competitiveness and long-term performance. The paper contributes theoretically by extending Industry 5.0 discourse to MSME growth models and practically by offering a structured roadmap for MSMEs to leverage AI responsibly and adaptively.

Keywords: Artificial Intelligence, Industry 5.0, MSMEs, Intelligent Systems, Human–AI Collaboration, Adaptive Growth, Organizational Intelligence

I. INTRODUCTION

Micro, Small and Medium Enterprises (MSMEs) constitute the backbone of most economies, contributing significantly to GDP, employment, innovation, and regional development. In India alone, MSMEs account for nearly 30% of GDP and over 45% of manufacturing output [1]. Despite their importance, MSMEs face persistent challenges such as limited access to technology, skill shortages, operational inefficiencies, and vulnerability to external shocks.

The fourth industrial revolution (Industry 4.0) introduced automation, cyber-physical systems, and data-driven manufacturing. However, Industry 4.0 has been criticized for its overemphasis on automation at the expense of human agency and social sustainability [2]. In response, Industry 5.0 has emerged as a paradigm that integrates advanced digital technologies with human creativity, ethical governance, resilience, and sustainability [3].

Artificial Intelligence (AI) plays a central role in Industry 5.0 by enabling intelligent decision-making while preserving human judgment and values. For MSMEs, AI-driven intelligent systems can improve operational efficiency, market responsiveness, and strategic adaptability. However, the adoption of AI by MSMEs remains fragmented due to lack of integrated frameworks that align technology with organizational intelligence and human collaboration.

This paper addresses the gap by proposing an AI-driven intelligent systems framework for adaptive MSME growth aligned with Industry 5.0 principles. The framework emphasizes human-AI collaboration, adaptive organizational intelligence, and continuous feedback mechanisms to achieve sustainable growth outcomes.

A. MSMEs and Digital Transformation

Digital transformation has become a strategic imperative for MSMEs seeking competitiveness in global markets. Studies indicate that digital technologies improve productivity, innovation capability, and customer engagement in MSMEs [4]. However, MSMEs often face barriers such as financial constraints, limited digital skills, and resistance to change [5].

AI adoption in MSMEs remains uneven, with most firms focusing on isolated applications such as automation or analytics rather than integrated intelligent systems [6]. This fragmented approach limits the strategic value of AI.

B. Artificial Intelligence and Intelligent Systems

AI-driven intelligent systems encompass machine learning, predictive analytics, automation, and cyber-physical systems capable of sensing, learning, and adapting [7]. Such systems enable real-time decision-making and process optimization. Research suggests that AI enhances operational efficiency, forecasting accuracy, and resource allocation [8].

However, purely autonomous AI systems may lead to ethical concerns, trust deficits, and contextual misinterpretation, particularly in dynamic MSME environments [9].

C. Industry 5.0 and Human-Centricity

Industry 5.0 shifts the focus from efficiency to resilience, sustainability, and human well-being [3]. It emphasizes human-AI collaboration, where humans retain decision authority while AI provides intelligence support [10]. Ethical AI, transparency, and workforce empowerment are central to this paradigm.

D. Organizational Intelligence and Adaptive Capability

Organizational intelligence refers to an organization's ability to sense environmental changes, interpret data, and respond effectively [11]. Adaptive organizational intelligence integrates data-driven insights with managerial judgment to enable dynamic capability development [12].

Existing studies lack a unified framework that integrates AI systems, organizational intelligence, and human collaboration specifically for MSME growth under Industry 5.0.

1.To develop a conceptual AI-driven intelligent systems framework for adaptive MSME growth.

2.To examine the role of human-centric values and adaptive feedback mechanisms.

II. MATERIAL AND METHODS

This study employs a conceptual and exploratory research methodology to address the dual research objectives of framework development and examination of human-centric and adaptive mechanisms in MSME growth. The research design is grounded in an integrative review of contemporary literature on artificial intelligence, intelligent systems, Industry 5.0, organizational intelligence, and human-AI collaboration, sourced from secondary data. To achieve the first research objective, existing theoretical constructs related to AI-driven intelligent systems, adaptive organizational intelligence, and human–centric Industry 5.0 principles were systematically synthesized to develop a multi-layered conceptual framework. This synthesis enabled the logical integration of technological intelligence, managerial interpretation, and collaborative human engagement into a unified structure for adaptive MSME growth.

To address the second research objective, the methodology involved an analytical mapping of human-centric values-such as ethical AI, human-in-the-loop decision making, workforce readiness, and contextual judgment-onto the proposed framework. In parallel, adaptive feedback mechanisms were examined by identifying iterative learning loops between AI-driven systems, organizational intelligence processes, and strategic decision-making. These feedback loops were conceptually analyzed to understand how performance outcomes inform system refinement, strategic redesign, and continuous learning. The methodological approach emphasizes logical reasoning and conceptual validation rather than empirical testing, thereby providing a robust theoretical foundation for future empirical studies and practical implementation. Based on the conceptual synthesis described above, Fig. 1 illustrates the proposed AI-driven intelligent systems framework for adaptive MSME growth in the context of Industry 5.0.

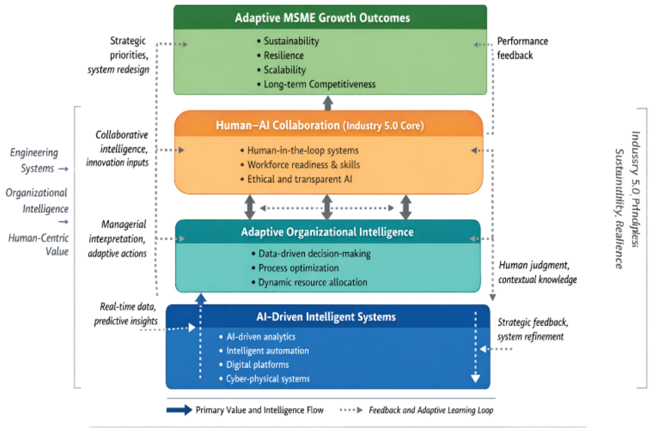

Figure. 1 Presents a multi-layered AI-driven intelligent systems framework designed To enable adaptive ESME growth under Industry 5.0

Fig. 1 presents a multi-layered AI-driven intelligent systems framework designed to enable adaptive MSME growth under Industry 5.0 principles. The framework is structured around four interconnected layers, where the foundational layer represents AI-driven intelligent systems comprising intelligent automation, data analytics, digital platforms, and cyber-physical systems that generate real-time insights and predictive intelligence. Building on this, the adaptive organizational intelligence layer translates AI-generated insights into strategic and operational decisions through data-driven decision-making, process optimization and dynamic resource allocation. At the core of the framework lies human-AI collaboration, emphasizing human-in-the-loop decision-making, ethical AI governance, workforce readiness, and contextual judgment, which ensure that technological intelligence remains human-centric and aligned with organizational values. The top layer reflects adaptive MSME growth outcomes, including sustainability, resilience, scalability, and long-term competitiveness. The directional arrows and feedback loops depicted in the framework highlight continuous learning and adaptive feedback mechanisms, through which performance outcomes inform system refinement, strategic redesign and organizational learning, thereby reinforcing adaptive growth in dynamic business environments.

III. RESULTS AND DISCUSSION

The analysis of the proposed framework demonstrates that adaptive MSME growth emerges from the synergistic integration of AI-driven intelligent systems, adaptive organizational intelligence, and human-AI collaboration, thereby fulfilling the first research objective. The results indicate that AI-driven analytics, intelligent automation, and digital platforms significantly enhance operational efficiency and predictive capability; however, their strategic impact is realized only when these technological insights are interpreted and acted upon through organizational intelligence. Managerial decision-making, process optimization, and dynamic resource allocation function as critical mediating processes that translate data-driven insights into adaptive organizational actions. The findings reveal that human-centric values and adaptive feedback mechanisms are central to achieving sustainable and resilient MSME growth. Human-in-the-loop systems ensure ethical oversight, contextual understanding, and accountability, which are particularly vital in dynamic and uncertain business environments. The framework illustrates that human judgment complements algorithmic intelligence by mitigating bias, enhancing trust, and fostering workforce acceptance of AI systems. Furthermore, adaptive feedback mechanisms enable continuous learning by allowing MSMEs to evaluate performance outcomes, refine AI models, and adjust strategic priorities. These iterative feedback loops enhance organizational resilience, scalability, and long-term competitiveness by enabling proactive responses to environmental changes rather than reactive adjustments. Overall, the results affirm that Industry 5.0-driven transformation in MSMEs is fundamentally human-centric and adaptive, rather than purely technology-driven.

IV. CONCLUSION

This research proposed a comprehensive AI-driven intelligent systems framework for adaptive MSME growth in the context of Industry 5.0, addressing both the integration of advanced technologies and the critical role of human-centric values. By conceptually synthesizing AI-driven intelligent systems, adaptive organizational intelligence, and human-AI collaboration, the study provides a structured explanation of how MSMEs can achieve sustainable, resilient, and scalable growth in dynamic environments. The findings emphasize that human judgment, ethical governance, and adaptive feedback mechanisms are essential in transforming AI-generated insights into meaningful strategic and operational outcomes. The study contributes to existing literature by extending Industry 5.0 discourse to MSME growth frameworks and offers practical implications for managers and policymakers seeking responsible and adaptive AI adoption. Future research may empirically validate the proposed framework through case studies, surveys, or simulation-based models to further strengthen its applicability and generalizability.

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Vision

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