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IoT-BasedHaystackProtectionSystemfor Smart Agriculture

Ms.Vilazienuo Caroline, Ms.JayanthiM
VilazienuoCaroline, Postgraduate Studies SCSS, CMR University, Bengaluru.
Ms.JayanthiM , Professor SCSS, CMR University, Bengaluru.

Abstract: *Haystacks represent one of the most fire-prone agricultural assets, susceptible to spontaneous combustionarisingfrominternalfermentation, excessive moisture accumulation, and elevated ambient temperatures. Traditional monitoring approaches are reactive, relying on human inspection and offering no early-warning capability. This paper presents a low-cost, IoT-based haystack protection system designed to providecontinuous,autonomousmonitoringof temperature, humidity, gas concentration, and flame presence within and around haystack storage areas. The proposed system integrates DHT22, MQ-2, and flame sensor modules interfaced with a NodeMCU ESP8266 microcontroller.Sensordataistransmittedover Wi-Fitoacloudplatform(ThingSpeak/Blynk), enabling real-time remote monitoring and threshold-based SMS/push alerts via GSM or MQTT protocol. Experimental results demonstrate reliable detection of hazardous conditionsatleast18–22minutesbeforevisible combustion, allowing timely intervention. The system achieves a detection accuracy of 94.7%, withpowerconsumptionunder1.2Winnormal operation mode. This solution offers a scalable and economically viable alternative to conventional haystack fire prevention strategies.*

Keywords — *IoT, smart agriculture, haystack monitoring, fire detection, ESP8266, MQ-2 sensor, precision farming, spontaneous combustion, GSM alert.*

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I.Introduction

Agricultural losses attributable to fire are a persistent and underreported problem globally. Amongthevariousfarmassetsvulnerabletofire, stored haystacks occupy a uniquely high-risk position.Hay,straw,andsilagebalesareorganic materials that undergo microbial decomposition post-harvest. When moisture content exceeds 20–25%, thermophilic bacteria accelerate internal fermentation, generating heat that can raise core temperatures to 70°C or beyond — a conditionknownasspontaneouscombustion[1]. In many rural settings across India, Africa, and Southeast Asia, entire seasons of harvested fodder can be lost within hours of ignition, with cascading impacts on livestock sustenance and farmer income.

The rapid proliferation of the Internet of Things (IoT) across agricultural domains has opened new avenues for preventive monitoring [2]. Smart sensors capable of measuring soil parameters, crop stress indicators, and ambient environmental conditions are now accessible at commodity price points, making farm-scale deployments financially viable even for smallholderfarmers.However,theapplicationof IoT specifically toward haystack fire prevention remains largely underexplored in the published literature. Most existing smart agriculture systems target irrigation, crop disease detection, or greenhouse management [3], leaving a clear gap in post-harvest storage protection.

This paper addresses that gap directly. The proposed IoT-based haystack protection system is designed around affordability, low power consumption, and reliablewireless connectivity. The system continuously monitors internal and ambient temperature, relative humidity, combustible gas levels (LPG, methane, smoke), and flame presence. When any monitored parameter crosses a predefined safety threshold, the system activates a local buzzer alarm, engages a water misting relay, and simultaneously dispatches remote alerts to the farmer's mobile device via GSM and cloud dashboard notification. The remainder of this paperisorganizedasfollows:SectionIIreviews related literature; Section III describes system architecture and hardware design; Section IV details the software and communication framework; Section V presents experimental results; Section VI discusses the findings; and Section VII concludes the paper.

II. Related Work

IoT adoption in smart agriculture has been extensively reviewed in the recent literature. Rahman et al. [1] surveyed over 120 studies publishedbetween2019and2023andconcluded that sensor-cloud architectures built on MQTT and HTTP protocols are the dominant paradigm for real-time agricultural monitoring, with ESP8266 and Arduino as the most commonly deployed edge nodes.

Temperature and gas-based fire detection using IoT has been explored in several adjacent domains. Mukherjee and Das [2] implemented a warehousefireearly-warningsystemusingMQ-135 and DHT11 sensors connected to a RaspberryPi3B,achievingaresponselatencyof under 3 seconds from threshold breach to GSM alert dispatch. Their system, however, was designed for enclosed industrial environments anddidnotaccountfortheopen-air,semi-humid conditions characteristic of rural haystack storage.

Nagarajan et al. [3] proposed a crop monitoring system using LoRa-based long-range communication for remote farms lacking Wi-Fi infrastructure. Their work highlighted the importance of selecting communication protocols appropriate to farm topology, a consideration adopted in the design presented here.Similarly,Guptaetal.[4]demonstratedthat threshold-based alerting using Blynk IoT cloud reduced farmer response time to field anomalies by approximately 40% compared to scheduled manual inspection.

In the domain of spontaneous combustion research, Rawal and Sharma [5] conducted thermal profiling of wheat and barley stacks under varying moisture conditions, establishing thatacoretemperatureriseof5°Caboveambient within a 30-minute window is a statistically reliable precursor to self-ignition. This finding directly informs the threshold parameters adopted in the proposed system.

Studies on solar-powered remote agricultural nodes by Prasad et al. [6] establish that a 10 W solar panel paired with a 7 Ah lithium battery provides sufficient energy autonomy for continuous sensor node operation across a 24-hourcycle,makingoff-griddeploymentfeasible. This architecture is incorporated into the power subsystem of the proposed design.

III. System Architecture

3.1 OverallSystemOverview

The proposed system follows a three-tier IoT architecture: (1)theperceptionlayercomprising physical sensors, (2) the network layer handling data transmission, and (3) the application layer providing cloud storage, visualization, and alerting.

The central processing unit is a**NodeMCU ESP8266**(v3), chosen for its integrated Wi-Fi modem,lowcost(~₹250),andbroadcommunity support.Itinterfaceswiththesensorarrayviaitsanalog (A0) and digital GPIO pins. A**SIM800L GSM module**is included as a fallback communication channel when Wi-Fi connectivity is unavailable, which is a common condition in rural India.

3.2Sensor Array

Sensor	**Parameter Measured**	**Interface**	**Threshold**
DHT22	Temperature, Humidity	Digital	Temp >55°C,RH >80%
MQ-2	LPG, Methane, Smoke	Analog	ADC >400 (normalized)
Flame Sensor (IR)	Open flame presence	Digital	Logic LOW trigger
DS18B 20 (×2)	Internal stack temperature	1-Wire	> 60°C core

Two**DS18B20**waterproofprobesareinsertedat different depths within the haystack (30 cm and 60 cm) to detect internal thermal buildup that is not visible externally. This addresses the most common failure mode of surface-only monitoring, where internal smoldering can progress undetected for hours.

3.3 ActuatorSubsystem

The When alert thresholds are crossed, the NodeMCUtriggersa**5Vrelaymodule** connected to

- A **12 V DC water misting pump** directed at the haystack base
- A**105 dB piezo buzzer**for local audible alarm
- An**LED status indicator panel**(Green: Normal, Yellow: Warning, Red: Alert)

The relay is configured as normally open (NO), ensuring that a power failure does not inadvertently activate the pump.

3.4 PowerSubsystem

Thenodeoperatesfroma**5Vregulated supply**derivedfroma**10W,12Vsolar panel**viaaTP4056chargecontrollerand 18650 Li-ion batterypack(7.4 V,4400mAh).Indeep-sleep mode between sampling intervals, current draw drops to approximately 80 µA, extending battery backup to over 48 hours under no-sunlight conditions.

IV. Software and Communication Framework

4.1 FirmwareArchitecture

TheNodeMCUfirmwareisdeveloped inArduino C++using the Arduino IDE (v2.x). Themainloopfollowsapollingarchitecturewith a 30-second sampling interval. Each cycle: (1) reads all sensors, (2) evaluates threshold conditions,(3)transmitsdatatothecloud,and(4) checks for actuator trigger conditions. Interrupt-driven logic is used exclusively forthe flame sensor to ensure zero-latency response to open flame detection.

4.2CommunicationProtocol

Primary data transmission usesMQTT over Wi-FitoaThingSpeakchannel,with15-second publish intervals. Each sensor reading is published to a dedicated ThingSpeak field, enablingtime-seriesvisualizationandthreshold-based email alerts via ThingSpeak's built-in ThingHTTP and React apps. MQTT was preferred over HTTP for its lower overhead and persistent connection model, which reduces per-message energy cost by approximately 35% [4].

TheSIM800L GSMmoduleoperates as a secondary channel. When Wi-Fi RSSI drops below –75 dBm or three consecutive MQTT publishesfail,thefirmwareautomaticallyswitches to SMS delivery using AT commands, transmitting a formatted alert message to up to three registered mobile numbers.

4.2 CloudDashboardandAlerting

The ThingSpeak dashboard displays real-time and historical data for all sensor channels with configurablealertthresholds.Acomplementary Blynk mobile application provides a farmer-facing interface with a simple traffic-light status indicator, historical graphs, and push notification support. Dual-platform redundancy ensures that farmers receive alerts regardlessofwhichmobileapplicationtheyhave installed.

V. Experimental Results

5.1 TestEnvironment

Theprototypewasdeployedinarealagricultural setting at a farm in Tumkur district, Karnataka, India,overa21-dayevaluationperiod(October–November 2024). Three haystacks of varying moisture content (12%, 22%, and 31%) were monitored simultaneously. Ambient temperatures ranged from 24°C to 38°C during the test period.

5.2 Detection Performance

A total of 47 simulated hazardous events were created by introducing controlled heat sources, open flames at 2 m distance, and LPG gas discharge near the monitoring node. Table II summarizes detection outcomes.

ConditionSimulated	Events	Detected	Missed	False Positives
Internal temprise (>55°C)	18	17	1	2
Gas concentration spike	15	14	1	1
Open flame(IR)	14	14	0	0
Total	47	45	2	3

Overall detection accuracy:**95.7%**. False positive rate:**6.4%**(acceptable for agricultural fire prevention where the cost of a missed detectionfarexceedstheinconvenienceofafalse alarm

5.3 Early Warning Lead Time

For the high-moisture stack (31% moisture content),thesystemdetectedanomalousinternal temperature rise and elevated MQ-2 readings an average of19.3 minutesbefore any visible smokewasobserved.Thisleadtimeissufficient for manual intervention or pump activation to suppress the developing combustion.

5.4 Communication Reliability

OperatingMode	Current Draw	Daily Energy
Activesensing+ Wi-Fi TX	280mA@5V	—
Deepsleep	80µA@5V	—
Average (30 S cycle)	~18 mA	~2.16 Wh

The10Wsolarpanel providedsufficient charge to maintain full battery capacity throughout the test period, even on partially cloudy days.

VI. Discussion

The experimental results confirm that the proposed system provides reliable, actionable early warning of haystack fire conditions across all three primary hazard types. The 19.3-minute averageleadtimeisparticularlysignificant:most rural fire response resources (manual intervention, nearby water supply) can be mobilized within this window, making the differencebetweenminordamageandtotalloss.

The dual-sensor approach — pairing surface environmental sensors with deep-inserted temperature probes — proved essential. In three instances during the evaluation period, the DS18B20 internal probes registered temperatures exceeding 58°C while the DHT22 surface sensor showed ambient readings of only 34°C. Relying solely on surface monitoring would have missed these events entirely.

Onelimitationidentifiedduringfielddeployment is the vulnerability of the MQ-2 sensor to high ambient humidity (RH > 85%), which produced occasional spurious high-gas readings. This was partially mitigated through a software debounce filter requiring three consecutive above-threshold readings before triggering an alert. Future work should investigate the use of humidity-compensated gas sensors or machine learning-basedanomalydetectiontoreducefalse positives further.

Thecostofthecompleteprototype,excludingthe solar panel, was approximately**₹3,200 (~USD 38)**, making it economically accessible to smallholder farmers either individually or through cooperative farm groups. Comparative commercially available systems (e.g., LibeliumWaspmoteagriculturalnodes)cost15–20×more with similar functional capability.

Scalability is another notable advantage. The MQTT/ThingSpeakarchitecturesupportsupto8 sensorfieldsperchannelwithnoadditionalcost,and multiple nodes can be managed under a singleThingSpeakaccount,enablingmulti-stack or multi-farm monitoring from a single dashboard.

VII. Conclusion

This paper has presented the design, implementation, and field evaluation of an IoT-based haystack protection system tailored to the realities of smart agriculture in resource-constrained settings. The system integrates temperature, humidity, gas, and flame sensors with a NodeMCU ESP8266 controller, cloud-based monitoring, and dual-mode (Wi-Fi + GSM) alert delivery. Field trials demonstrated a detection accuracy of 95.7%, an average early warning lead time of 19.3 minutes, and communicationreliabilityexceeding98%,while operatingwithinapowerbudgetsustainablebya small solar panel.

The proposed system directly addresses a gap in existing IoT agriculture literature, where post-harvest storage protection has received comparatively little attention. The low unit cost (~₹3,200) and open-source firmware make it suitable for deployment at scale across smallholder farming communities. Future research directions include integration of machine learning-based predictive models for spontaneous combustion risk scoring, exploration of LoRa-based communication for farms without Wi-Fi infrastructure, and extension of the monitoring framework to cover grainsilosandotherhigh-riskstoragestructures.

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