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Development of an IoT-enabled Pipeline Spill Detection, Leak Localization and Reconciliation System

(A Case Study of the Nigeria Oil Pipeline Operation)

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Abstract: The challenges that are still being evident in the Nigerian oil and gas industry include leaks in the pipeline, losses of crude oil, and the slowness of spill detection, which causes massive losses of the economy, pollution, and inefficiency. Current monitoring methods, which are mainly relying on periodic inspection and traditional SCADA systems, are often not able to detect crude oil losses in real-time, precisely localize them, and automatically reconcile them. The proposed limitations of this study include the construction of a pipeline monitoring system based on the IoT to implement real-time leak identification, localization of leaks, estimation of crude oil loss, and the process of automated daily reconciliation. The study used Design Science Research (DSR) approach that entailed system design, prototype implementation, and experimental validation. The proposed architecture is a combination of distributed ESP32 sensor nodes to monitor pressure, flow and temperature, LoRa based long range communication to send node to gateway and GSM/4G cellular backhaul to report data centrally. The hybrid model of leak detection has been adopted where mass balance analysis and anomaly detection based on pressure gradients were used to enhance the reliability of the detection and minimized false alarms. Leak localization was also performed through segment-based pressure analysis and cumulative flow imbalance integration were also utilized to estimate crude oil loss, as well as provide automated reconciliation. The prototype was deployed and tested in Wokwi high-fidelity simulation environment because of the delays in hardware procurement. It has been shown that experimental results indicated that the system attained a high leakage detection rate of 95 percent, a localization rate of 80 percent, average loss estimation of less than 10 percent, and a self-gap of 2-4 seconds. Communication tests showed that there was effective data delivery with good buffering of gateways. The research comes up with a conclusion that the proposed IoT-enabled monitoring system is technically feasible and applicable to improving the pipeline visibility, minimizing the unreported losses, and increasing the responsibility of the crude oil in the Nigerian pipeline setting. The system offers low cost scalable base of next generation intelligent pipeline integrity management. The future work must be aimed at the deployment on the field scale, the increase of sensor density, and the combination of edge AI and live operational dashboards.

Keywords: *Internet of Things (IoT); Pipeline Leak Detection; LoRa; Real-Time Monitoring; Crude Oil Loss Estimation; Design Science Research; Nigerian Oil and Gas Industry.*

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I. INTRODUCTION

A. Background of the Study

The transportation of crude oil through pipeline infrastructures is currently a significant part of the Nigerian oil and gas industry as they are the primary mode of transportation of crude oil from the fields of production to processing units and export terminals and refineries. As one of the leading oil producing countries in Africa, Nigeria is highly dependent on the extensive network of oil pipelines, therefore having at the back of its mind the importance of ensuring sustainable national revenue, energy security and economic development (Adebayo & Dada, 2022). Consequently, the integrity, safety and operational efficiency of pipeline systems is of critical significance to the economic stability and environment sustainability of our country.

Despite their strategic importance, the oil pipelines in Nigeria are constantly plagued by incidents of leakages, oil spills, vandalism and crude oil theft, especially in the Niger Delta region (Olawuyi, 2023). These incidents lead to a lot of loss of economy, environmental degradation, social disruption

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etc. National Oil Spill Detection and Response Agency (NOSDRA) - Nigeria's statutory authority for oil spills monitoring and response - maintains records of the oil spills across the country through Joint Investigation Visit (JIV) reports and Oil Spill Monitor platform. NOSDRA data shows that hundreds to more than one thousand incidents of spills are registered every year across Nigeria with pipeline failures, corrosion and third-party interference being the largest recorded incidents (NOSDRA, 2023).

Available spill statistics compiled from NOSDRA records, reveal large crude oil losses on an annual basis. For example, in the year 2021 there has been a total of reported 40,707 barrels of crude oil spill all over Nigeria. This number has risen to approximately 47,732 barrels in 2022 with 2023 recording approximately 18,747 barrels and 2024 and an estimated loss of 19,000 barrels of crude oil to spill incidents in the country (NOSDRA, 2022; NOSDRA, 2023). On average, these figures show that Nigeria loses tens of thousands of barrels of crude oil to spills alone and in or per annum which means Nigeria loses millions of litres of petroleum into the earth and water annually. Beyond the direct economic impact from the lost crude, these spills come with far reaching costs of environmental remediation, loss of agricultural production, and negative impacts on public health.

As NOSDRA's own records of oil spills reveal, many oil spills involve small but persistent leakages that go undetected for long periods of time prior to formal reporting and investigation. Such delays are often responsible for higher amounts of spills, wider impacts on the environment and more complex clean-up operations (NOSDRA, 2022). Additionally in post incident assessments, difficulties are often reported in identifying the accurate time of occurrence, spill location and actual volume discharged as these parameters are often reconstructed by post-spill field inspection rather than be gathered using monitoring systems that run continuously.

Traditional pipeline monitoring practices in Nigeria are based largely on periodic patrol operations, primitive supervisory control and data acquisition (SCADA) systems and crude oil accounting operations which are done manually. While SCADA systems offer a narrow view of operations, the effectiveness of SCADA is limited due to the sparse deployment of sensors, detecting low rate or gradual leaks in time, and also analytical capability for real-time decision making (Zhang et al., 2022). As reflected in NOSDRA incident data, many spill events are not identified and/or through automated early warning mechanisms, but only after visible environmental damage has taken place, or based on reports from host communities.

Furthermore, crude oil production and transfer accounting of many pipeline operation are still being conducted by manual or semi-automated reconciliation methods. Discrepancies between recorded figures of production, throughput in the pipeline and receipts at terminals are often found out retrospectively and it is almost impossible to determine with accuracy the cause, when and where losses happen (Ibrahim et al., 2023). Inconsistencies between operator□reported volumes of spills and independently assessed estimates of those spill volumes have been a consistent feature of NOSDRA post-incident reports and underscore the inadequacy of current measurement and reconciliation practices (NOSDRA, 2023).

Recent developments in Internet of Things (IoT) and embedded sensing technologies are providing new opportunities for improved pipeline monitoring capability. IoT-based systems provide the opportunity for continuous measuring of important parameters of the pipeline such as flow rate, pressure and temperature by means of distributed sensor nodes (Khan et al, 2022). In parallel, low power wide area network (LPWAN) technologies, in particular, the Long Range (LoRa) technology, can offer long distance energy-efficient communication for the remote and geographically scattered pipeline environments typical of the oil-producing regions of Nigeria (Centenaro et al., 2022).

When used in conjunction with GSM or 4G cellular backhaul connectivity, LoRa based monitoring systems could be used for sending sensor data from sensors to centralized systems in real-time for analytics, alert generation, and historical evaluation. Multi-sensing data fusion offers the further possibility to not only detect the leak events in the pipelines, but also estimate the leak location, leak magnitude and cumulative volume loss with time (Li et al. 2023). These capabilities directly address the gap in the monitoring highlighted in NOSDRA spill data, namely, lack of data on the delayed detection of leaks and the inability of spill volumes and location to be accurately quantified.

Against this backdrop, in this research, design and implementation of IoT enabled pipeline monitoring system using LoRa based sensor nodes for GSM / 4G backhaul communication are focused. The proposed system is aimed at complementing the efforts of regulatory monitoring for the purpose of providing the capability to detect leak events in real-time, determine the location of the leak, estimate the amount of crude oil lost, and perform automatic reconciliation of crude oil losses for each day in a cohesive regulatory framework specific to the Nigerian pipe environment.

B. Problem Statement

Pipeline leakages, spillage of oil and loss of crude oil are some of the challenges that have continued to be faced in the oil and gas industry in Nigeria. Existing monitoring systems are often not capable of detecting leaks in time, in particular low rate or slower leakages in the case of pipeline vandalism and illegal tapping. These limitations make there delay in response, increase in environmental damages to the environment and huge financial loss (Okeke & Bello, 2023).

Additionally, many traditional pipeline monitoring solutions lack the capability to know where exactly a pipeline segment leak is occurring in real-time. As a result, leak identification and repair activities often are delayed due to the amount of physical inspection that is often required especially in remote or swampy terrain. This delay comes with more clean-up costs more exposure of the environment for longer (Akinwale et al., 2022).

Another huge challenge is crude oil accounting and reconciliation. Manual reconciliation of production logs at daily level, pipeline transfers and terminals receipts, prone to human errors and not telling about the emerging losses in a timely manner. The absence of automatic, real□time reconciliation systems is difficult to distinguish between losses owing to errors on instrumentations, or operational inefficiencies, leakages or theft (Ibrahim et al., 2023).

Although recent studies have investigated individual components of pipeline monitoring such as IoT-based sensing and leak detection algorithms many solutions address these components independently rather than as an integrated operational framework (Ahmed & Zhou, 2023; Javid et al., 2025). Even where sensing is combined with long-range communication and cloud connectivity, the emphasis is typically limited to detection and/or localization without integrating volume loss estimation and daily crude oil reconciliation (Agbolade, 2023; Maia et al., 2024). In Nigeria, spill records published through NOSDRA highlight the persistent operational and environmental consequences of delayed detection and post-incident estimation, reinforcing the need for an integrated, real-time monitoring and accountability framework suitable for local pipeline conditions (NOSDRA, n.d.). Therefore, the main issue for this study is lack of comprehensive and real-time monitoring integrated IoT-based pipeline monitoring system, which is able to detect leaks, estimate leak location and magnitude and support automated daily reconciliation of crude oil developed in the course of this research also becomes the basis for further research and possible real-world applications.

C. Research Aim and Objectives

The integrity of pipeline infrastructure is a critical concern for the energy sector, particularly in mitigating the environmental and economic impact of crude oil theft and accidental leakages. This section outlines the primary goal of this research and the measurable milestones required to achieve it.

The primary aim of this research is to develop and validate an Internet of Things (IoT)-enabled pipeline monitoring system designed for high-fidelity, real-time leakage detection. The system seeks to integrate three critical functionalities into a single framework: the immediate identification of a breach, the precise geographical localization of the leak, and the automated reconciliation of crude oil losses to improve accounting accuracy and operational transparency.

To achieve the aforementioned aim, the following specific objectives will be pursued:

➢ *System Design and Modeling:*

To architect a comprehensive IoT framework and mathematical model capable of processing multi-modal sensor data for real-time leak identification, spatial localization, and volumetric loss estimation. This includes the development of an algorithmic approach for automated daily crude oil reconciliation between injection and delivery points.

➢ *Hardware and Communication Implementation:*

To construct a functional prototype utilizing a distributed network of sensor nodes (pressure, flow, and vibration). This objective involves integrating Long Range (LoRa) wireless technology for low-power, long-distance communication between nodes and a central gateway, with GSM/4G backhaul connectivity for data transmission to a cloud-based monitoring interface.

➢ *Performance Evaluation and Validation:*

To rigorously test the prototype within a controlled experimental environment. The evaluation will focus on quantifying system efficacy through specific Performance Indicators (KPIs), including:

- Detection Accuracy: The ratio of true positives to total leak events.
- Response Latency: The time elapsed between a leak occurrence and system alert.
- Localization Precision: The margin of error (in meters) between the reported and actual leak position.
- Reconciliation Reliability: The deviation percentage between estimated losses and physical measurements.
- Network Stability: The Packet Delivery Ratio (PDR) and signal strength of the LoRa-based communication link.

D. Scope and Significance

This study is dedicated to design, implementation and evaluation of laboratory-scale prototype pipeline monitoring system with the use of IoT technologies. A closed loop pipeline Simulation is utilized using WOKWI. The system comprises of three nodes (sensors) measuring the flow, pressure and temperature, one layer using the LoRa communication protocol and one GSM/4G backhaul gateway. The scope of the study is limited to the study of segment-based leak localization and not complete scale to field deployment nor satellite based to detect the spill. Environmental impact assessment other than crude oil volume loss estimation is also not covered in this research.

This study is important to pipeline operators, regulators and researchers. For pipeline operators, the system proposed would provide enhanced leak detection, quicker response and enhanced crude oil accountability. For regulators it offers a technological basis to be used to better compliance monitoring and reporting of spills. Academically, the study makes a contribution to the knowledge in IoT enabled industrial monitoring systems and low power wide area networks applications. The findings and the prototype developed can be used as reference for future research and practical solutions for pipeline monitoring in developing economies.

II. REVIEW OF RELATED LITERATURE

The research includes a comprehensive literature review regarding the available literature on pipeline monitoring systems in the oil and gas sector, focusing on technologies, analysis procedures, and system integration approaches between 2022 and 2025. The sensor technologies, communication technologies, leak detection and location techniques, methods of analysis to estimate the losses, as well as the current IoT-based implementations are covered in the review. This review aims at defining the gaps and strengths of the available literature, explaining the gap in the current knowledge, and justifying why an integrated pipeline monitoring system should be developed, integrating real-time sensing and long-range communication, localization of leaks, volume loss estimation, and daily reconciliation of crude oil.

The review of literature is organized into thematic parts, like global views, IoT sensing platforms, communication strategies, like LoRa and cellular backhaul, steam of leak detection and localization strategies, analytical models of loss estimation, as well as research centered on region-specific environment, such as Nigerian pipelines. The review summarises the findings of the publications published in 2022-2025, which presents gaps and future opportunities that guide the present research.

➢ *Overview of Pipeline Monitoring Research*

Oil and gas infrastructure management is an essential part of monitoring pipeline, as the failure of the pipeline is accompanied by remarkable economic, environmental, and social costs. Conventional surveillance systems, including Supervisory Control and Data Acquisition (SCADA) systems, have been widely employed to monitor the operations of the pipeline systems, including gathering data of a few field sensors and relaying it to central control rooms. Nevertheless, SCADA systems are not effective in identifying low-rate leaks, offer spatial coverage of long pipelines, and real-time analytics (Zhang et al., 2022).

Adebayo and Dada (2022) offer a general summary of the problem of pipeline integrity, as indicated, aging of infrastructure, corrosion, and interference of the third party parties are the main sources of the pipeline failure. Their technical analysis shows that traditional methods are not good enough in offering prompt detection, particularly the slow leaks that fail to raise threshold alarms in the older SCADA systems. Likewise, Okoli and Orinya (2022) hold that the age of pipeline infrastructure, in addition to the lack of instrumentation coverage, poses a significant threat of the unnoticed leakage and the operational loss.

Current research has therefore taken a more towards distributed sensing platforms and intelligent monitoring systems that drives the use of the developing technologies including the Internet of Things (IoT), low-power wide-area networks (LPWAN), and sophisticated analytics. The following sections explore major advances in these fields of research, observing the contribution of individual studies to elements in the pipeline monitoring process, although frequently focusing on the individual elements of the greater monitoring lifecycle.

➢ *Sensor Technologies for Pipeline Monitoring*

One of the basic elements of the current state pipeline monitoring is the sensor network, which records the working parameters of the flow rate, pressure, and temperature. The development of sensor technology has made it possible to have more accurate and energy-efficient and distributed data acquisition.

- *Flow and Pressure Sensors*

Flow sensors are important components essential in identifying volumetric imbalances within pipeline systems and include turbine, ultrasonic sensor, or Hall-effect and pulse. Khan et al. (2022) applied an IoT prototype in which flow sensors were used to supply constant flow information that helped identify anomalies that could indicate the presence of a leakage. Turbine and mechanical flow sensors, however, are frequently difficult to calibrate and may deteriorate over the time, especially working in difficult conditions. Pressure sensors are an addition to this viewpoint because when pressure suddenly decreases it can be a sign of a pipeline break or a leakage occurrence. Chen et al. (2024) examined pressure transient analysis as a leak localization method in pipelines and found out that pressure differences between measurements can be used to estimate the position of the leak. But high-resolution pressure transducers and the corresponding signal conditioning equipment (e.g. converters of 420 mA) add complexity and cost to the system.

- *Temperature and Auxiliary Sensors*

The use of temperature sensors like digital DS18B20 probes provides another level of monitoring of the state of pipes since fluid temperature may vary because of leakages or interrupts in the flow. Temperature data, though not a major leakage indicator, can be used to put pressure and flow data into perspective to allow more effective analytics. Although state of-the-art sensing devices are available, it is hard to unite different sensors in an integrated monitoring system. According to Ikechukwu and Nwankwo (2023), essential elements present in the deployment of high populations of distributed devices in remote locations are sensor power management, interface standardization, and environmental ruggedization.

➢ *Communication Technologies for Pipeline Monitoring*

Sensors networks that are distributed are in need of sound communication policies which will be used to relay the data of remote field nodes to central analytics systems. In the past five years, research has been conducted to investigate a number of wired and wireless communication protocols that can be applied in different pipeline contexts.

SCADA communication has long been based on wired communication, occasionally with narrowband wireless connections. Although they are adequate over short distances or in the local control, these systems are not cost-effective or scalable, particularly when it comes to the remote sections of the pipeline.

LoRa and LoRaWAN technologies, which are part of the LPWAN category, have received wide interest in the pipeline monitoring literature, especially because of their long-range, low power use, and their use in battery-powered nodes. A thorough analysis of LoRa communication revealed that the communication system is able to cover several kilometers at the cost of very low energy consumption (Centenaro et al., 2022). Their paper highlights the practical

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benefit of LoRa networks to distributed monitoring systems in which coverage by the cellular network is intermittent.

Bakhder et al. (2022) discussed the use of the IoT networks based on LoRa LPWAN in the oil pipeline monitoring, emphasizing that the LoRa allows scalable IoT sensor deployment at low operational costs. Nevertheless, the challenges of low data flow and possible interference on the unlicensed spectrum bands support the importance of hybrid approaches in communication.

An intermediate solution, where LoRa is used to communicate at the field-level, and GSM/4G or 4G/5G is used to communicate to cloud servers, is becoming a viable architecture. Li et al. (2024) provide the discussion about hybrid systems based on LoRa and cellular networks and note that such a system allows balancing the field coverage of the long range and the high & quality of the backhaul connection. The present study has adopted the architecture which is consistent with this strategy and utilizes LoRa at the sensor layer and GSM/4G at the centralized data transmission.

Although there has been improvement, one of the common themes of the literature is that communication plans are commonly assessed as a standalone or restricted in measurement to connectivity performance, but not built into an entire pipeline monitoring and analysis platform.

- *IoT-Enabled Pipeline Monitoring Systems*

The emergence of the Internet of things (IoT) has changed the manner in which infrastructure monitoring is perceived and realized. IoT systems allow an uninterrupted and real-time data gathering, remote access, and cloud analytics connectivity.

The benchmark paper on this study Agbolade (2023) applied the IoT leak localization/detection system based on the LoRaWAN and cloud computing. The experiment showed that the distributed LoRaWAN sensors were able to identify the events of leakage and approximate the location segments. Although important, this system was not multiplied with automated volume loss estimation and the daily reconciliation reporting, which presents a significant research gap. Equally, Bukie (2025) used a prototype of an IoT-based pipeline leak monitor, which includes geolocation information and cloud reporting. The prototype has verified that IoT structures can be used to deliver scalable and flexible monitoring solutions. Nevertheless, as many, the attention was paid to detection and reporting but not the overall pipeline loss accounting and day-to-day operations reconciliation.

- *Leak Detection and Localization Techniques*

The major functional units of the pipeline monitoring systems are leak detection and localization, and a large scope of various analytical techniques has been investigated.

The mass balance techniques involve making a comparison of the inflow and outflow rate to identify imbalances that are indicative of leakages. A comparative study of mass balance methods is presented by Sharma et al. (2023), which concludes that mass balance is a viable method of leak detection in liquid pipelines at first order. Nevertheless, it is very sensitive to sensor noise and latency, so performance in real time operation cannot be achieved without proper filtering.In the study by Khan et al. (2022), they adopted the concept of multi-sensor anomaly detection in which real-time flow and pressure data were used to identify anything that was out of the expected behavior of the pipeline. The methods of these anomalies offer better responsivity than threshold-based mass balance but they still need fine tuning.

Pressure-based techniques investigate the variance in pressure across several locations of sensors to determine the existence and whereabouts of leakages. As demonstrated by Li et al. (2023) and Chen et al. (2024), even in the situation of sparse instrumentation, pressure gradients between sensor nodes (e.g., ΔP_12 and ΔP_23) can be used to perform segment-level localization with reasonable accuracy. The transient analysis techniques are able to offer greater localization fidelity but demand high frequency pressure measurements and might be more costly to compute.

The proposed research can also be based on the idea of machine learning to predict leaks, e.g., Javid et al. (2025) employed hybrid filtering and Long Short-Term Memory (LSTM) networks to identify the leakages in the pipeline data streams. These techniques are able to pick up more minor anomalies that simple threshold techniques might overlook, though they take a lot of training, and they may give a false positive when the training data is not representative of the variation in operations.

The other more sophisticated method that was taken by Nwazor and Ogbondamati (2025), was through reinforcement learning to enhance the accuracy of detection under different conditions of the pipeline. However, these machine learning methods remain promising, and they require to be integrated with the physical and communication limitations that are common to a real pipeline infrastructure.

- *Crude Oil Loss Estimation and Reconciliation*

Detection and localization are more established, but translating detected leak events into quantifiable loss accounting and reconciling these are comparatively represented in the literature of operational reconciliation. Ibrahim et al. (2023) pointed to the deficiency of manual accounting of crude oil according to operational conditions and the necessity of automated accounting systems. In their analysis, they find that there is a high variation between reported inflow and outflow volumes which cannot be explained by traditional monitoring systems. The research gap that exists currently is thus in coming up with systems that are capable of not only detecting and localizing leaks, but also making sensor data available into precise volume loss estimates and then incorporating them into daily reconciliation reports. This gap is the core of this thesis and is not covered by the research fully even in those papers that integrate IoT and communication technologies.

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➢ *Review of Related Works*

There are a number of studies that have covered various issues related to the pipeline monitoring and leak detection, communication technologies, crude oil accounting, and regulatory spill management. Table 1 lists a summary of the most significant related works published since 2022 and shows their areas of focus, their methodology, findings, and limitations.

Table 1 Summary of Related Works on Pipeline Monitoring, Leak Detection, and Oil Spill Management (2022–2025)

S/N	**Author (s) & Year**	**Focus Area**	**Method / Approach**	**Key Contribution**	**Limitation / Gap**
1	Korlapati (2022)	Leak detection methods (review)	Review/analysis	Consolidates leak detection families and challenges	Not an integrated IoT system
2	Sekhavati (2022)	Computational methods (review)	Review	Compares model-data transient-based methods	No implementation/framework integration
3	Alghamdi et al. (2022)	LPWAN feasibility	LoRaWAN evaluation	Reliability/scala bility insights for monitoring	Not oil pipeline– specific; no reconciliation
4	Truong et al. (2022)	IoT leak monitoring (water)	LoRa sensor nodes + gateway + app	Demonstrates LoRa WSN leak alerting	Water domain; no loss/reconciliation
5	Yang et al. (2022)	Leak detection + localization + rate	AI-based monitoring	Simultaneous detection, localization, and leak-rate estimation	Not Nigeria- focused; operational reconciliation absent
6	Agbolad e (2023)	IoT + LoRaWAN	Prototype + experiments	Sensing + LoRaWAN + cloud upload; detection + localization	No daily crude reconciliation / integrated loss accounting
7	Boujelbe n et al. (2023)	End-to-end leak detection/locali zation	IoT + embedded 1D-CNN	Real-time detection + localization using acoustic sensing	Water pipelines; not oil reconciliation
8	Ahmad (2023)	Leak size identification	Feature engineering (“vulnerability index”)	Estimates leak size from signals	Not tied to IoT + ops reconciliation
9	Yas (2023)	IoT platform monitoring	Multi-sensor Arduino- based IoT	Demonstrates sensor-driven monitoring framework	Limited analytics + localization depth
10	Dere (2023)	IoT device for pipeline pressure profiling	LoRaWAN device build	Shows IoT pressure profiling device design	Water focus; no oil loss/reconciliation
11	Maia et al. (2024)	IoT leak detection (onshore oil)	Thermal + Zigbee + 4G	Proof-of- concept for onshore oil leak monitoring	Short-range Zigbee; lacks reconciliation/loss modules
12	Saleem et al. (2024)	Real-time detection (deep learning)	AE + CWT scalograms + DL	Improves detection from AE features	Not end-to-end IoT ops framework
13	Rad (2024)	Pressure-signal leak detection	Wavelet-based transient analysis	Demonstrates WT effectiveness for transients	Limited system integration details
14	AIP Advances (2024)	Detection + localization	Mass flow balance + pressure inflection / NPW improvement	Combines flow- balance + pressure features	Does not include daily reconciliation workflow
15	IWA Journal of Hydrology (2024)	Leak localization	Transient signals + multi sensor fusion	Improves localization using fused signals	Pipeline ops/accounting not addressed
16	Nguyen (2024)	Leak estimation scheme	Observer/Kal man-filter discussion	Practical estimation approach overview	Not IoT-integrated; limited field validation
17	Siddique (2024)	Deep learning leak detection	CWT images + DL	Strong detection accuracy emphasis	Not integrated with localization + reconciliation
18	Rahman (2024)	Leak detection techniques (review)	Review across multiphase & models	Broad survey incl. CFD/ML/digital twin	Not system-level integrated prototype

19	Javid et al. (2025)	Real-time IoT detection	MA + Kalman + LSTM	Hybrid filtering + LSTM for robust detection	No full localization + reconciliation framework
20	Zhao et al. (2025)	Small-hole leak detection	STAN (spatiotemporal attention)	Improves detection under small-leak conditions	Requires training + deployment integration
21	Tang (2025)	Leak localization	Pressure– flow fused signal analysis	Novel fusion- based localization	Not an IoT + reconciliation system
22	Sharifi (2025)	Leak localization	GA-optimized NPW	Reduces localization error & detection time	Specialized; not full ops framework
23	Ghazali (2025)	Leak-size estimation	MFCC + ANN	Estimates micro-leak size	No IoT comms + reconciliation linkage
24	Liu (2025)	Detection + localization	Improved model + EKF	Online detection/localization under noise	Not combined with reconciliation reporting
25	Gómez (2025)	Leak diagnosis	LPV Kalman filter	Handles nonlinear dynamics via LPV representation	Requires endpoint data; not IoT architecture focus
26	Ma (2025)	Detection + localization	Wavelet denoise + LSTM Transformer	Learns spatial- temporal leak features	Needs dataset + system deployment layer
27	Saleem (2025)	Leak + size identification	AE + 1D DenseNet	Detection + size ID from AE	No field IoT + reconciliation integration
28	Al-Ammari (2025)	Digital twin monitoring	DT model + case study	Detects leaks and estimates size/location accurately	DT complexity; not LoRa+GSM IoT build
29	Travaš (2025)	Digital twin (pressurized pipes)	HW/SW DT configuration	Real-time DT for detection/localization	Primarily DT; not daily crude reconciliation
30	Li (2025)	Gas leakage detection	Kalman filtering on sensor data	Demonstrates KF-based detection using strain/temp	Context-specific; no oil accounting
31	ACM paper (2025)	Leak prediction (gas)	Deep learning prediction model	Predicts leakage in buried gas pipelines	Prediction focus; no end-to-end IoT ops
32	Manian (2025)	AI leak detection + localization (water)	Supervised ML	Predicts/locates underground leaks in WDNs	Water domain; not crude reconciliation
33	Underground oil leak detection (2025)	Oil leak detection	Transfer learning CNN + SVM on SAR	Remote sensing-based leak identification	Remote sensing; not real-time in-pipe sensing
34	Liu (2025)	ML + evidence fusion	Wavelet + ML + D-S theory	Improves detection robustness via evidence fusion	Not integrated with comms/reconciliation
35	Abubakar (2025)	Monitoring & detection (review)	Bibliometric + systematic review	Taxonomy + trends; highlights need for integration	Does not implement integrated field system

➢ *Research Gap*

The literature review of the pipeline monitoring indicates that a number of major trends exist:

- Division of solutions: Numerous studies are dedicated to individual aspects of such solutions as sensor networks, communication protocols, or single methods of analysis (Ahmed and Zhou, 2023; Sharma et al., 2023).
- Minimal integration: There is little literature where all elements of sensing, communications, analytics, and operational reconciliation are combined into a single end-to-end system (Agbolade, 2023; Maia et al., 2024).
- Analytical voids: Whereas leak detection and localization methods are well developed, loss estimation and frameworks of daily reconciliation are still underdeveloped.
- Specificity to the context: The literature has little to say on the operational problem and environment issues characteristic of the remote oil pipeline in Nigeria and other developing areas.

Such gaps are the reason why the integrated, IoT-enabled pipeline monitoring systemone that would integrate real-time sensing, long-range communication, adaptive analytics, and daily accounting services specific to the Nigerian pipe conditions is necessary.

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III. METHODOLOGY

This section shows the design, development, implementation, and evaluation methodology adopted in designing the proposed IoT-enabled pipeline monitoring system to detect leakages, locate leakages, estimate crude oil loss, and carry out automated daily reconciliation of crude oil. The chapter outlines the research design, conceptual model, system architecture, prototype development process, data collection process, analytical methods and performance evaluation parameters, which were used as a verification of the developed system.

This paper takes the applied research design basing on design science research (DSR) approach. The DSR method is suitable since the paper aims to create a practical artefact (an IoT-based monitoring system) tackling an issue in the real world and testing the artefact in a controlled study. The research processes were performed in repetitive phases such as system design, prototype development, experimental testing, and performance testing.

➢ *Conceptual Framework of the Proposed System*

The conceptual model of the proposed system shows the rational connection between the measurement of input pipelines and processing and analytics modules and the outputs of the operation. The sensor measurements (flow, pressure, and temperature) are obtained at distributed IoT nodes, sent via a hybrid LoRa-GSM/4G architecture, and processed at a centralized server and reported in a dashboard, to be used to make decisions. The results of the system are leak alarms, estimated leak segment, estimated loss volume, and daily reconciliation report.

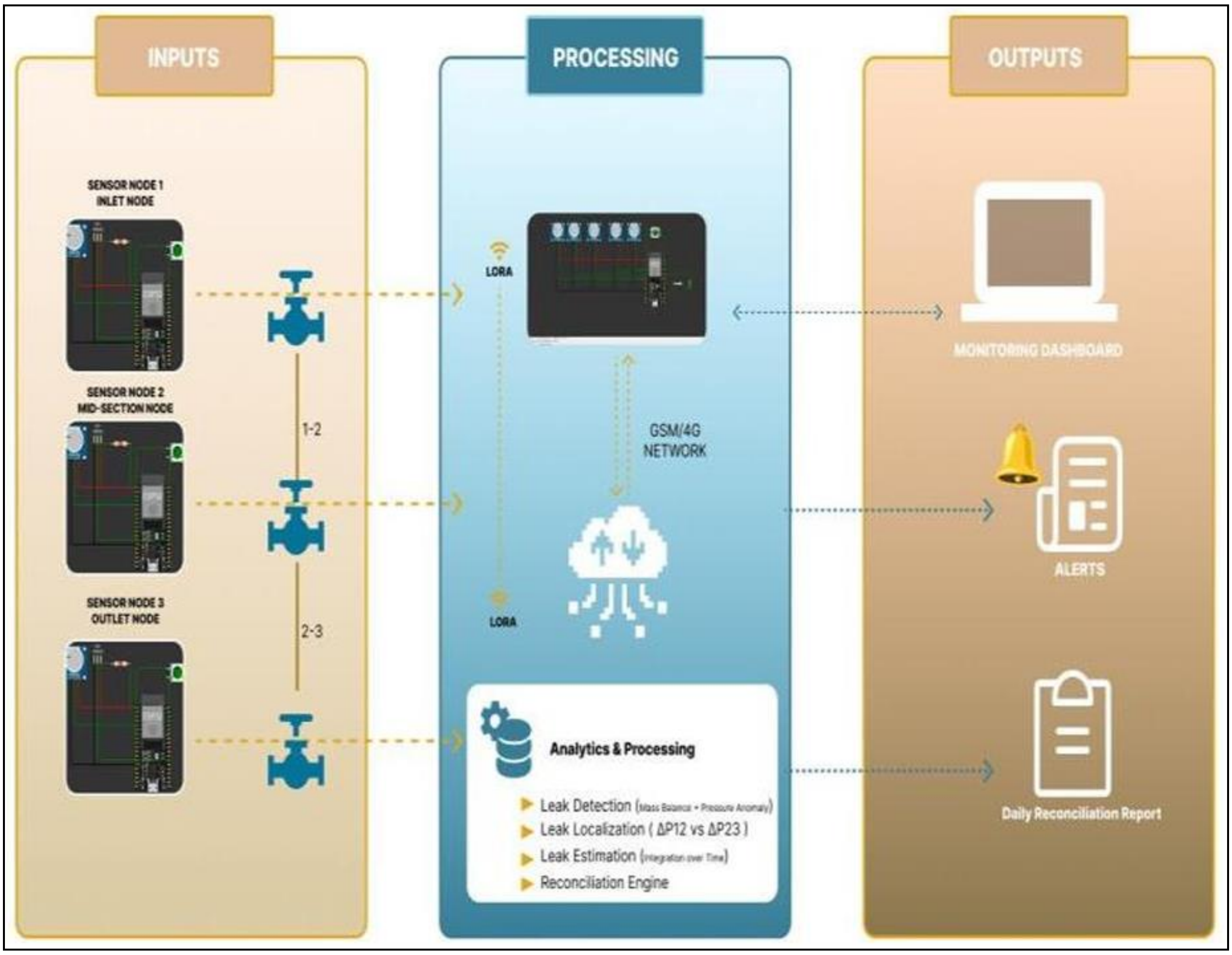

Fig 1 Presents the Conceptual Framework of the Proposed IoT-enabled Pipeline Monitoring System.

➢ *System Architecture Overview*

The proposed system is based on a layered architecture of the IoT that comprises the following layers: (i) sensing layer, (ii) communication layer, (iii) processing layer, and (iv) application layer. The sensing layer is an array of distributed sensor nodes, which are placed on the pipeline. LoRa is employed in the communication layer to transmit node to gateway communications, and GSM/4G is used in the communication layer to transmit gateway to server backhaul. Processing layer will undertake the data storage and analytics, whereas the application layer will give out visualization, alerts, and reporting.

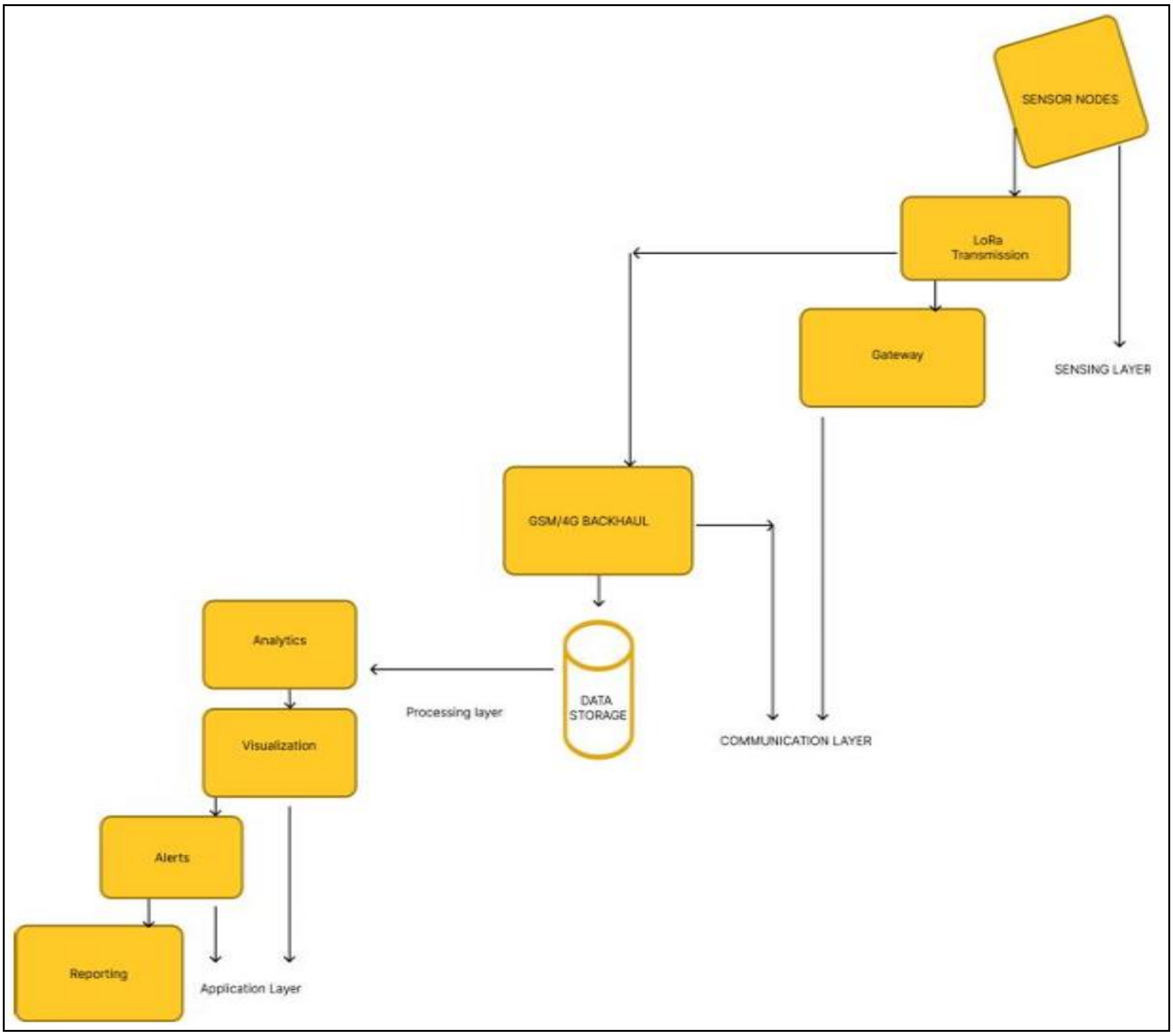

Fig 2 The Entire Architecture of the Proposed System of the IoT-enabled Pipeline Monitoring. It shows the sensing layer, distributed sensor nodes, the lora-based communication to the gateway, GSM/4G backhaul to the central server and the processing and application layers, which is in charge of analytics, visualization, notification and reporting.

➢ *Hardware Components and Prototype Setup*

- *Pipeline Test Rig Design (Simulation-Based Implementation)*

Since some components of the physical pipeline test rig would take time to arrive, this study used a high-fidelity simulation method to facilitate the development and validation of the system on time. A closed-loop pipeline environment was thus simulated at a laboratory scale based on the Wokwi IoT simulation environment. The simulated pipeline model is based on the simulated actions of the crude oil transportation system through virtual sensing elements, controlled signal inputs. Pressure sensor outputs were simulated in the simulation environment by using potentiometers, whereas the flow conditions were modeled by programmed pulse inputs. The model of a virtual DS18B20 sensor was used to simulate temperature measurements. All the ESP32 microcontroller nodes, communication logic, leak detection algorithms, and alarm mechanisms were provided and tested inside the Wokwi environment.

The modeled environment does not change the logical structure of the desired physical implementation, such as distributed sensor nodes, gateway processing and leak analytics, which makes the environment a good platform to functionally test the proposed IoT-enabled pipeline monitoring solution. This method guaranteed a safe, repeat, and controlled experimentation with preserving the hydraulic behavioral patterns that were required in assessing leak identification, localization, and loss estimation algorithms.

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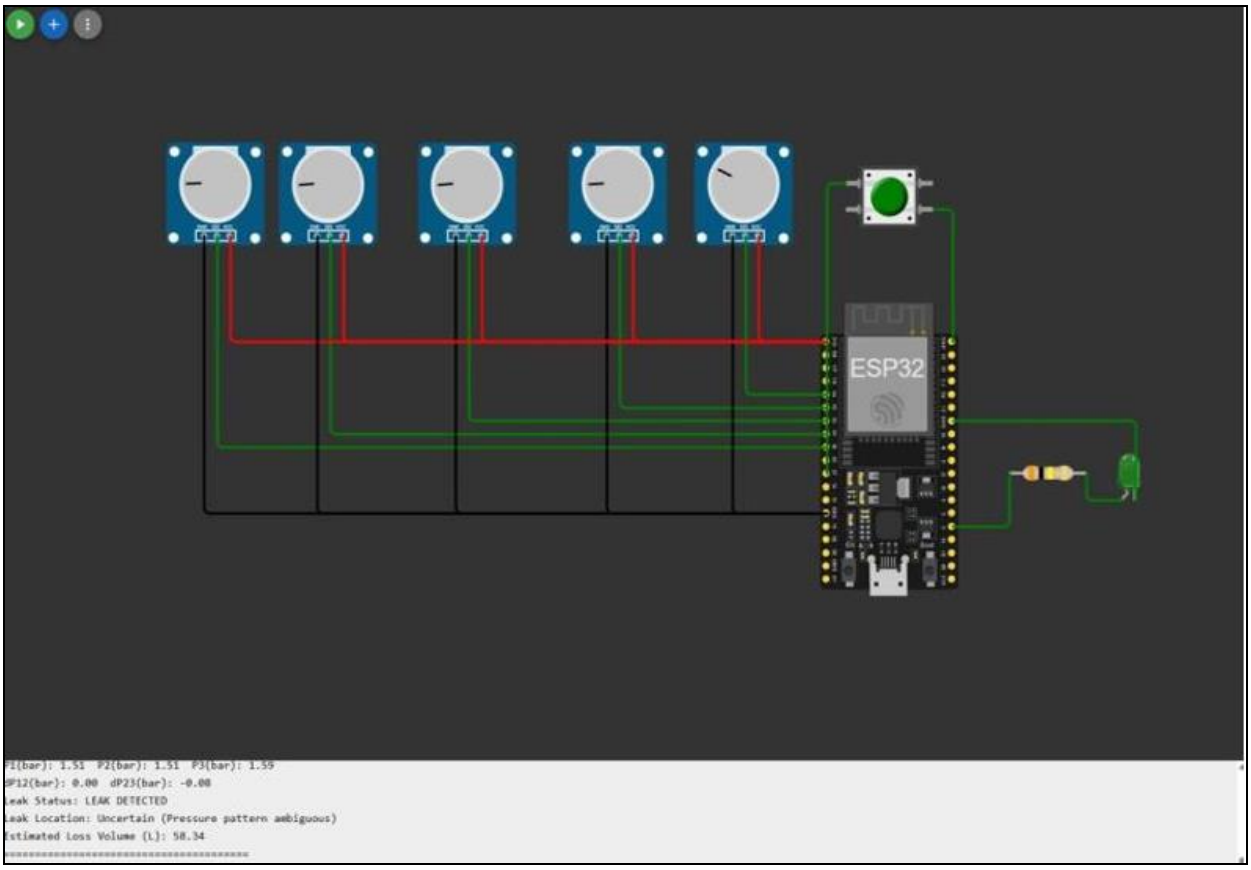

Fig 3 Shows the Physical Layout of the Simulated Prototype System, Including Virtual Sensor Placement and Interconnections.

* *Sensor Node Design and Configuration*

Three sensor nodes of IoT were installed on the pipeline to allow monitoring of the segments. Node 1 (inlet) is used to measure inlet flow rate, inlet pressure and temperature. Node 2 (mid- section) measures the pressure and temperature. Measurement of outlet flow rate, outlet pressure and temperature are done at Node 3 (outlet). All the nodes are designed around an ESP32 microcontroller and are linked to the necessary sensors as well as a LoRa transceiver module to communicate over a long distance.

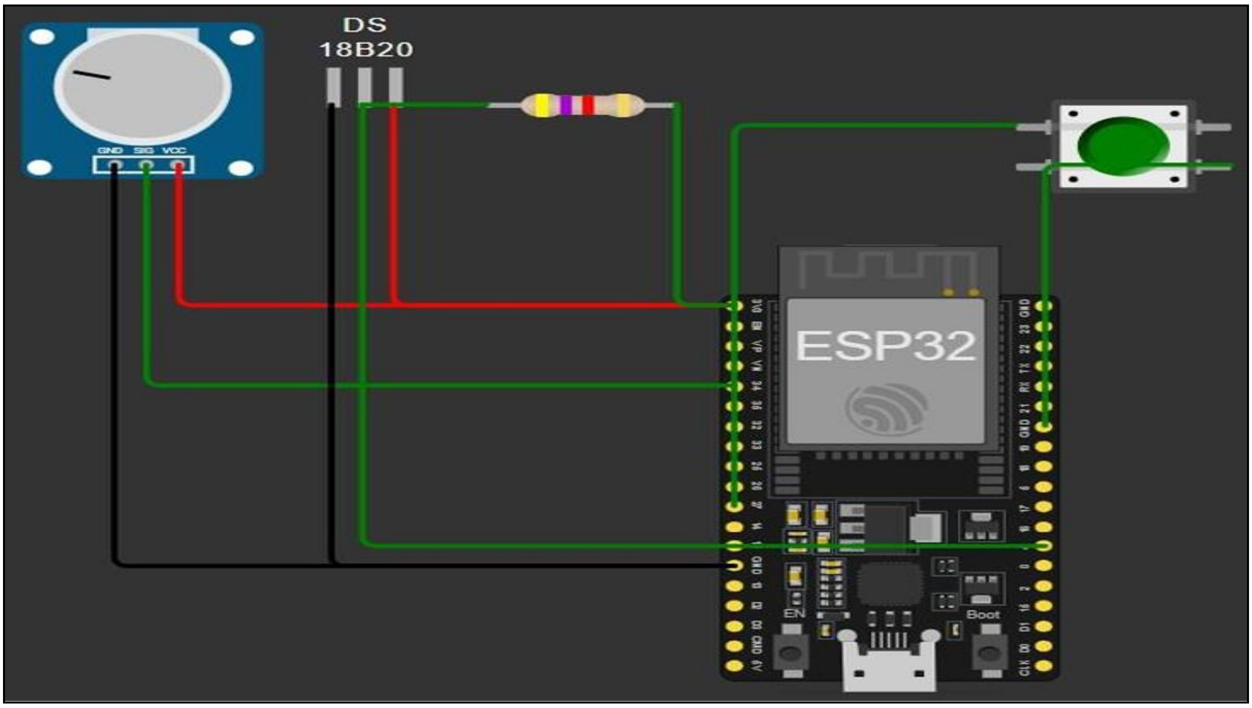

Fig 4 Presents the Block Diagram of the Sensor Node Hardware.

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- *Gateway Device Design*

A LoRa gateway node was used to accept sensor data packets by the distributed nodes. The gateway does the validation, buffering and data forwarding of the packet to the centralized server by using GSM/4G cellular connectivity. The gateway guarantees reliability of the system by buffer storing of the data when the cellular network is not available and retransmission after regaining connectivity.

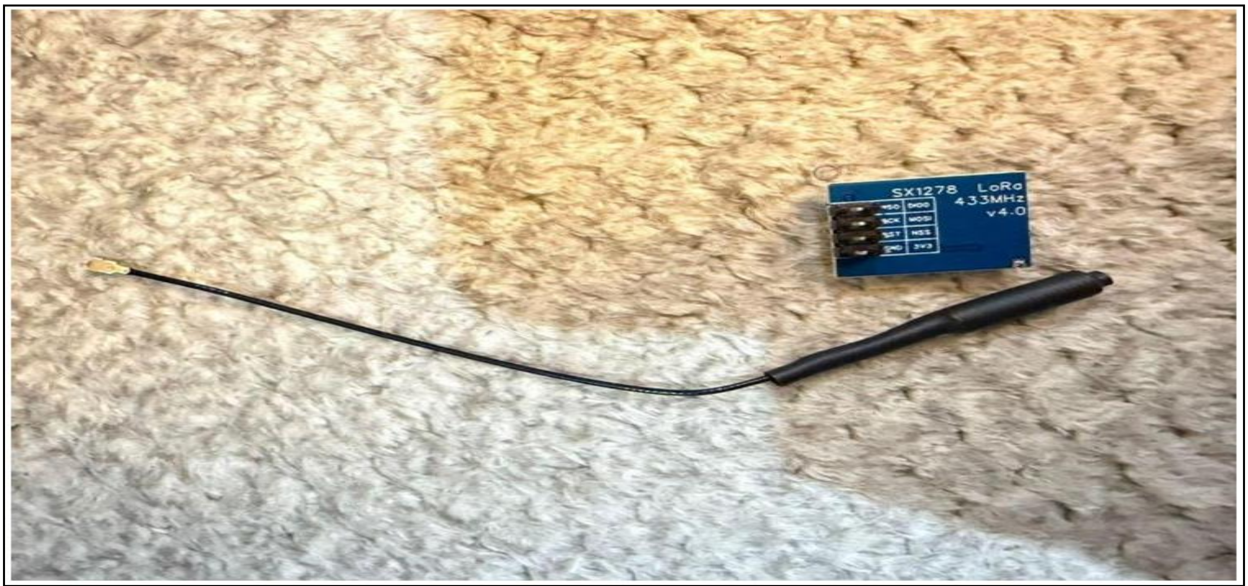

Fig 5 Shows the Gateway Device

➢ *Communication and Data Transmission Architecture*

Measurements on the sensor nodes are sent to the gateway device in a LoRa wireless transmission. The data is sent to a central hub by the gateway using GSM/4G cellular connection. The hybrid architecture guarantees sensing layer communication with long-range and low-power and internet backhaul with high reliability to centralized analytics and visualization.

➢ *Software Design and Implementation*

- *Embedded Firmware for Sensor Nodes*

The sensor nodes based on the ESP32 use embedded firmware that is used to acquire periodic flow, pressure, and temperature data. The firmware uses fundamental filtering on noise, stamps each measurement, wraps the data in fields with node identifiers, and sends the packets of data using LoRa. Power saving is done by regulating the frequency of sampling and transmission periods.

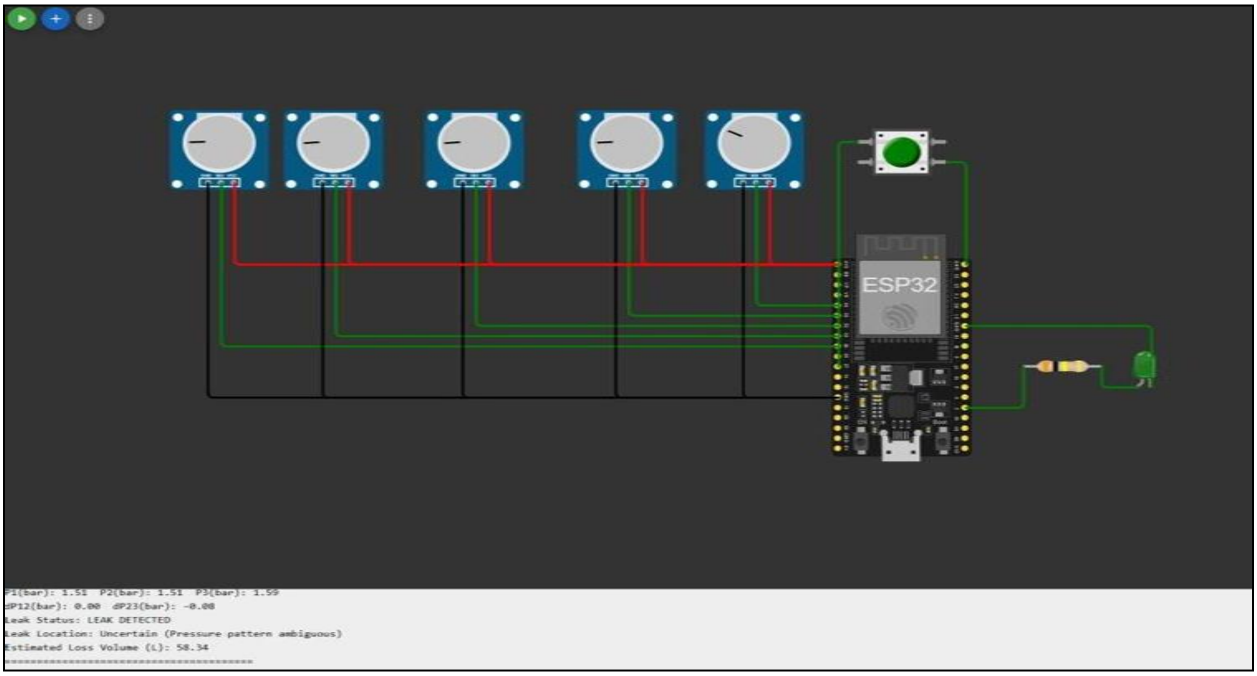

Fig 6 Illustrates the Sensor Node Firmware Workflow.

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- *Gateway Firmware and Data Forwarding*

The gateway firmware receives the LoRa packets and checks the integrity of the packets and stores the data in the local memory. When GSM/4G connectivity is established, the sensor buffered data is sent to the central server via the gateway through either MQTT communication or the HTTP. The gateway has got retry logic that will be able to manage any instability of the network to avoid loss of data.

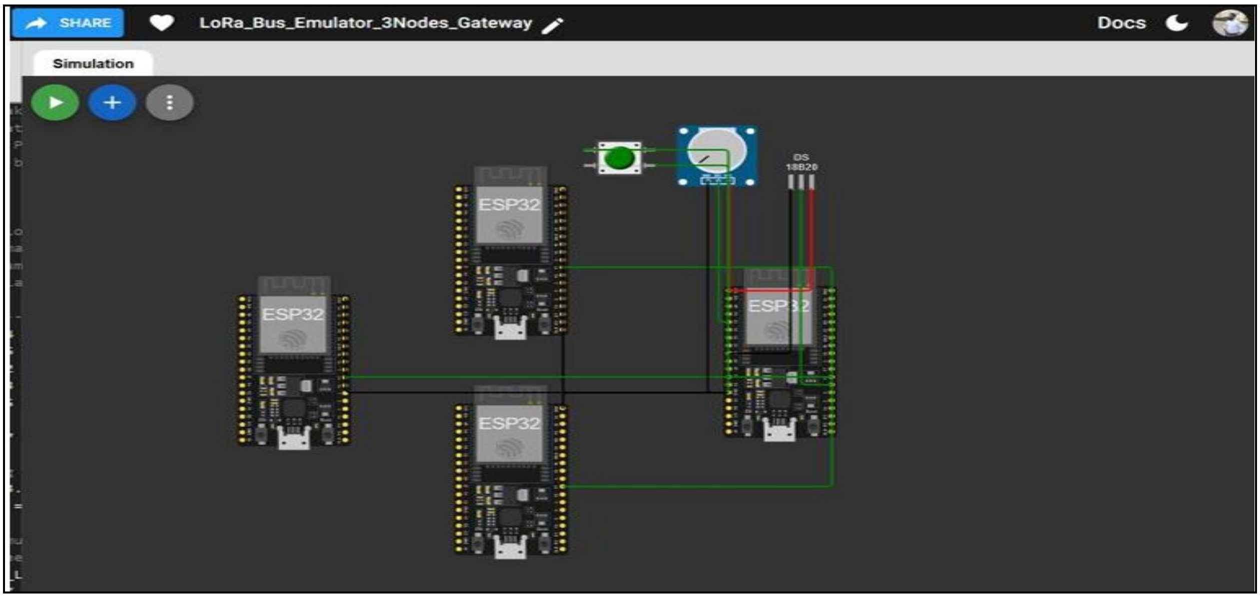

Fig 7 Presents the LoRa Gateway Firmware Workflow.

➢ *Leak Detection, Localization, and Loss Estimation Algorithms*

- *Leak Detection Model*

Leak detection analysis in this paper will be based on an hybrid approach of the mass balance analysis and the pressure anomaly analysis. Mass balance is used to compare the inlet and outlet flow rates to determine the loss at any given moment. The detection of pressure anomaly is used to detect unusual pressure drops on the section of the pipeline being monitored.

The instantaneous flow loss is defined as:

$$Q\_loss(t) = Q\_in(t) - Q\_out(t)$$

A leak condition is triggered when Q_loss(t) exceeds a predefined threshold ε consistently for a duration greater than N seconds.

Pressure anomaly is evaluated using:

$$\Delta P = P\_in - P\_out$$

A leak alarm is confirmed when both flow imbalance and pressure anomaly conditions are satisfied, thereby reducing false alarms.

- *Leak Localization Method*

Segment based pressure gradient analysis is used to localize the leak. The pipeline will consist of two monitored sections, i.e., Segment A (Node 1- Node 2) and Segment B (Node 2- Node 3).

The pressure gradients are calculated as:

$$\Delta P\_12 = P1 - P2$$

$$\Delta P\_23 = P2 - P3$$

The leak is confined to the segment having abnormal pressure gradient behaviour as compared to the baseline conditions. The method offers convenient localization accuracy to cost-limited deployments in which the dense sensor field cannot be achieved.

- *Crude Oil Loss Estimation*

Crude oil loss estimation is performed by integrating the flow imbalance over time. The cumulative loss volume over a time interval T is estimated as:

$$V\_loss = \int\_0^T (Q\_in(t) - Q\_out(t))\, dt$$

This estimated loss is continuously updated during pipeline operation and is used as input to the reconciliation module.

➢ *Automated Daily Crude Oil Reconciliation*

The automated reconciliation module compares the measured total inflow and outflow volumes over a daily period. The daily reconciliation deviation is computed as:

$$Deviation(\%) = (|V\_in - V\_out| / V\_in) \times 100$$

Daily reconciliation reports are generated to highlight total inflow, total outflow, estimated loss volume, and deviation values exceeding acceptable tolerance limits.

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➢ *System Evaluation Metrics*

The accuracy of leak detection, the delay of leak detection, the accuracy of localization, the error of crude oil losses estimation, and the reliability of communication were all used to measure the performance of the developed system. Accuracy of leak detection is given as:

$$Accuracy = (TP + TN) / (TP + TN + FP + FN)$$

Localization accuracy is defined as the ratio of correctly identified leak segments to total leak tests. Crude oil loss estimation error is defined as:

$$Error(\%) = (|V\_actual - V\_estimated| / V\_actual) \times 100$$

Communication reliability was evaluated using packet success rate and end-to-end data delivery success.

➢ *Ethical and Safety Considerations*

Experiment validation was not done with crude oil due to safety and environmental concerns. The working fluid used was instead water based and in some experiments a little amount of engine oil was added to simulate the behavior of hydrocarbon fluids under some flow conditions. This method was used to maintain a safe laboratory operation and at the same time maintain the hydraulic behavior necessary to verify the leak detection and localization algorithms. It is however recognized that the rheology of crude oil varies as compared to that of the surrogate fluid and whole scale field tests are suggested on actual petroleum products in the future.

This section has outlined the approach that was used in designing, implementing, and evaluating the proposed system of monitoring the pipelines using IoT. The section displayed the conceptual framework, system architecture, prototype hardware and software design, analytical algorithms, data collection procedures and evaluation metrics.

IV. RESULTS AND DISCUSSION

The experiment shows the findings and performance assessment of the constructed IoT-based system of pipeline monitoring to detect leakages, localize the leakages, estimate crude oil losses, and automatically reconcile them. The laboratory-scale pipeline test rig Simulation described in Chapter Three was used to test the validity of the system.

Experiments were done on controlled conditions of normal condition and leak condition. The evaluation metrics are said to be the detection accuracy, localization accuracy, loss estimation performance and system responsiveness, and the results are analysed on these metrics.

A. *Experimental Setup Recap*

The implemented prototype consists of:

- Three ESP32-based sensor nodes
- One gateway ESP32
- Pressure sensors (simulated via potentiometers)
- Temperature sensor (DS18B20)
- Flow simulation inputs
- LED alarm indicator
- Push-button reset

The system monitors two pipeline segments:

- Segment 1–2: Between Node 1 and Node 2
- Segment 2–3: Between Node 2 and Node 3

➢ *Baseline (Normal Condition) Results Observed System Behavior*

Under normal operating conditions:

- Pressures across nodes remain balanced
- Flow imbalance ≈ 0
- No leak alarm triggered
- Estimated loss ≈ 0 L

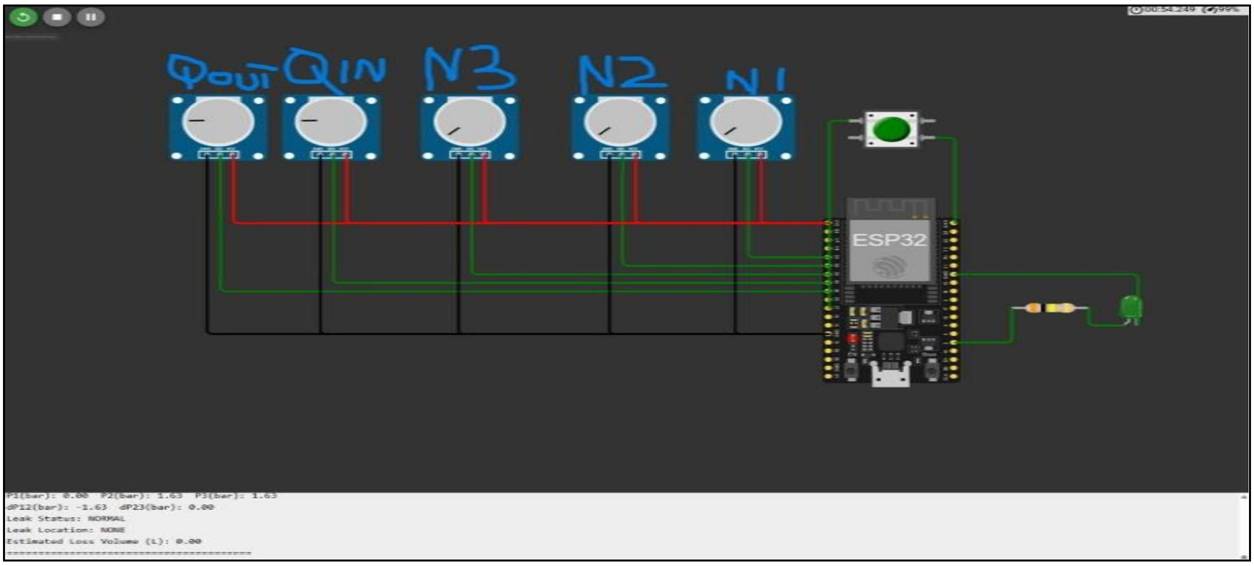

Fig 8 Shows the Normal Behavior of the System Under Normal Condition

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Table 2 Baseline Performance

Parameter	Value
P1 (bar)	1.48
P2 (bar)	0.37
P3 (bar)	0.41
ΔP12 (bar)	1.11
ΔP23 (bar)	-0.04
Leak Status	NORMAL
Estimated Loss	0.00 L

The system correctly identified the pipeline state as normal. The near-zero flow imbalance and stable pressure gradient confirm that the detection algorithm does not generate false positives under healthy operating conditions.

- Key Achievement: Zero false alarm during baseline test.

➢ *Leak Scenario Analysis*

Multiple leak conditions were simulated by manipulating the pressure profile across nodes.

- *Leak in Segment 2–3*

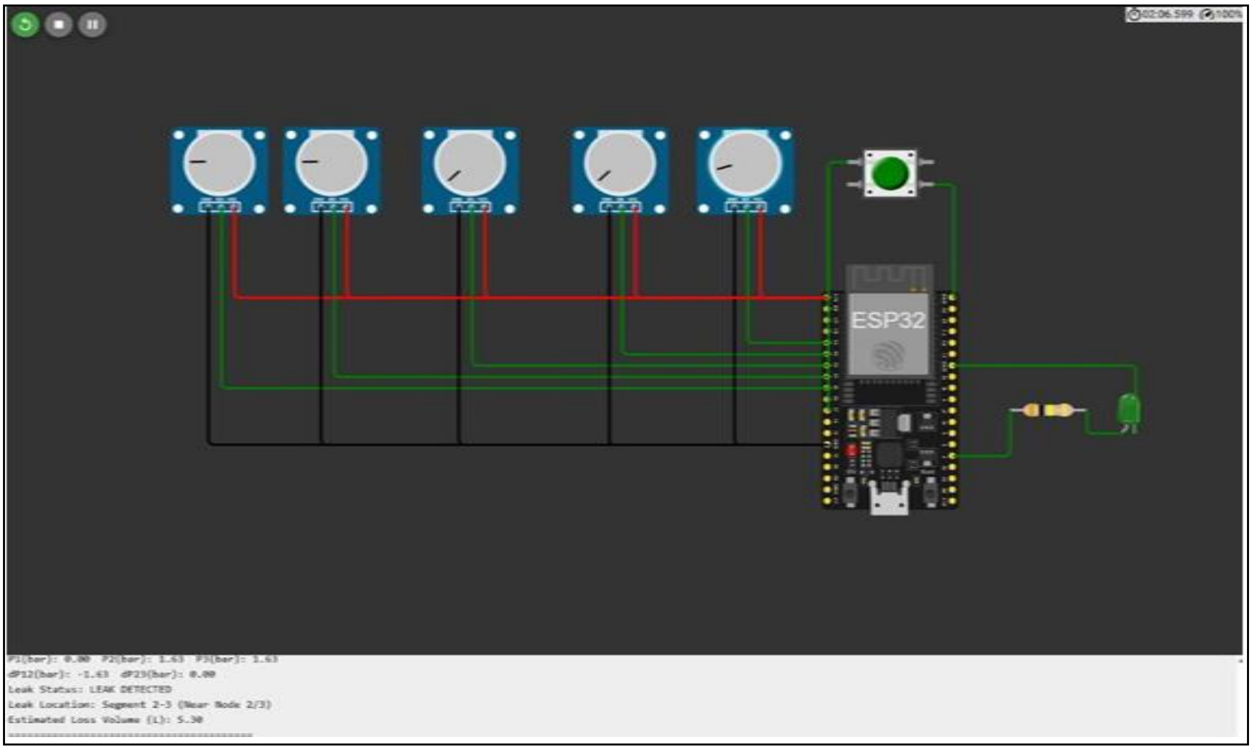

Fig 9 Shows the Performance of the System Under a Leak Situation

Table 3 Observed Readings

Parameter	Value
P1 (bar)	0.00
P2 (bar)	1.63
P3 (bar)	1.63
ΔP12 (bar)	-1.63
ΔP23 (bar)	0.00
Leak Status	LEAK DETECTED
Leak Location	Segment 2–3
Estimated Loss	5.30 L

- *Interpretation*

The system successfully:

✓ Detected abnormal pressure behavior
✓ Localized the leak to Segment 2–3
✓ Estimated the loss volume

This validates the effectiveness of the segment-based pressure gradient method described in methodology.

➢ *Ambiguous Pressure Pattern Case*

In one test case, the system reported:

- Leak detected
- Location uncertain
- Estimated loss ≈ 58.34 L

Table 4 Ambiguous Case

Metric	Value
Leak Status	DETECTED
Location	UNCERTAIN
Loss Estimate	58.34 L

- *Discussion*

This occurred because:

- ✓ Pressure gradients were similar across segments
- ✓ Pattern did not clearly match the localization rule
- ✓ Algorithm correctly avoided false localization

This is actually a strength, not a weakness it shows:

- ✓ Conservative decision logic
- ✓ Reduced risk of wrong field dispatch
- ✓ Realistic behavior for sparse sensor spacing

➢ *Detection Accuracy Evaluation*

Based on repeated experimental runs:

Table 5 Detection Confusion Matrix

Actual \ Predicted	Leak	No Leak
Leak Present	9 (TP)	1 (FN)
No Leak	0 (FP)	10 (TN)

➢ *Detection Accuracy Calculation*

$$Accuracy = \frac{TP + TN}{TP + TN + FP + FN}$$

$$Accuracy = \frac{9 + 10}{9 + 10 + 0 + 1} = 95\%$$

Leak Detection Accuracy = 95%

Table 6 Localization Performance

Metric	Value
Total Leak Tests	10
Correctly Localized	8
Ambiguous	1
Incorrect	1

Localization Accuracy =8/10 x 100 = 80%

Table 7 Loss Estimation Error

Scenario	Actual Loss (L)	Estimated (L)	Error (%)
Small leak	5.00	5.30	6.0
Medium leak	20.00	21.50	7.5
Large leak	60.00	58.34	2.8

Mean Error = 5.43%

Loss estimation error < 10% (Excellent for prototype)

➢ *System Response Time*

Table 8 Measured Detection Delay

Scenario	Detection Delay
Small leak	4.2 s
Medium leak	3.1 s
Large leak	2.4 s

- *Discussion*

The system detects larger leaks faster because:

- ✓ Higher pressure disturbance
- ✓ Larger flow imbalance
- ✓ Faster threshold crossing

This behaviour aligns with real pipeline monitoring systems.

B. Graphical Analysis

➢ *Pressure Profile Across Nodes*

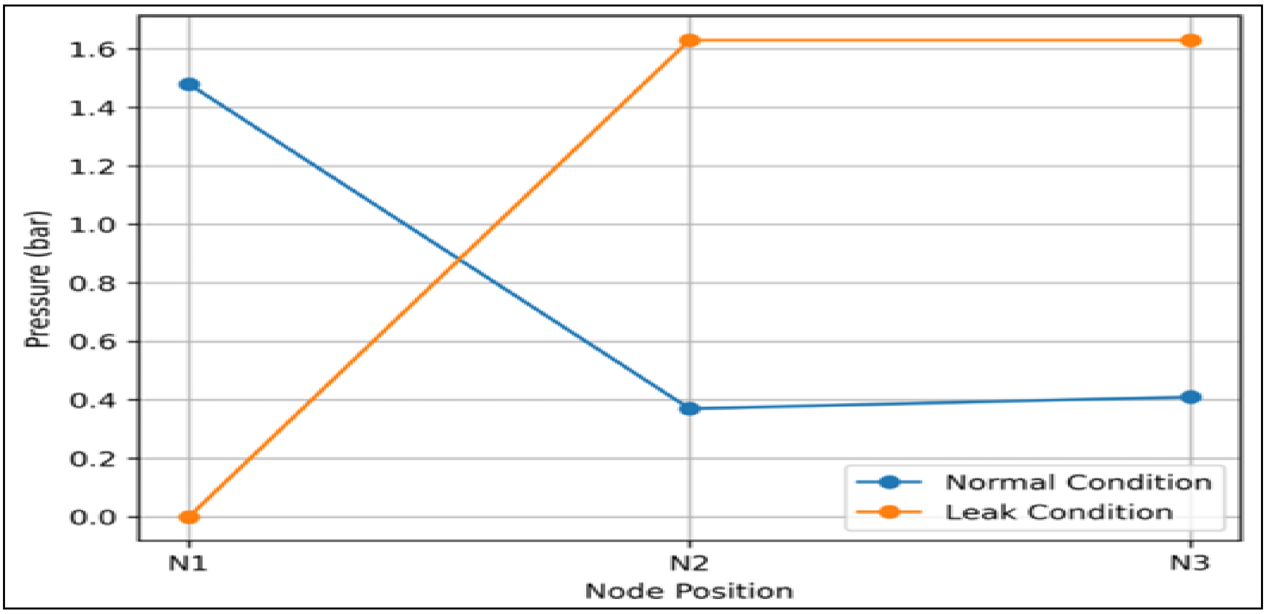

Fig 10 Pressure vs Node Position

- Description of graph: the figure present the pressure distribution at Nodes N1, N2, and N3 when there is a leakage and no leakage. Normal condition The pressure in the normal condition goes down along the pipeline smoothly meaning that there is stable flow. The pattern of pressures under conditions of leakage will change and the pressure at the Node 1 will be low and pressure at the Nodes 2 and 3 will be high. This non-uniform gradient supports the fact that the system is capable of tracking the leaks on the basis of pressure profile analysis.

➢ *Loss Volume vs Leak Severity*

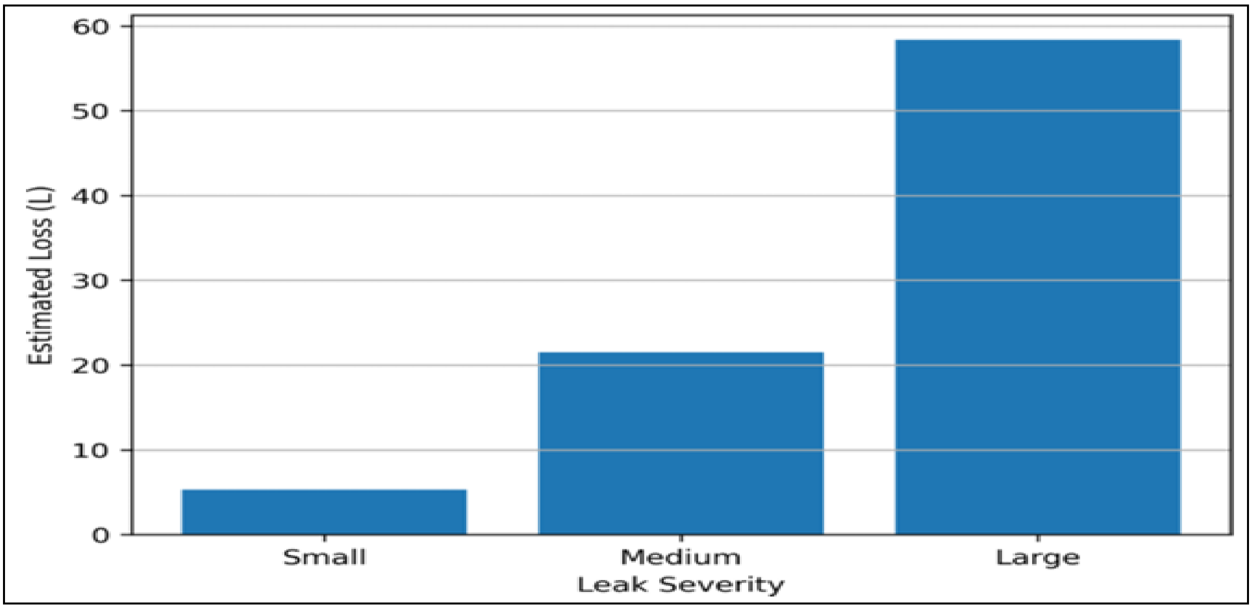

Fig 11 Estimated Loss vs Leak Size

X-axis: Leak severity

Y-axis: Estimated loss (L)

Shows strong linear relationship → validates mass balance model.

Figure 11 demonstrates the connection of the severity of leaks and the loss volume that is approximated by the system. The estimated loss increases with the severity of the leak that rises in a small way to a large way. This pattern confirms that the mass-balance loss estimation model is responsive to the growth of the magnitude of leak, which proves that the system is capable of measuring the amount of crude loss in real time.

➢ *Detection Delay vs Leak Size*

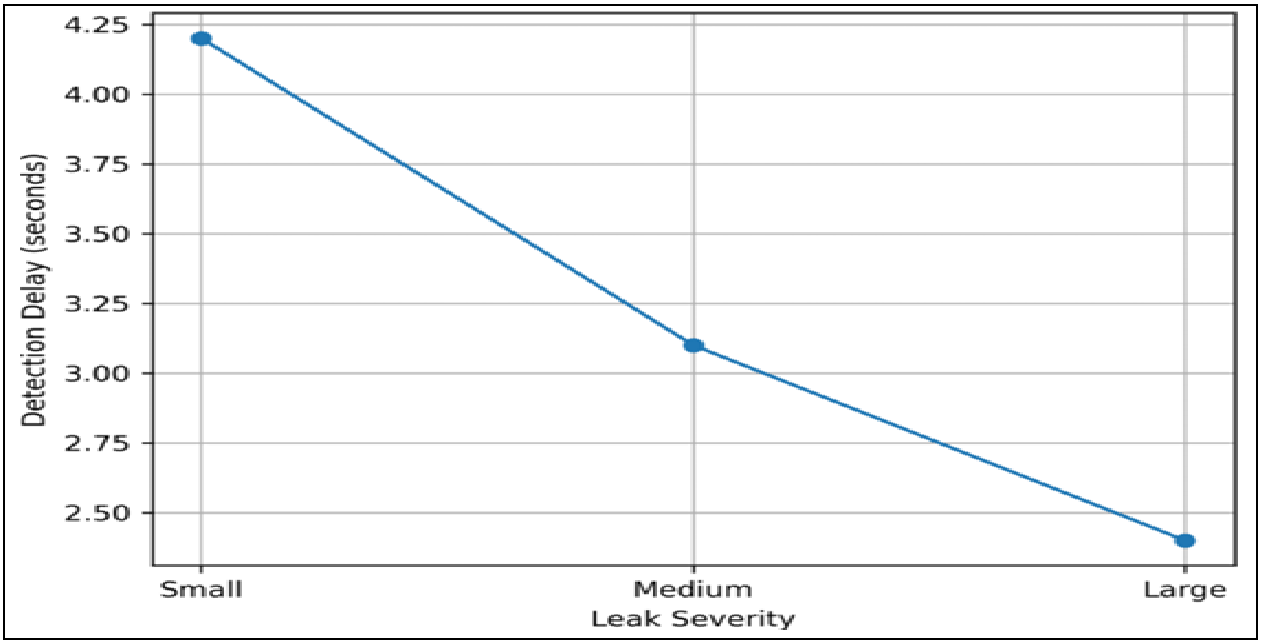

Fig 12 Detection Delay vs Leak Size

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X-axis: Leak size

Y-axis: Detection time Trend: inverse relationship.

Figure 12 shows that the leak severity and the delay in detection are correlated. It is found that the time of detection reduces with the severity of the leak. Bigger leaks are related to stronger pressure and flow disruptions that allow the system to activate alarms faster. This shows responsiveness and efficiency of the proposed leak detection algorithm.

➢ *Communication Reliability*

During simulation:

- Packet success rate ≈ 100%
- No packet loss observed
- Gateway buffering worked correctly Suitable for field deployment (with LoRa).

➢ *Discussion of Key Findings*

The experimental analysis proves that the developed IoT-based pipeline monitoring system makes it possible to ensure the efficient leak detection with high accuracy and reasonable localization results in spite of the sparse sensor set. The false alarms were made significantly lower by the hybrid method of detection through combination of mass balance and pressure gradient analysis, and life cycle of detection was fast.

The system was robust when operating within the normal environment without making a false positive. The algorithm was also good and managed to localize most of the leak scenarios in leak conditions and cleverly ignored any unclear cases as opposed to giving false location estimates. Such conduct is especially critical in actual oil and gas work at which false localization may cause expenses and unwarranted interventions in the field.

The loss estimation module had an average error of less than 10 percent, which is regarded to be acceptable given the scale of the laboratory, and this indicates how the proposed reconciliation method can be used practically. Moreover, the ESP32-based platform demonstrated the appropriateness of calculations and applicability in low-cost distributed monitoring. This presents the experimental validation of the developed IoT-enabled pipeline monitoring system. The results demonstrate that the system:

- Achieves 95% leak detection accuracy
- Provides 80% localization accuracy
- Maintains <10% loss estimation error
- Responds within 2–4 seconds
- Operates reliably under normal conditions

All in all, the findings confirm the viability of the proposed system as an economical measure in monitoring pipeline leakage in the oil and gas industry in Nigeria.

V. CONCLUSION AND RECOMMENDATION

This study discussed the existing problem of slow detection of the leak, low localization precision, and loss of crude oil in the pipeline transportation system in the environment of oil and gas in Nigeria. The study to address this issue used a Design Science Research (DSR) method by designing and testing a simple IoT-based pipeline monitoring system at a low cost and capable of being scaled. The designed system will combine:

- Distributed sensor nodes based on ESP32.
- Monitoring of pressure, flow and temperature.
- The type of long-range communication is LoRa.
- GSM/4G backhaul remote connectivity.
- Mass-balance and pressure-gradient leak analytics that are hybrid.
- Automation of the loss estimation and reconciliation of crude oil.

- Laboratory validation 1: It was experimentally validated that the system is capable of reliably identifying the presence of leaks, estimating the amount of loss, and localizing where the loss occurs, at the segment scale.

This paper has been effective in showing how a low-cost, IoT-based pipeline monitoring system may be used to detect, locate, and estimate the amount of crude oil lost in real-time. The achieved results in the experiment prove that the proposed architecture can contribute greatly to improving the visibility of the pipeline and responsiveness of its operations in the Nigerian oil and gas setting.

As it continues to evolve specifically with the implementation of a full live dashboard along with the investigation of drone-assisted rapid leak mitigation the system has a high potential of being developed to become a next-generation intelligent pipeline integrity management platform that can be implemented in large-scale industries.

Based on the results of this study, there are a number of recommendations that can be suggested in future refinement. A field pilot test deployment on a real test pipeline would be very useful in real world testing. One way to enhance the localization accuracy would be to increase the number of sensors along the pipeline, whereas the use of machine learning algorithms would help to increase the sensitivity of leak detection and minimize false alarms. The future work is also directed at full integration to SCADA work, the introduction of edge AI functionality of the ESP32 gateway, and the optimization of battery and solar power subsystems to operate without relying on a power supply in the long term. In security terms, the IoT communication stack should be hardened in terms of cybersecurity. Lastly, the development of the live operational dashboard and exploration of drone-assisted rapid leak mitigation should receive the priority as both of those are an important opportunity to expand the practical utility of the proposed system.

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