Review

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Review

Crude Oil Spillage in the Niger Delta—Causes, Impact and Detection Approaches

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Abstract: Pipelines are widely used globally, particularly in Nigeria, to transport raw and processed hydrocarbon fluids, including crude oil, from the point of production to the shore for export, processing facilities and distribution of refined products to depots for sales and consumption. Although pipelines are designed to withstand environmental and physical shocks, intermittently, pipelines are exposed to natural or human-induced conditions that damage pipelines and disrupt their functionality. These disruptions could result from operational defects or vandalism, causing an economic loss of up to US$ 658.5 million as observed in the Niger Delta from 1990 to 2022. Furthermore, product loss of about 705,100 barrels observed over the same period has caused environmental and social impacts, damaging the natural environment, destroying livelihoods supported by the ecosystem, and deteriorating the health of residents as documented in several literatures. To mitigate these issues and ensure the safe and reliable conveyance of crude oil in pipelines, measures must be taken to timely detect spillages and intervene during oil spillages to minimize damage and loss. Such detection methods include external, visual/ biological and internal/computation-based approaches. This paper uses a mixed-method approach to review the literature on the causes and impact of crude oil pipeline leakage in the Niger Delta region of Nigeria and highlights some methods that could be applied to detect pipeline leakage, as well as their strengths and inefficiencies. This paper further assesses the joint investigation visit mechanisms for oil spill response used in the oil and gas industry in Nigeria and identified that between 2006 to 2021, it took an average of 4 days to report oil spill occurrence, and 21 days to respond. Also, for 18 percent of the spill occurrences in that period, there were no JIV. This study suggests that the gap in the JIV mechanism can be addressed by integrating technology to enhance detectability and minimize the cost of monitoring. The paper also guides the way forward to develop and improve the reliability of pipeline leak detection systems.

Keywords: detection approaches; Niger Delta; oil spillage; pollution; pipeline; vandalization

1. Introduction

1.1. Background and Context

Crude oil is one of Nigeria's primary natural resources and contributes significantly to Nigeria's foreign exchange earnings, budgetary resources, and economic development [1]. Crude oil and other products are typically transported via pipelines that traverse the Niger Delta region (Figure 1), connecting 22 petroleum storage depots and four (4) refineries situated in Portharcourt (2), Kaduna and Warri, as well as offshore terminals in Excravos (Delta) and Bonny Island (Rivers) and jetties in Alas Cove (Lagos), Calabar (Cross River) and Warri (Delta) [2]. These pipeline networks are susceptible to spillages due to vandalism and operational issues faced by international and local oil and gas companies, such as corrosion, equipment failure and operation and maintenance errors [3].

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When oil spills, it constitutes environmental and economic hardship for the country through environmental degradation and contamination of land and water that negatively affects the health and livelihoods of Niger Delta residents [4,5]. Over the years, various methods with varying advantages and disadvantages have been adopted to monitor spillage in the Niger Delta. The most prominent is the differential pressure method [6] widely adopted by oil and gas companies to detect possible crude oil due to pipeline defects or diversion by vandals.

Still, this approach seldom provides information on the possible location and cause of spillage [7,8]. Other methods include human surveillance assisted by guard dogs [9], computational and technological solutions such as satellite remote sensing, unmanned aerial vehicles, acoustic, accelerometer, and ground penetration seismic and echo sounders [10]. Moreover, once the spill is detected, a Joint Investigation Visit (JIV) team stipulated under Section 5 of the National Oil Spill Detection and Response Agency (NOSDRA) Act (2006) is established to investigate and report the cause and impact of the spill. The JIV comprises the owners/operators of the spiller facility, community and state government representatives, the Nigerian Upstream Petroleum Regulatory Commission (formerly the Department of Petroleum Resources) and NOSDRA [11]. All these approaches highlighted above provide several advantages and disadvantages and are discussed in detail in section 2.5.

1.2. Rationale and Objectives

The last comprehensive literature review of oil spill detection approaches in the Niger Delta region was undertaken in 2011 [12]. More recently, Adegboye et al., [10] reviewed advancements in principles and practices of pipeline oil spill monitoring but included several approaches that are not feasible in the context of Nigeria due to capacity and environmental constraints. Thus, the objective of this review is to bridge the existing literature gap regarding oil spill detection in the Niger Delta region of Nigeria. The review will also present the analytical linkages between spill detection approaches, specifically the JIV and the causes and effects of oil spillage and provide recommendations on how different leakage detection approaches can help identify the causes of oil spillage and reduce the associated environmental, and health, social and economic impacts.

1.3. Methodology

A mixed-method review approach [13] is adopted in this study and focuses on a combination of a systematic review of relevant and recent literature around i) the causes of oil spillage in the Niger Delta, ii) impacts of oil spillage, iii) pipeline leakage detection approaches, and iv) oil spill monitoring and management approaches in Nigeria. The literature search only considered articles published between 2010 to 2024 and in the English Language. The literature used in this review was derived through the execution of Boolean search techniques in notable databases, such as Scopus, PubMed, ScienceDirect and Web of Science, using a combination of keywords like “Oil spill impact in the Niger Delta”, “Causes of oil spill in the Niger Delta”, “Environmental and health impact of oil spill”; “Oil spill leakage detection and monitoring approaches”, and “Use of technology for pipeline leakage detection”. The literature findings were summarized and analyzed to present the suitable and relevant aspects of Oil spill monitoring, response, and detection approaches in Nigeria.

2. Literature Review

2.1. Study Area:

The study area presented in Figure 1 shows the distribution of the pipeline network, oil and gas processing plants and condensate fields scattered across the Niger Delta region of Nigeria. Figure 1 also displays the spatial distribution of oil spill locations in the region. The Niger Delta region, situated in southern Nigeria and bordered by the Atlantic Ocean, is renowned for its rich biodiversity, intricate waterways, and extensive mangrove forests [2]. However, the region is the regional host of oil and gas exploration and transportation infrastructure in Nigeria and garnered global attention due to pervasive environmental degradation resulting from recurring spillage caused by decades of oil exploration and production activities [4]. These properties make the Niger Delta region an ideal study area for literature reviews centred on oil spillage and detection methods to improve oil spill management.

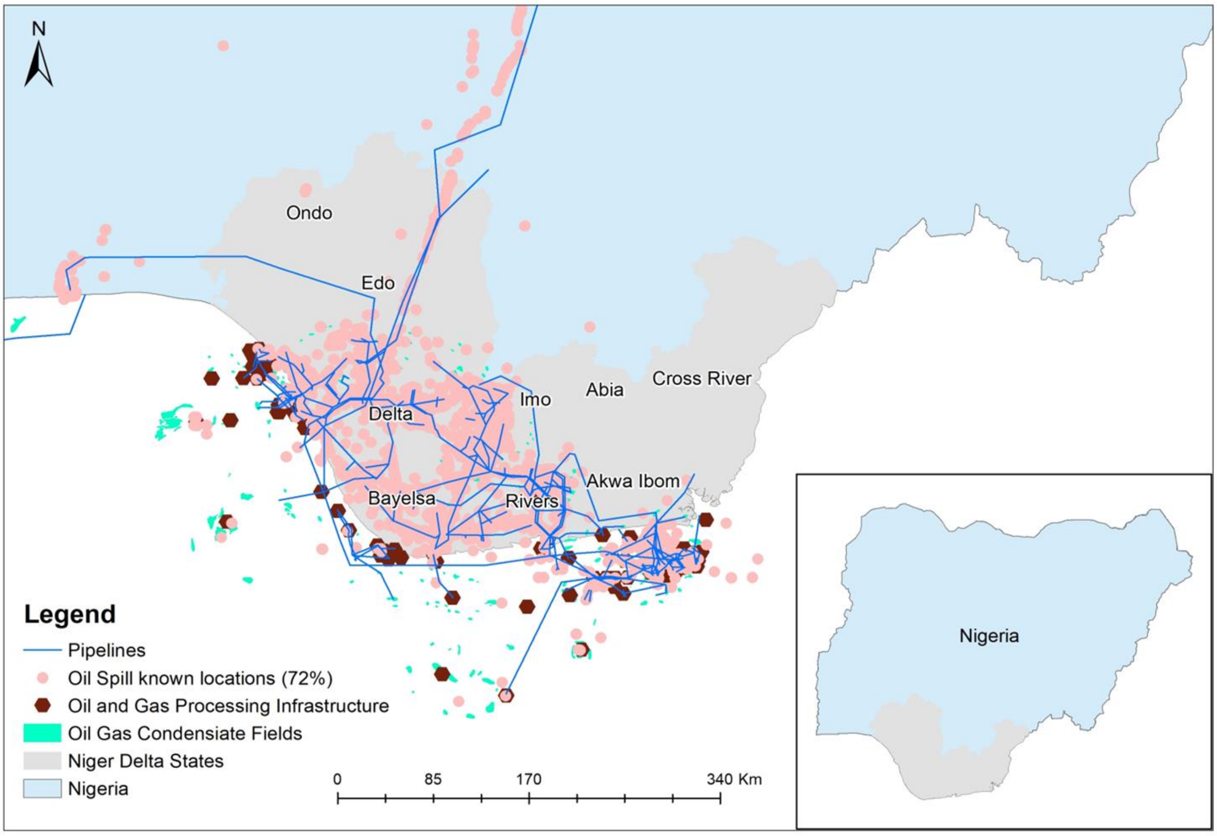

Figure 1. Oil and gas pipeline network and oil spill distribution (Map plotted from Nigerian National Petroleum Corporation (NNPC) and NOSDRA data).

2.2. *Causes of Oil Spillage in Nigeria*

Oil spillage in the Niger Delta region is caused by the operations of international and local oil and gas companies, sabotage/vandalization and unknown, yet-to-be-determined causes as documented by NOSDRA in its oil spill monitor database. Figure 2 displays the causes of oil spills from 1990 to 2022, showing sabotage as the leading consistent cause of oil spills. The plot also reveals that pipeline sabotaged peaked in 2013 due to increased militant activities in the Niger Delta region. Furthermore, Figure 2 presents the cost of crude oil lost due to oil spillage, totaling US$ 658.5 million from the spillage of 705,100 barrels.

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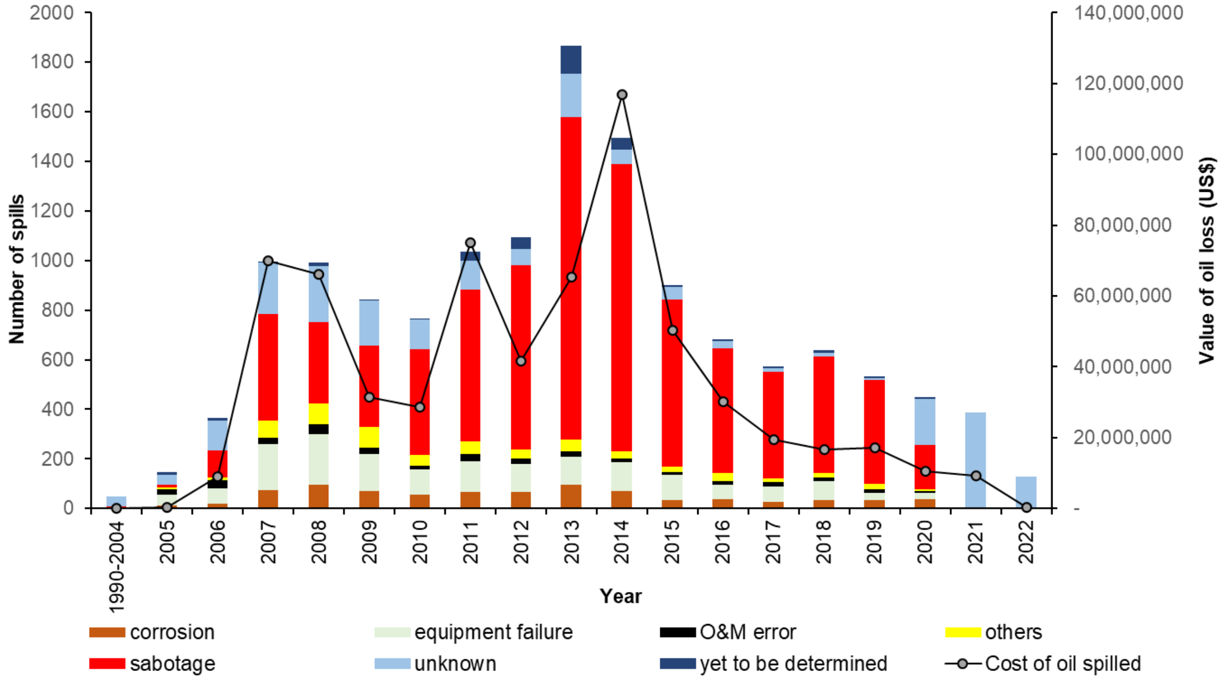

Figure 2. Chart showing the trend of oil spillage from 1990 to 2022, including causes and cost (Compiled from NOSDRA data, assessed 2022).

2.2.1. Operational Spillage and Others/Unknown/Yet to Be Determined

Operational oil spillage is primarily caused by inefficiency in the operations of international and local oil and gas companies in the Niger Delta region. NOSDRA categorizes operational oil spillage as those caused by corrosion, equipment/mechanical failure, and O&M (Operation and Maintenance) errors. Pipeline corrosion results from the deterioration of the pipeline material due to its interaction with the environment (Figure 3a) [14]. Corrosion of pipeline infrastructure is exacerbated in the Niger Delta due to the salinity of the swampy and coastal environment. Equipment failure results from the defect of mechanical components of pipeline infrastructure, including welding defects at joints, pressure surge at flanges and casket deterioration (Figure 3b), resulting from stress, strain, and collapse [3]. O&M error is caused by human error during operations, preventive or corrective maintenance. An analysis of data sourced from the NOSDRA oil spill monitor from 1990-2022 revealed that equipment failure was responsible for 11 percent of the 13,934 oil spill incidences, while corrosion and O&M error caused 6 and 2 percent of all oil spills. Spillages from others, unknown and yet-to-be-determined causes constituted 22 percent of all spills documented in the same period.

2.2.2. Sabotage/Vandalization

Other than operational spillage, pipeline sabotage or vandalization is a key contributor to spillage in the Niger Delta. Chen et al., [15] defined sabotage and vandalism as the unauthorized destruction of pipelines by a person or group to disrupt the petroleum product supply chain or divert petroleum products to sell in the black market. This act is prohibited under Nigerian Law and constitutes economic sabotage. An analysis of data sourced from the NOSDRA oil spill monitor from 1990-2022, sabotage was responsible for 59% of 13,934 oil spill incidences in the Niger Delta region. Also, although NOSDRA data does not sub-categorize the various types of pipeline vandalism, Ahmed and Moh'D [16] classified sabotage as oil bunkering, pipeline vandalism/scooping and oil terrorism. Oil bunkering involves the direct siphoning of crude oil into tanks and vessels for illegal sales in the black market. Oil bunkering is typically achieved by drilling a hole into the pipeline and connecting a control valve for continuous oil tapping aided by pumps (see Figure 3c) to fill barges that are transported and sold offshore [15,17]. Pipeline vandalism/oil scooping is similar to bunkering, but quite rudimentary, and initiated by aggrieved youths that puncture pipelines (see Figure 3d) or take advantage of existing leakages to siphon petroleum products into drums and storage cans for sale in the black market, or processing in artisanal refineries before sales in local communities and personal use [8,18]. Oil terrorism is the act of intentionally blowing up oil and gas infrastructures, including pipelines and platforms using explosives, as well as the seizure of oil wells, flow stations, vessels, oil barges and other oil facilities by organized militant groups to disrupt the exploration and distribution of petroleum products [8,19]. Oil bunkering and pipeline vandalization pose a severe economic risk to Nigeria, as well as environmental impact, while oil terrorism, also known as ecological terrorism, poses the most environmental, health and socio-economic risk to Niger Delta residents due to the indiscriminate and uncontrolled nature of spillage [8,15,20].

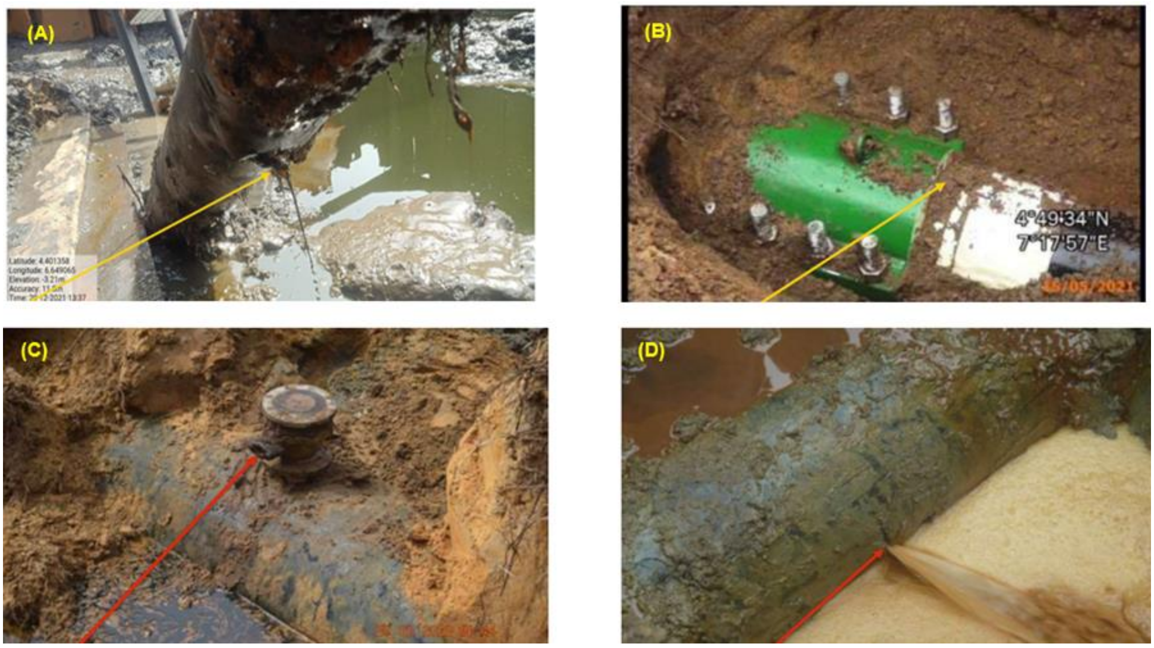

Figure 3. (a-d): Examples of oil spillage instances caused by operations and vandalization: (A) Spillage caused by corrosion at Belema, Rivers, (B) Spillage caused by equipment failure at Egberu, Rivers, (C) Spillage caused by vandalism using an illegal valve, Delta, and (D) Spillage caused by vandalism using a hacksaw, Bayelsa (Compiled from Shell Spill Database, assessed, 2022).

2.3. Oil Spill Incident Monitoring Response and Management in Nigeria

In the event of an oil spill incident, a Joint Investigation Visit (JIV) team is mobilized to visit the spillage site to investigate the cause(s) of the spillage and gather information on the immediate impact of the incident, including the volume of the spill, spread, area and ecosystem affected. The outcome of the JIV report would inform the deployment of management measures like source shutdown, containment, clean-up, decontamination, etc [11]. The graphical presentation of NOSDRA oil spill monitor data, Figure 4 shows that it took an average of 4 days (minimum [1 day], maximum [13 days]) for oil spill incidences to be reported after occurrence. Also, it took an average of 21 days (minimum [5 days], maximum [101 days]) for a JIV to be implemented after the occurrence of an oil spill.

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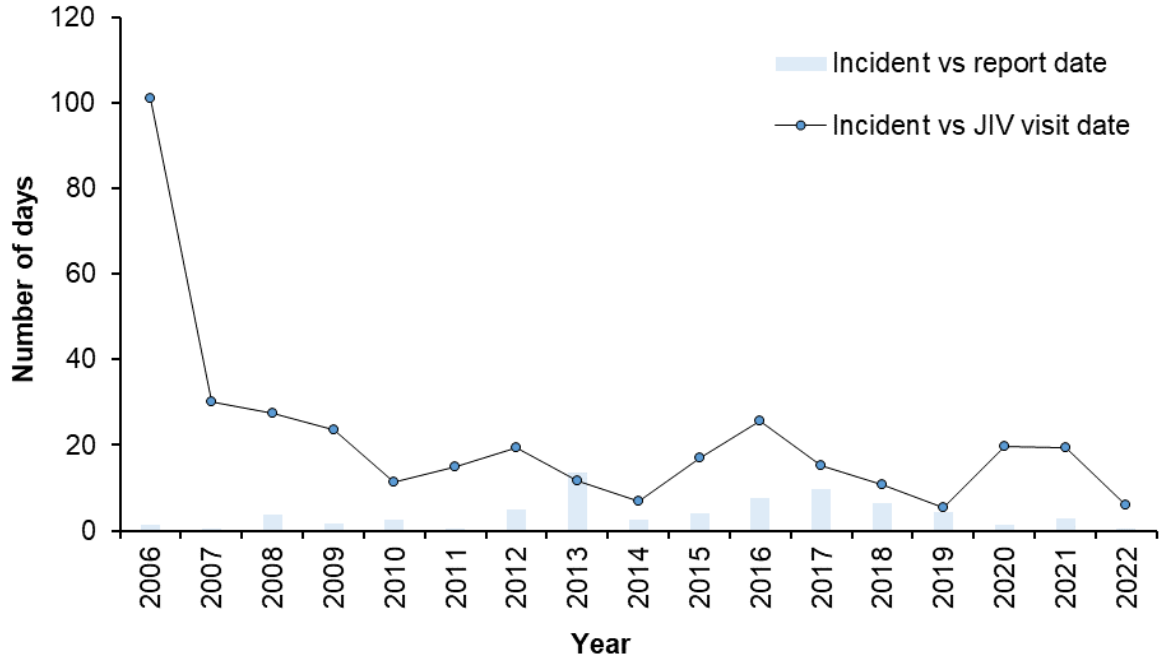

Figure 4. Graph showing the deviation between oil spill incident vs reporting date; and incident vs JIV visit date (Compiled from NOSDRA data, assessed, 2022).

Rim-Rukeh, [11], and Ekperusi and Ekperusi, [21] suggested that the time lag between spillage occurrence and the JIV can be attributed to scheduling delays due to the multi-stakeholder team composition, which further delays spillage clean-up that is stipulated to occur 24 hours after spillage, as directed by the "Environmental Guidelines and Standards for the Petroleum Industry in Nigeria". Moreover, although the JIV process provides a participatory approach to oil spill monitoring, it lacks independence and transparency and is affected by capacity constraints. In several instances, NOSDRA noted the absence of JIV following spillage incidences, and Figure 5 shows that JIV was not undertaken for more than 18% of the 10,902 spill incidences that occurred from 2006 to 2021. The adoption of technology could improve the time between an incident occurrence, and reporting, facilitate JIV coordination, and enhance the independence and transparency of the JIV process, thus strengthening early detection of oil spillage [11].

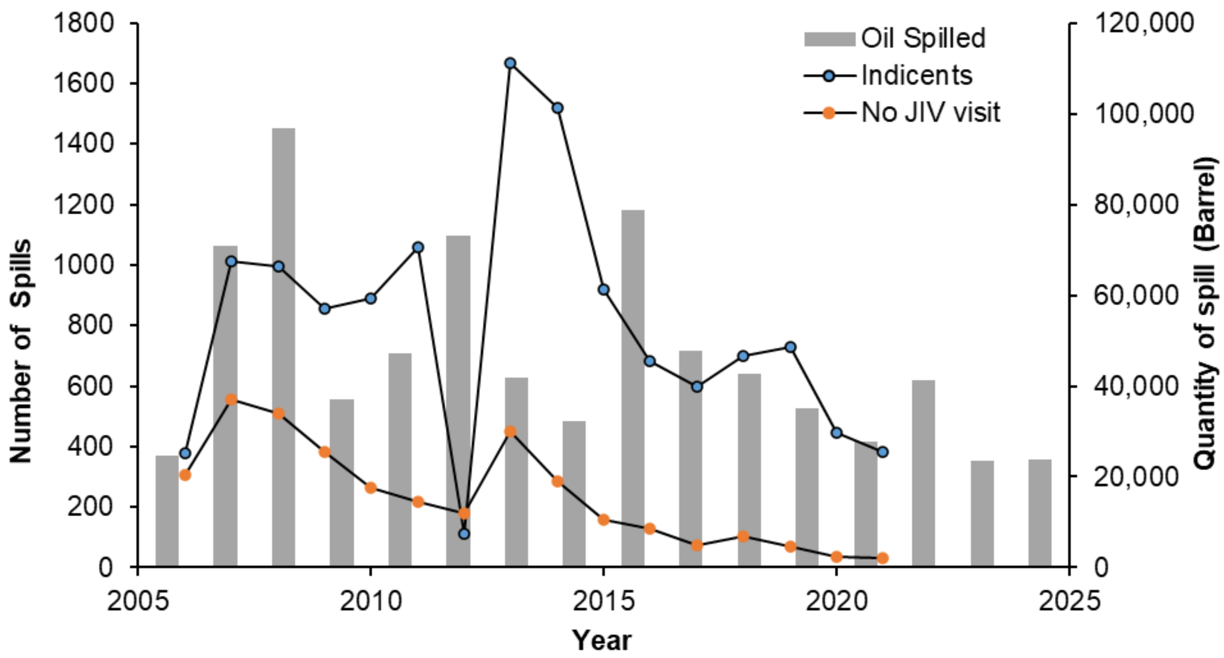

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Figure 5. Graph incidents and when no JIV visits occurred (Compiled from NOSDRA data, assessed, 2022).

2.4. Impacts of Oil Spillage in Nigeria

Continuous oil spillage due to company operations and vandalization impacts the ecology and society. Chang et al., [22] developed a framework to identify the short- and long-term impacts of oil spillage and contributing factors (Figure 6). The framework reinforces the interlinkages between short-term ecological effects (oil spill occurrence, oil spill and ecosystem injury) and short and long-term health, social, ecological (ecosystem recovery) and economic impacts. To address the short-term effect of oil spillage, the location of the spill must be detected early, and the magnitude quantified to determine the optimal response and management effort.

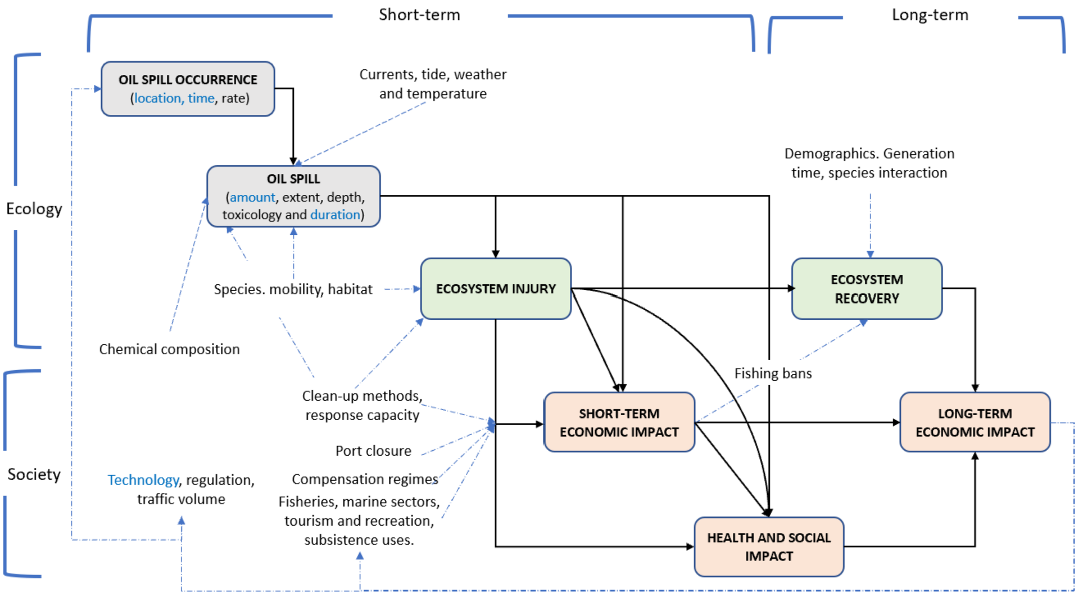

Figure 6. Framework for oil spillage impact [22].

2.4.1. Ecosystem/Environmental Impact

The Niger Delta region is one of the most diverse ecosystems in the world, constituting river networks, mangrove swamps, freshwater swamps, and rainforests, in addition to terrestrial and aquatic animals [4]. The contamination of land, water (including groundwater and sediments), air, flora and fauna that inhabit these ecosystems is arguably the most profound impact of oil spillage and cascades to health and socio-economic impacts. Crude oil contains toxic heavy metals such as lead (Pb) and chromium (Cr) that contaminate soil and groundwater aquifers when exposed to oil spillage, thus degenerating inherent microorganisms, and degrading the topsoil. Oil spillage affects the physio-chemical properties of water (e.g., salinity, turbidity, suspended solids, temperature, pH, conductivity, and chemical oxygen demand). As soon as spills occur in water bodies, they dissolve and sink to the bottom to contaminate sediments, and floating oil films decrease aeration, thus smothering certain aquatic organisms and animals to death [23,24]. In addition, soil and water contamination significantly affect mangroves in the Niger Delta region, resulting in reduced plant growth due to a decrease in photosynthetic rate and diminished stem height, density, and above-ground biomass, eventually plant death [25].

Moreover, mangroves, which constitute a significant part of the Niger Delta's biodiversity, are also grossly affected by oil spills when mangrove roots are coated by crude oil or direct absorption, thereby inhibiting breathing surfaces such as roots, stems, and seedlings [26]. When oil spills, about 35% evaporates into the surrounding atmosphere and introduces toxic fumes such as benzene and toluene that impact air quality [27]. Furthermore, oil spills directly affect the abundance and

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distribution of birds by reducing reproductivity, survival, and other physiological impairments [28]. Lastly, the Niger Delta ecosystem provides various services, i.e., regulating, provisioning, cultural and supporting. Adekola et al., [29] valued the provisioning services of the ecosystem at US$25 billion/year in 2010, i.e., three times the oil produced from the Niger Delta region during that period. Oil spillage has resulted in the pollution and contamination of rivers, loss of biodiversity and destruction of forests, especially mangroves that help sequester carbon from the atmosphere (i.e., reducing greenhouse gas emission), protect the coastline from erosion and sea-level rise, and provide a breeding ground for fishes [23].

2.4.2. Health Impact

Oil spillage has a detrimental impact on the health of the people in the Niger Delta, particularly in oil-producing communities vulnerable to oil spillage. The adverse health effects of oil exploration and, by extension, oil spillage can be attributed to the direct exposure of residents through the ingestion of heavy metals in contaminated drinking water, as well as indirectly by consuming animals and plants grown in the spill-contaminated area [30]. Some health effects of oil spillage include cancer, skin conditions, respiratory problems, fetal development, and neurological and fertility challenges [31].

Furthermore, external exposure to crude oil constituents such as chromium can cause skin ulcers, while ingestion can induce stomach ulcers, kidney, and liver damage and eventually death [32]. A recent study by Bruederle and Holder, [33] revealed that oil spill-affected areas experienced a 100% increased neonatal mortality, reaching up to 38.3 deaths per 1000 live births. In a pilot study in Ogoni, benzene levels in the groundwater were 900 times the WHO (World Health Organization) guideline. Residents of the study areas suffered health symptoms attributable to the inhalation of volatile organic compounds (VOCs), such as neurologic symptoms like headaches, sleepiness, dizziness, and confusion, as well as skin irritation, eye and throat irritation, gastrointestinal symptoms, and aplastic anaemia [34]. Olawoyin et al., [35] also assessed the exposure of Niger Delta residents to carcinogenic pollutants in the soils, including Zinc (Zn), Lead (Pb), Iron (Fe), Cadmium (Cd), Chromium (Cr), Nickel (Ni), Copper (Cu), and Manganese (Mn) that exceed recommended levels. The risk assessment study found that soil contamination due to heavy metals (Pb and Cr) was comparable in industrial and residential areas, posing cancer risk to residents, particularly children.

2.4.3. Socio-Economic Impact

The environmental and health impacts of oil spillage exposure typically translate to socio-economic effects, resulting in the loss of livelihoods and financial loss to residents and the Country. Niger Delta residents are predominantly farmers and fishermen; thus, the exposure of land and water to crude oil contamination impacts the productivity and quality of produce. Ndubueze-Ogaraku et al., [36] compared and found significant differences in shellfish sales between oil-impacted and unimpacted areas in the Niger Delta. Spillage-affected regions saw a 55% decline in sales. A similar trend was also observed for cassava farming in the Niger Delta region. Ahmadu and Egbodion, [37] reported reductions in farmland and cassava production due to oil spillage. Farm size, yield, and land productivity in spill-affected areas were reduced by 0.61 ha, 6119 MT, and 1447 MT/ha, respectively. Farmers in these areas disclosed that oil spillage was responsible for approximately 45% variation in land productivity for cassava production. Fishermen also reported a similar faith as farmers. Osuagwu and Olaifa [38] and Akpokodje and Salau, [39] reported that oil spillage and forest degradation negatively affected fish production and increased the required labour, land and capital needed to sustain productivity. Generally, the lives and livelihoods of residents of oil spill-impacted areas of the Niger Delta are significantly impacted, resulting in increased restiveness and agitations compounded by the absence of social amenities such as schools, hospitals, potable water, physical infrastructures, and employment opportunities [40]. Beyond the local socio-economic impact of spillages, the economic impact of oil spillage is also felt at the national level, where the loss of crude oil negatively affects Nigeria's foreign exchange earnings, budgetary resources and, consequently, the economy [41], as well as the additional cost of oil spill remediation, community compensation and security.

Given the environmental, health and socio-economic impact of oil spillage, spill incidents must be detected early using several methods and addressed through decontamination and remediation efforts to reduce bioaccumulation in soil and water, to allow agricultural and aquacultural activities to flourish, thereby sustaining the livelihood of Niger Delta residents.

2.5. Pipeline Leakage Detection Applications in Nigeria

Oil pipeline leakage and vandalism are recurring challenges in the oil and gas sector in Nigeria. Over the years, many methods have been deployed to help curb the challenge, including soft and hard measures that range from community engagement, and security deployment to the use of technology, such as cameras, sensors, internal system computations, Short Message Service (SMS), satellite remote sensing and unmanned aerial vehicles (UAVs)/drones. Adegboye et al., [10], proposed a classification for the pipeline leakage detection approaches (Figure 7) consisting of external, visual/biological and internal/computation-based methods. Leakage detection methods adopted in Nigeria are reviewed to identify potential research gaps and opportunities for improvement. The practices identified by the inclined pattern in Figure 7 are those that have been adopted in Nigeria and will be further explored in subsequent sections.

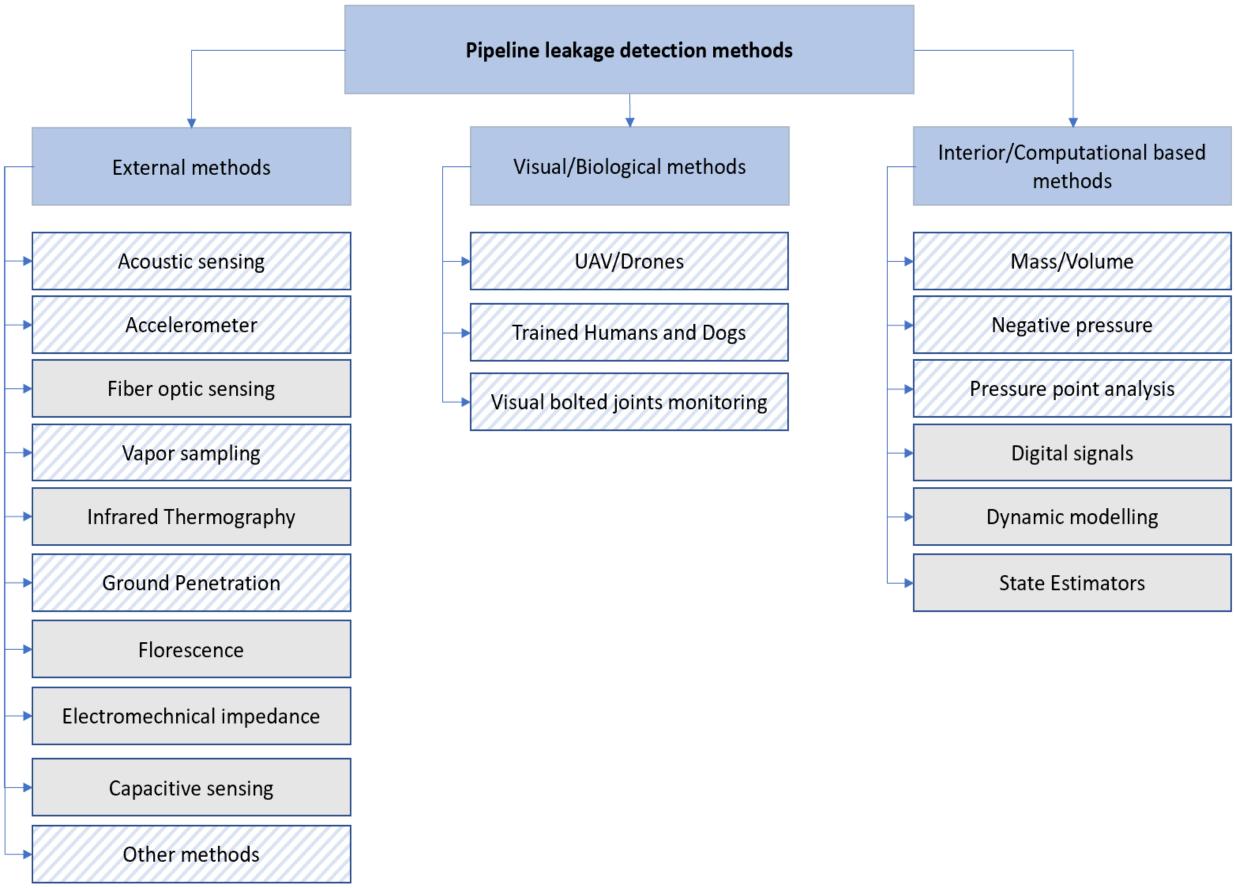

Figure 7. Categorization of pipeline detection methods (Adapted from [10]).

2.5.1. Acoustic

Acoustic sensing involves the use of sensors such as hydrophones and electromagnetic acoustic transducers (EMAT) or piezoelectric meters to detect inherent signals that escape from a punctured pipeline to find a leak [10,12]. Carpenter [42] deployed a vibroacoustic monitoring system to monitor the integrity of the pipeline between Kwale and Akri pumping stations in the Niger Delta region, using accelerometers, geophones, and hydrophones to record low-frequency elastic waves moving

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along the pipe body as well as pressure waves rolling into the fluid. Data from the vibroacoustic was transmitted via email and SMS. Fagbami et al., [43] also introduced a first-of-a-kind DTS (Distributed Temperature Sensor) and intelligent DAS (Distributed Acoustic Sensor) system at the Umugini pipeline in the Niger Delta that uses variations in sound (acoustic) and temperature to detect potential intrusions with the pipeline ROW (right-of-way) and pipeline leakage.

2.5.2. Accelerometer

This wireless technology device facilitates the sending and receiving of short messaging services (SMS) on potential pipeline vandalization locations. Lukman et al., [44] developed an anti-theft oil pipeline vandalism detection system that assembled a Piezoelectric sensor that helped detect vibration on the pipeline, which consisted of a microcontroller for analogue and digital signal processing and programming, and a GPS (Global Positioning System)/GPRS (General Packet Radio Services) module. The vibration effect on the piezoelectric sensor is detected by measuring the pressure-induced voltage change across a piezoelectric element [45]. The result generated from this system included the transmission of vibration coordinated (longitude and latitude) via SMS to a control centre. Aba et al., [46] also applied a piezoelectric sensor to detect spillage from a pipeline but transmitted the result using Wifi that broadcast to ThingSpeak – an IoT analytics platform.

2.5.3. Ground Penetration

In 2020, Ofualagba and Ejofodomi [2] designed and engineered an automated oil and gas pipeline vandalism detection system that used geophones to detect seismic signals of potential vandals. The system converted ground vibration to voltage and in combination with other system components like Arduino microcontroller, Global System for Mobile Communications (GSM)/GPRS/GPS, and long-range transceiver shields, was able to promptly collect and transmit information such as the date, time, the sort of activity that was noticed. The system could also communicate the alarm confidence level, and GPS location, and provide the route to the vandalism site via SMS. This is possibly the only system adopted in practice, as disclosed by the Nigerian National Petroleum Commission [47]. Furthermore, Ofualagba and Ejofodomi, [2], proposed to further develop the system to integrate an autonomous Visual Line of Sight (VLOS) drone technology to facilitate prompt response and capture aerial photos.

2.5.4. Unmanned Aerial Vehicles (UAV) or Drones

Although Ofualagba and Ejofodomi, [2] propose integrating drones into the improved version of its automated oil and gas pipeline vandalism detection system to capture pictures, Akande et al. [48] and Benyeogor et al., [49] demonstrated the possibility of deploying drones for airborne pipeline surveillance, particularly for gas pipelines, building on the work of Omijeh et al., [50], that design and constructed an optimal UAV payload pipeline inspection and surveillance. The leak detection system (also known as vapor sampling) was achieved by mounting an instrumentation system payload (constituting an LPG (Liquefied Petroleum Gas) sensor, motion tracker, Bluetooth module and radio receivers) on a UAV to measure Volatile Organic Compounds (VOCs) at a 4–15-meter height and transmitting that data to the ground station via telemetry. David and Omowunmi, [51]; and Idachaba, [52], also deployed drone technology combined with a microcontroller, GPS module, and sensors (force-sensitive resistor, sound sensor and piezoelectric element) that collect and transmit information via a radio transmitter. The force-sensitive resistor helps detect pressure, squeezing and weight, the acoustic sensor helps to sense surrounding sounds and the piezoelectric element measures changes in pressure, acceleration, and force and converts them to an electric charge. The signals from sensors are programmed on the microcontroller and communicated to the UAV for physical inspection.

2.5.5. Trained Humans and Guard Dogs

The use of trained security personnel (from either private security companies, State security agencies such as the Police, Military (Army and Navy), and Paramilitary agencies (e.g., Nigeria Security and Civil Defense Corps (NSCDC) and in some instances accompanied by trained guard dogs has been one of the longstanding approaches used for pipeline surveillance and security in Nigeria [53]. The use of trained security personnel can also be coordinated, where security outfits unify as part of the so-called Joint Taskforce (JTF), where security personnel, in consultation with host communities, plan, communicate and coordinate to ensure an effective operation [9]. Although guard dogs have also accompanied security personnel for short-term surveillance operations, their industry penetration (i.e., how much it is being used in the industry) is low, and they can only be deployed for onshore operations [54,55]. Furthermore, although the use of security personnel has an industrial penetration of 70%, the response time is slow, and humans are prone to corruption [7].

2.5.6. Negative Pressure Approach

Azeez and Akinlolu, [56] designed an Intelligent Pipeline Vandalism Detection and Reporting System (IPVDRS) that leverages a pressure sensor to detect possible vandalism, trigger an alarm, and create a GPS coordinate on a map to help the authorities navigate to the location of the incident. IPVDRS senses the presence of leaks and vandalism by ascertaining if the pipeline pressure has reduced below a predetermined threshold. The negative pressure approach depends on detecting instantaneous pressure wave alteration [57]. The pressure sensor was also adopted by Daniyan et al., [58] and Okorodudu et al., [59], using Visual Studio and Arduino, respectively to communicate observed leakage via Bluetooth and SMS. The outcomes of both systems demonstrated the potential of electronic sensor-based systems for pipeline integrity monitoring and benefits such as reducing inspection time [58].

2.5.7. Interior Computational-Based Approach (Mass/Volume Balance and Pressure Point Analysis)

Mass-volume balance and pressure point analysis are also established methods for pipeline leakage detection used by oil and gas companies in Nigeria [60–62] and rely on computation principles such as mass conservation and comparative analysis between measured and simulated/expected fluid pressure [63]. These techniques rely on existing mass-volume, flow and pressure meters connected to the pipeline network to determine any variation in mass volume, pressure, and other fluid characteristics (such as temperature, density, and flow rate) of the crude oil between upstream and downstream stations [10]. The main advantages of this approach are that it relies on existing tools, thereby minimizing cost, and can be rapidly deployed for subsea installations. Although this approach is advantageous in detecting when vandals installed valves along the pipeline to syphon crude oil (Figure 3c). The computation approach does not provide the leak's location and cause.

2.5.8. Satellite Remote Sensing (RS)

Before the recent adoption of UAV technology, oil and gas companies used to deploy helicopters for pipeline surveillance intermittently; however, the cost of deploying helicopters is high, the procedure is cumbersome, and such operations can be hindered by weather conditions, security issues, and vegetation cover [64]. Satellite remote sensing, especially high-resolution imagery and synthetic aperture radar provides an alternative for UAVs and helicopters for large-scale pipeline surveillance. Advancements in remote sensing technology allow for satellites to be scheduled to capture high-resolution images over an area of interest repeatedly, which is relatively costly. Nonetheless, free/open-access satellite data availability, such as Landsat and Sentinel Imageries from the National Aeronautics and Space Administration (NASA)/ United States Geological Survey (USGS) and European Space Agency (ESA) respectively have the potential to observe soil and vegetation changes that can be linked to oil spillage using geospatial analysis [65]. Satellites can also be directly synchronized with ground sensors, providing real-time data capture and transmission on the pipeline integrity [66]. The use of oil satellite technology for oil spill detection in Nigeria has been

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widely researched [67]. However, the RS methodology has mainly focused on investigating the retrospective impact of spillage on vegetation, land, and water [68]. Furthermore, unless high-resolution satellite scheduling is deployed, RS is mostly used for indirect pipeline monitoring.

2.5.9. Other Monitoring Techniques

In addition to the pipeline leakage detection measures highlighted above, other measures for pipeline leakage monitoring include the open-circuit technique that detects pipeline damage using a flexible circuit sheet wrapped on the surface of the pipe, that when fractured, will create a break in the metal conductors [69]. Visual bolt joint monitoring is usually undertaken during preventive maintenance or after identifying pressure or mass-flow deviations in the pipeline network [7,8]. Also, Chibuzor et al., [70] designed and developed an oil pipeline vandalism detection and surveillance system incorporating a video camera sensor board, motion and nightlight sensors and GPS module for vandalism detection and communicated the information via Wifi and GPRS.

4. Discussion and Gaps

The effectiveness of pipeline leakage detection technologies varies according to the approach deployed, operational circumstances, and complexity of the pipeline networks. But for any leak detection system to be considered suitable for practical application and wide-sale deployment, it must first meet the sensitivity, accuracy, reliability, and flexibility requirements set forth by the American Petroleum Institute [71]. Furthermore, the integration of wireless communications technology enables remote monitoring of oil and gas pipeline networks, offering advantages such as minimal cost, quick response times, and the capacity to isolate the location of leakages. This section discusses research gaps and future research areas based on the various pipeline leak detection techniques reviewed in this study.

A combination of external, physical, and computational-based methods has been adopted for pipeline leakage detection for oil and gas installations in the Niger Delta, including electronic sensors with various characteristics, UAVs, satellite remote sensing and others. Each technique provides unique advantages and disadvantages but can be combined to optimize benefits. External approaches monitor the physical aspects of the pipeline's operation, including disturbances such as vibration and deterioration of pipeline integrity, and are observed and communicated to identify anomalies [12]. The main advantage of the external approaches is that it enables non-disruptive monitoring with limited operations interference. Contrastingly, the accuracy of external leak detection systems is restricted if leaks occur outside the sensors' receptive field since leaks can only be reliably detected if they occur close to the monitoring sensor. Internal measures alternatively monitor and communicate observable changes in the internal condition of the fluid in the pipeline, such as mass volume, flow rate, pressure, temperature, and density [10]. Visual and biological methods are usually deployed to validate the feedback from external and internal procedures or proactivity employed to protect pipelines in vandalism-prone locations, such as the Joint Task Force (JTF), volunteers, and private security that secure pipelines [72]. A key limitation of the biological approach is the logistical difficulties associated with mobilizing personnel to remote areas and human susceptibility to corruption [7].

As Nigeria begins exploring oil in other parts of the country, the lessons from this study can inform proactive action to enhance oil spillage monitoring and mitigate the environmental, health, social and economic consequences of oil spill occurrence. Additionally, more advanced techniques currently not applicable in the Niger Delta due to legacy and financial constraints, such as fibre optics, distributed acoustic systems and infrared [64], can be integrated into the early-stage design and development of crude oil transportation pipeline networks. Also, experimental studies such as using IoTs and Drone technology [2] can be strategically planned and scaled. This review also highlights the limitations of the current oil spill incident monitoring response and management practices in Nigeria - The joint investigation visit. The JIV approach adopted by NOSDRA results in delays in oil spill detection and response, thus exacerbating the impact of oil spills. In some instances, such as oil scooping where additional valves and pipes are connected to the leading crude oil transport line to syphon crude oil and during gradually occurring operational spill, the JIV mechanism is unable to capture spillage occurrences. Leak detection methods not captured in this review are yet to be deployed in Nigeria or are ideas under discussion, such as fibre optics and infrared [64,73]. Furthermore, many of the leak detection technologies adopted in Nigeria are mainly experimental; thus, there is a need for close collaboration with the oil and gas industry to ensure new systems developed are practical and usable, like the case of Ofualagba and Ejofodomi, [2].

5. Conclusions

To identify potential future research opportunities to enhance pipeline leakage detection, a thorough literature assessment on oil and gas pipeline leak detection techniques has been carried out in this study. This review builds on the work of Agbakwuru, [12], Adegboye et al., [10], and Olaiya et al., [73], provides an additional assessment of pipeline leakage detection approaches applicable in the Niger Delta, the operational mechanism of each method and the strength and limitations of these approaches. The leak detection techniques have been divided into three categories: external, visual/biological inspection and internal/computational. One of the main oil spillage detection and response mechanisms employed in Nigeria is the JIV which is usually activated following an oil spillage incidence. Nonetheless, the JIV is reactive rather than proactive and typically results in delays in reporting and response. In some instances, the JIV is not activated, resulting in undocumented causes and the impact of spill incidences and inaction. The deficiency in the JIV mechanism could increase the impact of oil spills on the environment and residents of the Niger Delta. A major gap identified from this review is the absence of sensing methods that can identify the location of leaks and estimate the rate and quantity of the spill to aid rapid response and containment efforts, thereby preventing significant environmental, social, and financial harm. This research gap could be bridged through the introduction of a network of detection sensors between the upstream and downstream of the pipeline provides a cost-effective and practical approach to identifying the leakage location and quantifying the loss [74]. Another promising area to investigate further is the possibility of deploying Unmanned Aerial vehicles and robots for leak detection and localization in intricate pipeline networks. Also, the use of machine learning and artificial intelligence to predict pipeline leakage hotspots needs to be explored, especially for the proactive identification of possible vandalism hotspots

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