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Innovative pipeline installation techniques and workforce training models for reducing oil spillage and enhancing environmental sustainability in the energy sector in Nigeria

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Abstract

Introduction: In Nigeria's oil-producing areas, oil spills are still a major natural problem that does a lot of damage to the environment and the economy. Innovative pipeline construction methods and training programs for workers have been suggested as good ways to reduce oil spills and protect the environment. This research looks at how Horizontal Directional Drilling (HDD), Smart Pipeline Monitoring Systems (SPMS), and Workforce Development Programs (WDP) can help cut down on oil spills in Nigeria's Rivers, Delta, and Bayelsa States. The study is based on the theories of Technology Adoption and Human Capital. It focusses on how new technologies and skilled workers can help keep pipelines from breaking.

Materials and Methods: The study used a survey and cross-sectional research methodology, and 600 questions were sent to people in the oil industry and in the communities in Rivers, Delta, and Bayelsa States using useful selection. Referrals were used to find oil experts using a method called "snowball sampling." Five hundred and twenty-seven of the surveys were sent back and can be used for research. The study used structural equation modelling (SEM) to test three theories about how HDD, SPMS, and WDP directly affect reducing oil spills.

Results: The findings indicated that all three parameters substantially contribute to the decrease of oil spills. The HDD had a substantial negative impact ($\beta = -0.168$, $T = 4.906$, $p = 0.000$), demonstrating its efficacy in mitigating land disturbance and decreasing spill hazards. SPMS had a significant effect ($\beta = -0.319$, $T = 9.852$, $p = 0.000$), underscoring its function in real-time pipeline surveillance and leak identification. WDP exerted the most significant influence ($\beta = -0.484$, $T = 14.410$, $p = 0.000$), highlighting the critical role of proficient staff in maintaining pipeline integrity. The model accounted for 55.9% ($R^2 = 0.559$) of the variation in the decrease of oil spills, demonstrating predictive significance ($Q^2 = 0.294$).

Discussion: The findings correspond with Technology Adoption Theory, which posits that organisations embrace novel technology when they improve efficiency and mitigate hazards. The substantial influence of HDD and SPMS underscores the necessity for sophisticated pipeline construction and monitoring systems to avert breaches. The results corroborate Human Capital Theory, emphasising that expenditures in staff training enhance operational efficiency and environmental safety. The research emphasises the need of a cohesive strategy that merges technology with proficient labour to tackle oil leak issues in Nigeria's oil sector.

Conclusion: The study finds that HDD, SPMS, and WDP substantially mitigate oil leakage in Nigeria. The results underscore the need of using contemporary pipeline construction methods, real-time monitoring technologies, and extensive personnel training initiatives to improve environmental sustainability. The report advocates for legislative incentives to promote technology adoption, compulsory training programs for oil industry employees, and enhanced

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regulatory frameworks to guarantee the proper execution of these initiatives. Future studies should investigate the long-term effects and cost-benefit evaluations of these changes in Nigeria's oil industry.

Keywords: Horizontal Directional Drilling; Smart Pipeline Monitoring Systems; Workforce Development Programmes; Human Capital Theory; Technology Adoption Theory

1. Introduction

Oil spills is a significant environmental and economic issue in Nigeria, especially in the Niger Delta area, where oil drilling and transportation operations are widespread (Ukhurebor et al., 2021). The recurrent incidence of pipeline failures attributed to ageing equipment, vandalism, and insufficient monitoring systems has intensified the environmental deterioration of local populations (Igwebuike, 2020). These spills not only lead to the depletion of valuable crude oil but also present significant risks to aquatic ecosystems, soil fertility, and human health (Singh et al., 2020). Despite regulatory initiatives, oil spills persist in hindering sustainable development, requiring new strategies that use sophisticated pipeline construction technology and worker training methodologies to alleviate their effects.

A significant innovation in pipeline technology is Horizontal Directional Drilling (HDD), which improves pipeline construction by minimising surface disruptions and mitigating exposure to external dangers (Teodoriu and Bello, 2021). In contrast to traditional trenching techniques, HDD facilitates the installation of pipes under aquatic environments and ecologically sensitive regions, therefore reducing the probability of leaks and spills (Kaushal et al., 2020). Studies indicates that HDD enhances pipeline durability and operational efficacy; nevertheless, its implementation in Nigeria has been constrained by technical limitations and a lack of qualified staff to proficiently execute and sustain the technology (Eze et al., 2017). This highlights the need to assess HDD's efficacy in mitigating oil spills and improving pipeline integrity.

A significant advancement in addressing oil spills is the Smart Pipeline Monitoring System, which utilises Internet of Things (IoT) sensors, artificial intelligence (AI), and real-time leak detection technology (Ahmed, 2022). These devices provide ongoing monitoring of pipelines, identifying first indicators of leakage, pressure variations, and even sabotage. The use of such devices might markedly enhance reaction time in mitigating pipeline breakdowns and decreasing the quantity of spilt oil (Elijah et al., 2021). Nonetheless, despite their shown advantages in other oil-producing countries, the efficacy of smart monitoring systems in Nigeria remains inadequately examined, especially regarding cost-effectiveness, infrastructure preparedness, and regulatory backing (Ahmed, 2022).

Although technical solutions are crucial, Workforce Development Programs are important to the proper implementation and upkeep of pipeline infrastructure (Narkhede and Gardas, 2018). A proficient staff skilled in innovative drilling methods, predictive maintenance, and emergency response is essential for minimising oil spills (Iqbal et al., 2019). The present condition of technical education and training for oil industry experts in Nigeria is insufficient, resulting in a skills gap that obstructs the adoption of contemporary pipeline technology (Oluwasanmi. 2019). Investing in specialised training programs and capacity-building activities may improve staff competence and foster best practices in pipeline management throughout the sector.

This research aims to evaluate the individual and collective effects of HDD, smart pipeline monitoring systems, and staff development programs on the decrease of oil spills in Nigeria. This will provide empirical information about the efficacy of these interventions and propose policy suggestions for their implementation in the Nigerian oil and gas sector. The study seeks to fill current research gaps and enhance the discourse on environmental sustainability and the impact of technology-driven solutions in alleviating oil spills in oil-producing areas.

1.1. Research Questions

- What is the effect of Horizontal Directional Drilling (HDD) on oil spillage reduction in Nigeria?
- How does the Smart Pipeline Monitoring System influence oil spillage reduction in Nigeria?
- What is the impact of Workforce Development Programmes on oil spillage reduction in Nigeria?

1.2. Research Objectives

The broad objective of the study is to assess the impact of advanced pipeline installation techniques and workforce training programmes in reducing oil spillage and enhancing environmental sustainability in Nigeria's energy sector. The specific objectives are:

- To evaluate the effect of Horizontal Directional Drilling (HDD) on oil spillage reduction in Nigeria.
- To examine how Smart Pipeline Monitoring Systems contribute to oil spillage reduction in Nigeria.
- To assess the influence of Workforce Development Programmes on oil spillage reduction in Nigeria.

1.3. Review of Related Literature

This section review literature on Horizontal Directional Drilling, Smart Pipeline Monitoring Systems, Workforce Development Programmes and Oil Spillage, Empirical review and theoretical framework.

1.4. Concept of Oil Spillage

Oil spillage, generally known as an oil spill, is characterised in diverse academic sources with varying emphases. Ishak et al. (2020), defined an oil spill as the discharge of liquid petroleum into the environment, particularly marine regions, as a result of human activity, resulting in contamination. Tarr et al. (2016), characterised it as the inadvertent release of oil into aquatic environments, leading to ecological pollution. Thakur and Koul (2022), viewed oil spills as incidents in which oil is released into coastal seas, resulting in ecological damage. Saleh et al. (2017), see oil spillage as the inadvertent discharge of oil into the environment, presenting hazards to ecological and human health. Michel and Fingas (2016), defined an oil spill as the release of oil from its container into the natural environment, resulting in pollution. Daly et al. (2016), described it as the discharge of crude or refined oil products into marine ecosystems, resulting in ecological harm. Han et al. (2018), viewed oil spills as the inadvertent discharge of oil into the environment, requiring prompt action to alleviate consequences. Michel and Rutherford (2014) defined oil spills as the release of petroleum hydrocarbons into marine or coastal ecosystems, leading to pollution. Wilkinson (2017), characterised an oil spill as the discharge of oil into navigable waterways or adjacent shorelines, detrimental to human health and the environment. Finally, Ite et al. (2018), defined oil spills as the release of oil from ships or offshore installations into marine ecosystems, resulting in contamination. Hence, this study defined oil spillage as the inadvertent discharge of petroleum substances into natural environments, especially aquatic systems, due to human activities, leading to ecological degradation and posing risks to environmental and public health.

1.5. Concept of Smart Pipeline Monitoring Systems

Smart Pipeline Monitoring Systems (SPMS) are sophisticated frameworks that amalgamate diverse technologies to guarantee the effective and secure functioning of pipeline systems. Buffa et al. (2021), asserted that SPMS are designed to tackle issues related to scheduling, demand-side management, operational condition monitoring, safety analysis, and fault detection in pipeline systems. Ali et al. (2022), characterised SPMS as systems that use real-time big data and distributed computing for integrity management, enabling efficient monitoring and unintentional leak mitigation in multiproduct pipeline networks. Fan et al. (2022), asserted that SPMS include the whole life cycle of pipelines, enabling the digital transmission of survey, design, and construction data, which underpins intelligent pipeline technology. Zheng et al. (2022), emphasised the need for ongoing automated monitoring systems that provide early identification and alerting of flaws, such as corrosion and leaks, prior to their progression into significant catastrophes. Khan et al. (2022), concentrated on the predictive maintenance part of SPMS, which entails anticipating prospective problems based on existing data to proactively manage maintenance requirements. Huang et al. (2022), provided a deep neural network-based intelligent health monitoring system that analyses collected guided wave signals to forecast essential fracture metrics in pipelines, therefore improving the predictive maintenance functionalities of SPMS. Maskeliūnas et al. (2022) examined the use of SPMS in demand-side management of smart pipeline networks, emphasising its function in enhancing resource allocation and consumption efficiency. Chen et al. (2021), explored the incorporation of intelligent emergency management into SPMS, enabling fast responses to pipeline issues via automated processes. Grzegórska et al. (2021), provided sophisticated leakage detection techniques that are essential elements of SPMS, using powerful algorithms to swiftly identify and pinpoint leaks. Smart Pipeline Monitoring Systems can be defined as integrated, technology-driven frameworks that utilise real-time data analytics, predictive algorithms, and automated inspection tools to oversee, manage, and preserve pipeline integrity throughout its life cycle, thereby improving operational efficiency and safety.

1.6. Concept of Horizontal Directional Drilling

Horizontal Directional Drilling (HDD) is a trenchless construction technique used for the installation of subterranean pipes, conduits, and cables following a specified route while minimising surface disturbance. Hashash et al. (2021), stated that HDD entails the drilling of a pilot borehole along a specified route, then widening the borehole and retracting the pipeline into the expanded cavity. Mazumder et al. (2018), characterised HDD as a multifaceted utility construction method enabling the installation of pipes under barriers like rivers and highways without the need for open-cut excavation. Carlin (2014), emphasised HDD as a notable advancement above conventional cut-and-cover techniques, allowing pipeline installation under barriers with specialised construction focus. HDD technology has progressed since its origin in the 1960s, marked by improvements in drill rig capabilities and their application to diverse geological formations (Ma et al., 2016). The procedure generally has three phases: pilot hole drilling, hole expansion (reaming), and pipeline pulling, as delineated by Ibeh and Nnakaihe (2016). HDD is especially beneficial in urban settings where surface disturbance must be minimised, providing a technique for pipeline installation in densely populated regions (Kaushal et al., 2020). Salleh et al. (2019), underscored HDD's significance in mitigating environmental effect by decreasing the need for massive excavation. Moreover, HDD has been acknowledged for its suitability in the installation of pipes under sensitive regions, including rivers and existing infrastructures, while causing minimum environmental disruption (McMullan et al., 2015). HDD is a trenchless construction method that enables the installation of underground pipelines and utilities along a specified route, reducing surface disturbance and environmental impact through a multi-phase process that includes pilot hole drilling, reaming, and pipeline pullback.

1.7. Empirical Review and Hypotheses Formulation

A lot empirical research have looked at Horizontal Directional Drilling's (HDD) function in reducing oil spills in different settings. Often acknowledged as a successful method for pipeline construction, HDD lowers surface disturbance and decreases the probability of leaks (Rahman & Chilingarian, 2020). Studies by Adegbite et al. (2021) and Omoregie and Dawodu (2019), suggested that HDD allows pipelines to be buried deeper and avoids ecologically sensitive locations, hence greatly reducing the danger of oil leaks. Particularly in the Niger Delta, where traditional trenching techniques cause soil degradation and pipeline susceptibility to vandalism, HDD has proved very important for pipeline development initiatives in Nigeria (Obasi et al., 2022). The results imply that oil companies using HDD may improve pipeline integrity, save maintenance expenses, and support environmental sustainability. Widespread adoption is still hampered, nevertheless, by issues like high implementation expenses and the necessity for specialised labour training (Akinwale & Fakorede, 2020). Studies have also underlined the vital part Smart Pipeline Monitoring Systems (SPMS) play in reducing oil spills by improving real-time monitoring and leak identification. Okwu and Nwafor (2021), claimed that SPMS technologies—including fiber optic sensors, pressure monitoring devices, and AI-based predictive maintenance—have greatly enhanced pipeline safety in key oil-producing nations. Oil companies using SPMS in the Niger Delta reported a 30% drop in spill events from early detection and automatic shut-off systems, according to a study by Uche et al. (2022). A comparable study by Mensah and Boateng (2020) in Ghana's oil industry showed that SPMS implementation resulted in quicker reaction times and less environmental harm in pipeline breakdown situations. Notwithstanding these advantages, issues include high installation costs, technical complexity, and lack of regulatory enforcement impede full-scale deployment in Nigeria (Ekong & Etim, 2021). Empirical data highlighted even more the need of Workforce Development Programmes (WDP) in oil leakage avoidance, especially in educating people to run and maintain sophisticated pipeline equipment. Research by Ogundele and Udo (2022) and Kalu et al. (2022) underlined that well-trained oil industry workers are better skilled in spill prevention strategies, emergency response, and the running of HDD and SPMS technologies. Okoli and Eze (2021), discovered in a study on oil industry worker capabilities that businesses that spent in organised training initiatives saw a 40% drop in pipeline failures and operational mistakes. Research by Abubakar and Bello (2020), in the Nigerian oil industry also showed that talent development initiatives increase environmental safety standard compliance, hence lowering the possibility of oil leaks. Onyekachi & Osei (2021), showed, nevertheless, that uneven training programs, insufficient money, and opposition to new technology create major obstacles for efficient oil sector personnel growth.

Based on the reviewed empirical studies, this study hypothesizes that:

- **H1:** Horizontal Directional Drilling (HDD) has significant effect on oil spillage reduction in Nigeria.
- **H2:** Smart Pipeline Monitoring Systems has significant influence on oil spillage reduction in Nigeria.
- **H3:** Workforce Development Programmes has significant impact on oil spillage reduction in Nigeria.

2. Theoretical Framework

This study is underpinned by Technology Adoption Theory and Human Capital Theory

2.1. Technology Adoption Theory

The Technology Adoption Theory (TAT), explores how individuals and businesses accept and use new technologies. The theory states that people decide to use a technology based on things like how useful they think it is, how easy it is to use, how ready their organisation is for it, and pressures from outside sources (Marangunić and Granić, 2015). The Technology Acceptance Model (TAM) is one of the most popular models in this field. It suggests that people will accept a technology based on how useful and beneficial they think it is. Rogers' (1995), Diffusion of Innovation (DOI) theory also argued that people adopt new technologies through a process that includes becoming aware of them, being interested in them, evaluating them, trying them out, and finally adopting them (Olatokun and Igbinedion, 2009). This process is affected by things like how well they work with other things, how complicated they are, and how easy they are to see. TAT is a useful tool for understanding how technology is being used in the oil industry because it shows how companies use technology to improve efficiency, lower risks, and gain a competitive edge in the business world.

Technology Adoption Theory can be used to explain how Horizontal Directional Drilling (HDD) and Smart Pipeline Monitoring Systems (SPMS) help keep oil spills in Nigeria to a minimum in this study. The study's results show that these technologies greatly lower the risk of spills by making it easier to build pipelines and keep an eye on them in real time. Adopting HDD reduces damage to the environment by letting pipes be put in without digging up a lot of land. This is in line with TAT's theory that technologies are accepted when they clearly improve operations. Similarly, the use of SPMS in pipeline management backs up the theory by showing that companies adopt technology when it makes them more efficient and cuts down on waste. The rate of acceptance can be affected by things like cost, readiness of facilities, and the ability of people in the business to use these new ideas. Using TAT in this study shows how important it is for oil companies and policymakers to get these technologies widely used by getting rid of barriers and making sure that groups understand their long-term benefits in reducing oil spills and protecting the environment.

2.2. Human Capital Theory

Human Capital Theory (HCT) states that investing in people's skills, knowledge, and abilities makes them more productive, efficient, and good for the economy (Yaqoob et al., 2022). The theory, which was first put forward by economists like Becker (1964) and Schultz (1961), posited that education and training make workers better at their jobs, which leads to better job performance and overall organisational success (Bradley, 2021). HCT contends that businesses and countries gain a lot when they spend in developing their workers because trained workers are more creative, efficient, and able to adapt to new technologies (Yaqoob et al., 2022). Continuous training and upskilling are very important for keeping performance high, lowering risks, and better operating results in fields that need specialised knowledge (Rafner et al., 2022). The theory argued that human capital is just as important as physical capital, and companies that put growth of their workers first will have better long-term results.

Human Capital Theory is very useful for this study because it helps us understand how Workforce Development Programs (WDP) have helped reduce oil spills in Nigeria. Researchers found that properly trained workers are a big part of preventing oil spills because they know how to use cutting-edge pipeline technologies like Horizontal Directional Drilling (HDD) and Smart Pipeline Monitoring Systems (SPMS) correctly. Continuous training makes employees better at installing and maintaining pipelines, spotting potential dangers, and taking steps to stop leaks and spills before they happen. HCT says that investment in human capital makes organisations more successful, and this fits with that. Prioritising workforce development in Nigeria's oil sector, where pipeline breakdowns and environmental risks are frequent, makes sure that workers have the skills they need to keep pipelines safe and the environment safe. So, the study makes it even more important for oil companies and lawmakers to put money into regular training programs for workers to improve their skills. This will help make sure that oil pipes are managed in a way that is safe and lasts.

3. Materials and Methods

The research employed a cross-sectional survey approach to comprehensively explore the impact of advanced pipeline installation techniques and workforce training programmes in reducing oil spillage and enhancing environmental sustainability in Nigeria's energy sector. A cross-sectional research method was used as it facilitates data collecting at a singular moment, hence allowing the study to document contemporary circumstances and interrelations among variables without necessitating prolonged observation (Ojeleye et al., 2022). This methodology is very effective in evaluating the magnitude of oil spills and how Horizontal Directional Drilling, Smart Pipeline Monitoring Systems and Workforce Development Programmes impacted oil companies in curtailing oil spillage at a certain time. The survey study approach enabled the acquisition of primary data from a varied cohort of respondents, including community people, environmental specialists, and oil industry stakeholders. A structured questionnaire was used to gather quantitative data about the incidence of oil spillage, Horizontal Directional Drilling, Smart Pipeline Monitoring Systems and Workforce Development Programmes. The integration of these two research approaches for a thorough examination, yielding both statistical data and contextual insight into the issue. The study utilised a convenience sampling method and snowball sampling technique. Convenience sampling method distributing 600 questionnaires to community members, environmental experts, and stakeholders in the oil industry across Rivers, Delta, and Bayelsa States in Nigeria over a seven-week period while snowball sampling techniques was employed to get referrals from experts in the oil sector, of which 517(86.2%) were returned and analysed.

Meanwhile, self-developed questionnaire was used to measure the study variables of Oil Spillage, Horizontal Directional Drilling, Smart Pipeline Monitoring Systems and Workforce Development Programmes on adapted four-point Likert scale of 1= strongly disagree to 4=strongly agree. First, oil spillage was measure using 5-item. Sample of item are “Oil spillage is a frequent occurrence in my community” and “Efforts to clean up oil spills in this area have been inadequate” with Cronbach’s alpha of 0.869. Horizontal Directional Drilling was measured using 5-item. Sample of items are: “HDD is an effective technique for installing pipelines in areas with sensitive ecosystems” and “I believe HDD helps minimize the risk of oil spills during pipeline installation” with reported alpha of 0.735. Smart Pipeline Monitoring Systems was measured using 5-tems with reported alpha coefficient of 0.823. sample of items are “Smart Pipeline Monitoring Systems help detect leaks and faults in pipelines more quickly than traditional methods” and “Real-time monitoring through smart systems helps in preventing pipeline failures before they happen”. Lastly, Workforce Development Programmes was measured using 5-item. Sample of items are “Proper training ensures that workers can effectively operate advanced pipeline installation technologies” and “Continuous training helps workers stay updated on the latest techniques in pipeline installation and maintenance” with reported Cronbach’s alpha of 0.872. The Cronbach’s alpha coefficients are greater 0.7 threshold which shows that the instrument is consistent and reliable for this study.

3.1. Data Presentation and Analyses

The collected data was analyzed using Structural Equation Modeling (SEM) after conducting preliminary assessments, including tests for multicollinearity, outliers, normality, and common method bias, to ensure the suitability of the dataset. SmartPLS, an SEM software, was employed to evaluate both the measurement and structural models.

3.2. Measurement Model

This model was utilized to assess the outer loadings, reliability, validity, effect size (f^2) and coefficient of determination (R^2) of the exogenous variables on the endogenous variable.

Initially, the research assessed item loadings to determine their suitability for further analysis. Hair et al. (2018) recommended retaining only items with loadings of 0.70 or above for future research. However, recognizing the practicality of lower loadings, Hulland (1999), argued that items with loadings of 0.50 and higher should be retained while considering their impact on convergent validity and reliability. Consequently, in this study, items with loadings of 0.50 were retained, and those below 0.5 were deleted i.e., HDD3, SPMS 2 and WDP1 (see Table 1 and Figure 1).

The study also assessed convergent validity using Average Variance Extracted (AVE). According to Hair et al. (2021), an AVE value of 0.50 or higher indicates that the constructs exhibit convergent validity. As shown in Table 1, all AVE values exceed the 0.50 threshold, confirming the presence of convergent validity. Additionally, construct reliability and consistency were evaluated using composite reliability. Hair et al. (2020), recommended a composite reliability value of 0.70 or above for a construct to be deemed reliable. Table 1 demonstrates that all composite reliability values exceed this threshold, confirming the reliability of the constructs.

Finally, the coefficient of determination (R^2) was examined for both models. The R^2 value for the model is 0.559 (56%), indicating that 156% of the variance in the endogenous variable (OS) is explained by the exogenous variables (HDD, SPMS & WDP). Chin (1998) classified an R^2 value of 56% as moderate, suggesting that while the model explain some variance, additional factors may contribute to the endogenous variable beyond those included in the study.

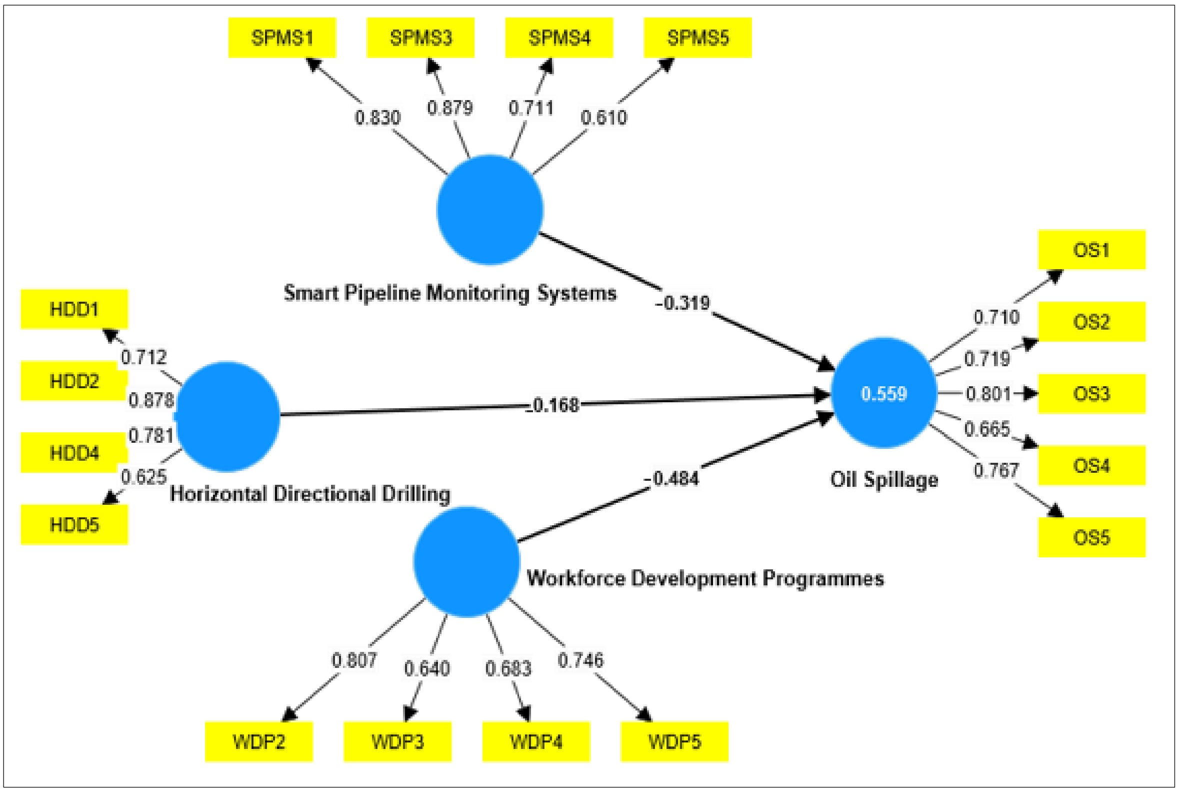

Figure 1 Measurement Model

Table 1 Heterotrait-Monotrait Ratio (HTMT) Matrix 1

Constructs	Indicators	Outer Loadings	Cronbach's Alpha	Composite Reliability	AVE	Decision
Horizontal Directional Drilling	HDD1	0.712	0.745	0.839	0.570	Accepted
	HDD2	0.878				
	HDD4	0.781				
	HDD5	0.625				
Oil Spillage	OS1	0.710	0.785	0.853	0.539	Accepted
	OS2	0.719				
	OS3	0.801				
	OS4	0.665				
	OS5	0.767				
Smart Pipeline Monitoring Systems	SPMS1	0.830	0.762	0.847	0.584	Accepted
	SPMS3	0.879				
	SPMS4	0.711				
	SPMS5	0.610				
Workforce Development Programmes	WDP2	0.807	0.707	0.812	0.521	Accepted
	WDP3	0.640				
	WDP4	0.683				
	WDP5	0.746				

Additionally, discriminant validity was assessed using the Heterotrait-Monotrait (HTMT) correlation ratio due to the limitations of cross-loadings and the Fornell and Larcker criterion in detecting a lack of discriminant validity when loadings fall between 0.65 and 0.85. Kline (2011) recommended an HTMT ratio of less than 0.85 for non-comparable constructs to establish discriminant validity. As shown in Table 2, all HTMT values fall below the 0.85 benchmark, confirming that discriminant validity is established.

Table 2 Heterotrait-Monotrait ratio (HTMT) – Matrix 2

Constructs	**Horizontal Directional Drilling**	**Oil Spillage**	**Smart Pipeline Monitoring Systems**	**Workforce Development Programmes**
Horizontal Directional Drilling				
Oil Spillage	0.594			
Smart Pipeline Monitoring Systems	0.393	0.627		
Workforce Development Programmes	0.587	0.848	0.388	

3.3. Structural Model

The structural model was employed to test the hypothesized relationships. i.e., the influence of HDD, SPMS & WDP on OS in Nigeria.

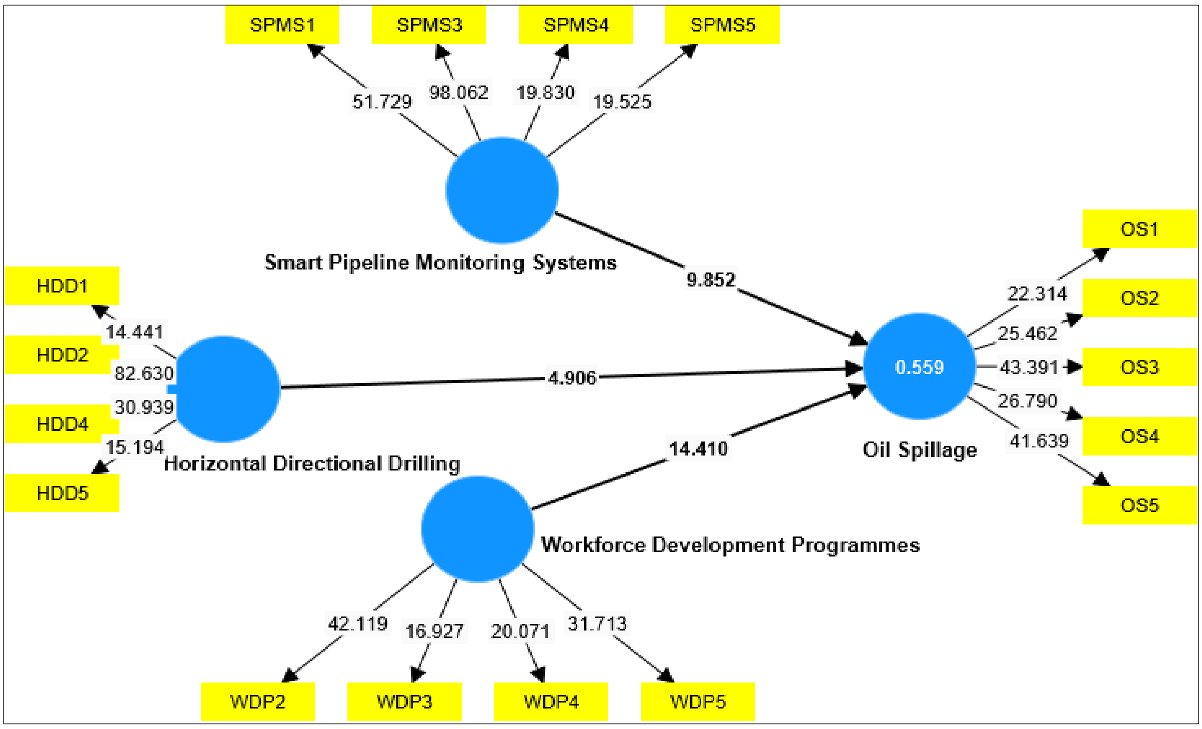

Figure 2 Structural Model

The results from Table 3 reveal significant findings regarding the direct relationships between Horizontal Directional Drilling (HDD), Smart Pipeline Monitoring Systems (SPMS), and Workforce Development Programmes (WDP) on oil spillage. The first hypothesis, H1, examines the impact of HDD on oil spillage, and the results indicate a negative relationship with a beta coefficient of -0.168. This suggests that as the use of HDD technology increases, the occurrence of oil spillage decreases. With a T-statistic of 4.906 and a P-value of 0.000, the hypothesis is strongly supported, indicating that HDD is an effective method for reducing oil spillage.

Table 3 Test of Direct Hypotheses

Hypotheses	Relationship	Beta	STDEV	T statistics	P values	Decision
H1	Horizontal Directional Drilling->Oil Spillage	-0.168	0.034	4.906	0.000	Supported
H2	Smart Pipeline Monitoring Systems-> Oil Spillage	-0.319	0.032	9.852	0.000	Supported
H3	Workforce Development Programmes->Oil Spillage	-0.484	0.034	14.410	0.000	Supported
	R^2= 0.559		Q^2= 0.294			

Similarly, hypothesis H2 explores the relationship between Smart Pipeline Monitoring Systems (SPMS) and oil spillage. The findings show a more substantial negative relationship, with a beta value of -0.319, indicating that SPMS implementation significantly reduces the likelihood of oil spillage. The T-statistic of 9.852 and a P-value of 0.000 confirm the robustness of this relationship, offering strong support for the hypothesis. The smart monitoring systems enhance the safety and effectiveness of pipeline operations, leading to fewer incidents of oil spills.

Hypothesis H3, which tests the impact of Workforce Development Programmes on oil spillage, also shows a significant negative relationship, with a beta of -0.484. This suggests that well-trained workers play a crucial role in minimizing oil spillage, as their skills and knowledge lead to better operational practices. The high T-statistic of 14.410 and a P-value of 0.000 further support the hypothesis, confirming that workforce development is a critical factor in reducing environmental risks. The overall model's R^2 of 0.559 indicates that 55.9% of the variation in oil spillage can be explained by these three variables, and the Q^2 value of 0.294 suggests the model has good predictive relevance, enhancing the study's credibility and significance.

4. Discussion

The results demonstrated that Horizontal Directional Drilling (HDD) substantially mitigates oil leakage in Nigeria, as shown by the negative beta coefficient of -0.168 and the elevated T-statistic of 4.906. This indicates that the use of HDD technology in pipeline construction leads to a reduction in oil leak occurrences. HDD mitigates environmental effect by facilitating pipeline installation with little land disturbance, hence decreasing the likelihood of accidents and leaks (Carlin, 2014). In Nigeria, where pipeline vandalism and environmental degradation pose substantial challenges, this technology presents a viable alternative to alleviate the detrimental impacts of oil production and transportation (Akinwale and Fakorede, 2020). The robust statistical evidence supporting the hypothesis underscores HDD's capacity to improve environmental sustainability in Nigeria's oil industry, making it an essential element in initiatives aimed at diminishing the occurrence and intensity of oil spills.

The study results displayed that Smart Pipeline Monitoring Systems (SPMS) significantly reduce oil leakage in Nigeria, as evidenced by the negative beta coefficient of -0.319 and the strong T-statistic of 9.852. This adverse correlation indicates that the deployment of intelligent monitoring systems is essential for identifying and mitigating possible pipeline problems, such as leaks or corrosion, prior to their escalation into substantial spills. Through the constant real-time monitoring of pipeline conditions, SPMS provide early action, hence reducing the danger of oil spills (Ekong & Etim, 2021). In Nigeria, where oil pipeline infrastructure often suffers damage from natural and anthropogenic factors, the use of SPMS may significantly improve the safety and sustainability of pipeline operations. The robust statistical significance of the results underscores the efficacy of these technologies in tackling a principal environmental challenge within the Nigerian oil sector, rendering them indispensable for mitigating environmental risks linked to oil transportation and enhancing the efficiency and security of pipeline management (Uche et al., 2022).

The study results indicated that Workforce Development Programmes (WDP) significantly reduce oil leakage in Nigeria, as shown by the negative beta coefficient of -0.484 and the elevated T-statistic of 14.410. This indicates that proficient and adept personnel are crucial in averting oil leaks during pipeline construction and maintenance activities (Kalu, et al., 2022). Workforce development programs provide staff with the technical skills and expertise to operate innovative technologies, like Horizontal Directional Drilling and Smart Pipeline Monitoring Systems, efficiently and safely (Narkhede and Gardas, 2018). Furthermore, these programs underscore the significance of safety measures, environmental consciousness, and proper equipment management, all of which mitigate the risk of accidents and spills. In Nigeria, where pipeline vandalism and environmental degradation are widespread, personnel training is essential for mitigating the danger of oil spills. The robust statistical evidence highlights the significance of investing in human capital to improve operational safety and environmental sustainability, positioning WDP as a crucial approach for enhancing the overall performance of the oil industry while reducing its environmental effects.

4.1. Implications

The study's results underscore the need of incorporating new technology and staff training into pipeline management methods in Nigeria. The substantial influence of Horizontal Directional Drilling (HDD), Smart Pipeline Monitoring Systems (SPMS), and Workforce Development Programs (WDP) on mitigating oil spills illustrates that the implementation of advanced technologies and the investment in human capital are essential for enhancing environmental sustainability in the oil industry. The Nigerian government and oil industry should prioritise the installation of HDD and SPMS to improve pipeline safety and reduce the danger of environmental damage. Moreover, an emphasis on workforce development will guarantee that employees have the requisite skills to operate these systems proficiently, so substantially reducing the danger of oil spill. The results indicate that it is crucial to address both technical and human elements to attain long-term sustainability and minimise the environmental impact of oil operations.

The research theoretically corresponds with Technology Adoption Theory, which underscores the significance of innovation in enhancing operational practices and results. This hypothesis posits that the use of new technologies, such as HDD and SPMS, might result in substantial performance enhancements by mitigating inefficiencies and minimising hazards. The results substantiate this idea by demonstrating that the use of these technology significantly reduces oil spills. Furthermore, the research aligns with Human Capital Theory, which posits that expenditures in education and training improve the productivity and efficacy of personnel within an organisation. The crucial impact of Workforce Development Programs in mitigating oil spills substantiates this idea, demonstrating that proficient personnel are more adept at managing intricate technology and complying with safety regulations. Both theories emphasise the need of an integrated strategy that merges technical advancement with personnel development to enhance results in oil pipeline management and environmental conservation.

5. Conclusion and Recommendations

The research shows that Horizontal Directional Drilling (HDD), Smart Pipeline Monitoring Systems (SPMS), and Workforce Development Programs (WDP) substantially mitigate oil spills in Nigeria. The results indicate that the implementation of HDD reduces environmental disturbance, SPMS improves real-time surveillance and early leak detection, and WDP provides staff with the necessary skills to operate these technologies effectively. The findings highlight the need for a cohesive strategy that merges technology advancement with human capital enhancement to guarantee environmental sustainability in the oil industry.

Based on the findings, the study recommended that:

- Setting the order of importance for horizontal directional drilling (HDD) for pipeline projects: Companies that work with oil should push for Horizontal Directional Drilling (HDD) to become the normal way to build pipelines. This method minimises damage to the environment, lowers the chance of oil leaks, and protects the stability of the pipeline, especially in areas that are sensitive to the environment. Companies should spend money on HDD technology and training to make building and maintaining pipelines more efficient and long-lasting.
- Required Installation of Smart Pipeline Monitoring Systems (SPMS): Smart Pipeline Monitoring Systems (SPMS) should be required to be installed across all oil assets by government agencies and business partners. These systems improve real-time monitoring, early leak discovery, and fast reaction mechanisms, which makes oil spills much less likely to happen. It should be required by law that all oil companies use SPMS in their pipeline operations. To make pipelines safer, these companies should use advanced technologies like sensor-based tracking, automatic alerts, and AI-driven prediction analytics.
- Making Workforce Training and Capacity Development Programs Permanent: Oil companies need to set up and maintain permanent comprehensive workforce training programs to make sure that their workers have the technical know-how to properly operate modern pipeline technologies. The main topics of training should be using and taking care of HDD systems, monitoring pipelines with SPMS, and following the best practices for avoiding spills and dealing with emergencies. Workers should also be able to take training classes on a regular basis to keep up with changes in technology and business rules.
- Development and Enforcement of Eco-Friendly Pipeline Regulations: Regulatory bodies should make and follow rules that encourage and control the use of environmentally friendly pipeline technologies. These rules

should include strict environmental effect studies for pipeline projects, HDD execution standards that must be met, and the use of SPMS. Oil companies should be forced to follow the best practices for managing pipelines in a way that doesn't harm the environment. Companies that don't follow these rules should be punished, and companies that use eco-friendly technologies should be rewarded.

- To make pipeline management more sustainable, government agencies, oil companies, and private investors should work together more closely. This will help pay for and put into action technological advances and programs that help workers get better at their jobs. Public-private partnerships (PPPs) can help get money for things like expanding training programs, researching and developing pipeline technology, and setting up high-tech tracking systems. These relationships can also help people share information and build their skills, which can lead to a more sustainable, efficient, and environmentally responsible oil pipeline management system.

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