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Crude Oil and Natural Gas Conduit Corrosion Durability (CCD) in Coastal Mangrove Swamp Environments of Niger Delta Regions-Nigeria

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Abstract*: Pipeline network among other means of crude oil and natural gas transportation have been long identified as one of the most essential and effective oil production midstream unit that ensures availability of crude oil as industrial feedstock and its distillates as products for man daily consumption as fuel/energy and petrochemicals precursors. This system is highly attacked by corrosion agents which affects its durability over time as a function of the pipeline type. In this work, crude oil and natural gas conduit corrosion durability (CCD) in coastal mangrove swamps environments of Niger Delta regions-Nigeria is been assessed correspondently with the degree of the environmental physiochemical response to the corroding system with 77 days exposure period. Using three pipelines of same material properties; 45 inches (3.75 ft or 114.3 cm) long, 3.1 inch (0.258333 ft or 7.874cm) internal diameter, making the volume of 377.38 cubic inches (0.2184 ft^3) and 59.8424 g/cm density, subterranean as conduits in Okrika, Kalabari and Bonny coastal mangrove environments of the Niger Delta regions -Nigeria, the LCS non-coated pipelines corrosion response were determined as a function of the exposure period, as well the soil physiochemical properties behavior with the studied period, using physical and non-destructive testing methods. The result was able to identify that the LCS non-coated pipelines of 8.46kg individual weights depleted to 7.032kg, 7.109kg and 6.934kg over 77 days' exposure period in Okrika, Kalabari and Bonny coastal regions respectively, leading to the increase in the metal cumulative weight loss. It was also identified that Bonny coastal mangrove regions (S_3) tends more corrosion enhancing compared to other two, with a cumulative weight loss of 1.526kg attained within the 77 days studied period, which is greater than that attained by Okrika (S_1) and Kalabari (S_2) as 1.428kg and 1.351kg respectively. Also, corrosion rate of 4.1328×10^{4} mm/yr was recorded for the Bonny coastal mangrove environment, while 3.8674×10^{-4} mm/yr for Okrika mangrove and 3.6589×10^{-4} mm/yr for Kalabari mangrove. It was also noticed the mangrove environmental DO and pH reduces with increase in the exposure time, while*

EC increases slowly. The internal corrosion assessment of the pipelines was also carried out using Long Range Ultrasonic Testing (LRUT) equipment which was able to identify a small depletion of the pipeline over time of study. Conclusively, LCS metal used as conduit in mangrove region experience a fast and spontaneous degradation in a coastal mangrove region of Niger Delta, especially that of Bonny, and the rate of corroding affects the environmental physiochemical properties. Hence, it's recommended that proper assessment of the pipeline should always be carried out to safe guide the transported fluid from been spilled over time, also, efficient coating/inhibition should be applied on the pipelines running through the mangrove regions as they gets corroded fasted than expected.

Keywords: pipeline, oil spillage, Okrika, Bonny and Kalabari regions, River state, weight loss, Long Range Ultrasonic Testing (LRUT) equipment, barges and tankers, transportation measures durability

INTRODUCTION

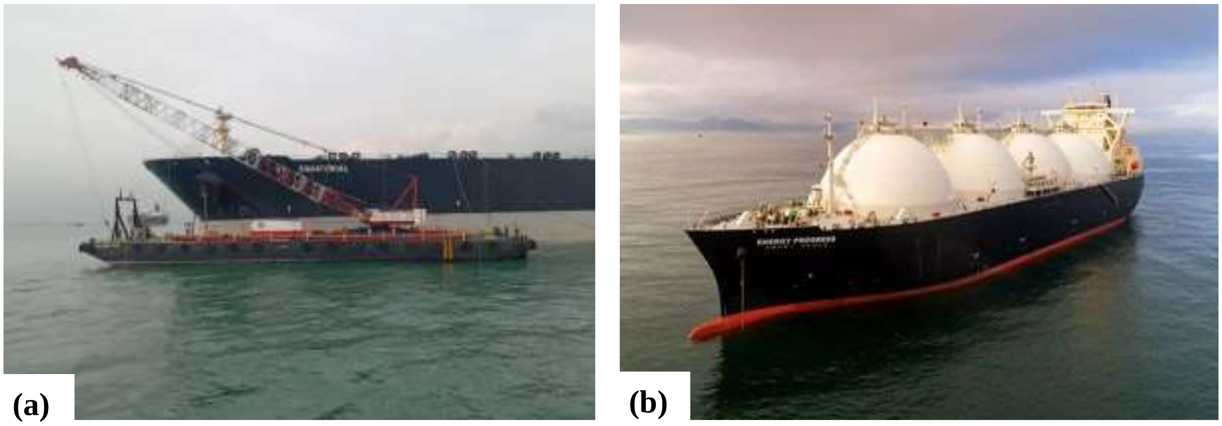
Oil and gas industries fully depend on transportation measures durability (TMD) efficiency for effective exhibition of oil and gas production / distribution practices. Crude oil and other fossil fuels (Natural gas and coal) are products of organic matters generated on daily bases in large quantities as energy source and petrochemicals (Ugi *et al.*, 2023; Sammy *et al.*, 2023; Igwe *et al.*, 2026a; Igwe *et al.*, 2026b; Ogolo *et al.*, 2026; Lambert *et al.*, 2026; Nathaniel *et al.*, 2026), of which after been recovered from their respective reservoirs, they are processed and downstreamed into useful distillates (essential products) in refineries. The processing and downstream act of fossil fuel such as crude oil give rise to highly demanding products; gasoline (PMS), kerosene (DPK), diesel (AGO), petrochemicals, etc. which are needed for diverse purposes by man (Perry's and Green, 2007; Ugi *et al.*, 2023 Igwe *et al.*, 2026a). To gets to the stage of achieving or yielding these significant products from crude oil, the produced or recovered oil is first transported to refineries where the oil is distilled at favorable operating conditions to qualitative and quantitative distillates which are usually transported to various stations around the globe for the final products consumers who uses the products as energy and precursor (Favennec, 2022; Green, 2007; Ugi *et al.*, 2023).

In most cases the recovered crude oil and natural gas are been transported to different countries as marketable products, earning millions of capitals for the crude oil active countries, and these financial benefits have been supportive to most of those countries economic, social, national and financial status (Arailym *et al.*, 2020; Igwe *et al.* 2026a; Ologunde *et al.*, 2020; Okoro *et al.*, 2017; Favennec, 2022). Countries such as Nigeria whose supply team includes Spain, India, France, the United States, and the Netherlands, can perfectly attest to the facts about the benefits of crude oil trading, as the system has drastically facilitated the nation's economic and financial background since the year 1956 when oil and gas was first discovered at Oloibiri community in Bayelsa State (Niger Delta regions of Nigeria) by the Shell-BP consortium after multiple years of exploration efforts (Ogbuigwe *et al.*, 2018; Atei and Stephen, 2015), and till date Nigerians are still celebrating the benefits of the crude oil era, with massive crude oil and condensate produced at around 1.71 to 1.84 million barrels per day (bpd), and approximately 2.8 to 3.0 trillion cubic feet (Tcf) is attained, while the Nigerian Upstream Petroleum Regulatory Commission (NUPRC) estimates the nation's technical capacity exceeds 2.5 million bpd, recurring challenges like aging infrastructure, pipeline vandalism, and structural underinvestment cap annual output, which is in billions of tons yearly. Nigeria as an oil and gas producing country supply and distributes crude oil and natural in large quantities at the international market as salable products, making the country 15th largest oil procuring country in the world (largest in Africa) and 12th largest natural gas distributors in the world (still largest natural gas producers in Africa), with over 250 oil production fields, categorized by geographic environments and operational status of the country, circulated majorly within the **Niger Delta Basin** and extending into offshore deep-water and shallow-water territories (Igwe *et al.*, 2026b; Sammy *et al.*, 2023) Nigeria is haven over 37 billion barrels of crude oil and condensate reserves as well as over 215.19 trillion cubic feet (TCF) natural gas, hence stands a long-lasting status of continues oil and gas production.

The efficient utilization of crude oil benefits by any country involves the integration of the upstream, midstream and the downstream oil and gas sectors, with the midstream responsible for treatment of recovered crude oil for quality distillates, as well as the transportation of the crude oil from either the production zone to the storage, treatment or downstream sectors (such as the refinery). Transportation as known involves the movement of items from one location to other, and that is achievable either via air, land or sea transportation means, but in the case of crude oil and natural gas, transportation is done using either land, or water. Fundamentally, oil and gas transportation is been carried out using either of the listed methods:

i. Marine Vessels and Barges

Barges and the Marine vessels (Tankers) are large vessels (marine vessels are the largest among the two), used in transporting large amount of crude and other petroleum products, all round the world. Their ability of conveying large amounts of fuel per time makes them the cheapest means of crude oil transportation, in costs per barrel. They are the only means of conveying crude conveniently through oceans. Barges are not just only smaller than they Tankers, but they also lack method of propulsion when compared. This makes barges (a) ineffective for use in transporting crude oil for long distances compared to the Tankers (b)



(a) **(b)**

Figure 1: Barges and the Marine vessels (Tankers) for crude oil transportation

ii. Pipelines

Pipelines are the most cost-efficient approach of crude oil transportation, used to transport oil from wells to refineries and storage facilities. They are viewed as the most cost-efficient way to move or transport oil and other liquid products on land. (Karangwa, 2008) Pipelines are as well one as the safest transportation means for crude oil with incidence rate of just 0.58 per billion-ton miles. (Suburban, 2021) Most countries such as Canada, fully (over 99.99 percent) relies on oil transportation through federally regulated pipelines. Crude oil from well heads are directly collected most times using pipes, then pumped across land to dischargeable points, of which most times are the refineries. However, pipelines can as well be used in delivering already refined fuels or products from the refinery, to distribution facilities or stations for easier consumers' reach. These pipelines are of different types, length and texture, they are not just a frame work of solid straight lines, they have various components and auxiliary units; such as the *booster pumps which are responsible in controlling the flow pressure of the crude oil or products along the pipeline, *the inspection areas which are ensuring that the fuel is traveling without attracting or getting contaminated along the process, due to the collection and delivery points that are along the pipeline pathway. The initial installation or setting up of pipeline system, as chemical products and crude oil transportation means, although seems costly and scaring to put in place, but be sure of the fact that the operation cost of the system is significantly less compared. (Karangwa, 2008) Also, pipeline transportation system requires lesser man power and management. (Trench, 2001)

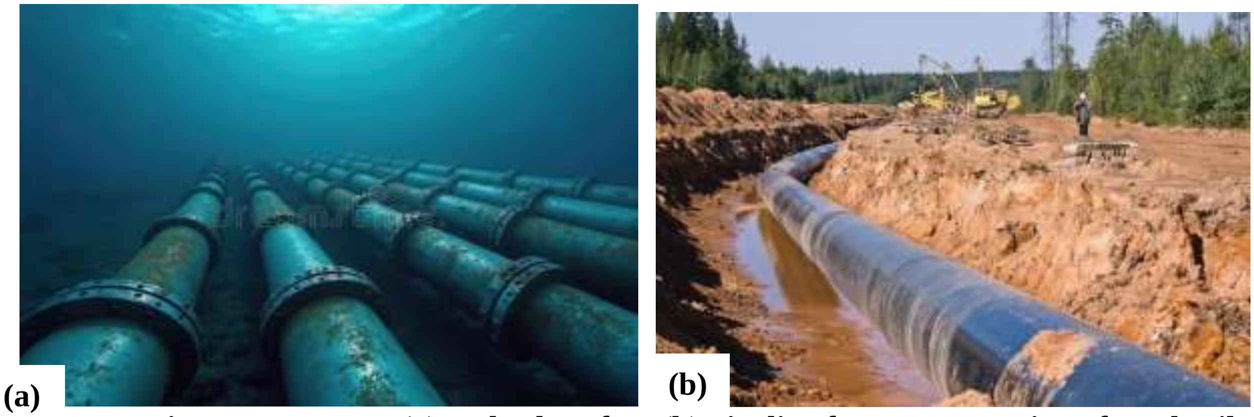


Figure 2: Deepsea (a) and subsurface (b) pipeline for transportation of crude oil

Pipelines are of diverse installation orientation, some are buried some few meters beneath the earth crust while some are Deepsea pipelines (subsea lines), both conveying oil and gas products at very large quantities. Deepsea pipelines are engineered to withstand extreme hydrostatic pressure, freezing deep-water temperatures, and complex hydrodynamic forces. In contrast, **surface pipelines** are typically laid on land (overland) or exist as temporary floating setups, dealing primarily with atmospheric weather rather than deep-sea hazards (Xingsen *et al.,* 2024; Liu *et al.,* 2026; Chen *et al.,* 2023; Zhaohui and Wenbin, 2022). Some of the greatest advantages of the deepsea pipelines transportation of crude oil is its limited vandalization tendencies, hence it is located deep down the ocean area, it is very hard for vandalizers to tamper with, though the system is very expensive to establish compare to the surface pipeline system, but it is more safer in transferring oil and gas products. Also, hence the ocean tends not to have stable environments due to the ocean current, deepsea pipelines are lesser to cessation effects. Finally, deepsea pelerine systems enhances environmental safety as closed deep-sea pipelines provide a highly secure containment system, reducing the risk of routine spills and lowering the carbon footprint. Surface pipelines which are mostly buried few meters beneath the earth crust are also of some advantages which includes their easiness to maintenance, leakage control and enhance adequate lite pipeline monitoring. Surface pipelines are also cheaper to install compare to the deepsea pipelines system.

iii. Trains

Trains or Tank cars as commonly referred, are another means or method applied in moving crude oil across defined landmass, or across rails to refinery or train's planned destinations. They carry a massive amount (in thousands of liters) of fuels or crude. Tankers or train cars capacity cannot be compared to marine vessels, even though some, such as the DOT-111 tank car, holds 131 cubic meters (35,000 US gal) and above, that is far less than the capacity of the smallest marine vessel. These rail cars, can as well just as pipelines be used in transporting both the crude oil products and the crude itself, not as marine ships which are mainly to convey crude oil and not its products. Tank cars require lot of horsepower and man's power to ensure safe delivering of products. They are exposed to almost all known types of risk, and are not opened for used within areas of bad roads.


Figure 3: Train transportation of crude oil and it's distillates

Trucks

Tank trucks and the Tank cars or rail cars are always appearing confusing to understanding of many, but the truth is that they are different, best description is as seen at Figure 1.3a and Figure 1.3b below. Tank trucks are mainly used in transporting finished or refined products of crude oils, also in transportation of petrochemicals. Transportation of products from refinery to fuel stations for consumers reach, are been done mainly using Tank trucks. Trucks are known to have the smallest carrying capacities among all other crude oil transporting means, and can only transport within a short distance among all. So, they are rarely used to transport crude oil itself, from the production wells due to their small carrying capacity, but sometimes they are called to duty when other means of transportation of crude proves abortive.


Figure 1.3: Tank trucks (a) and Tank cars (b) used in transportation of crude oil.

All means of transportation are liable to certain factors which makes them risky to proactive to some extent. After the deadly Lac-Mégantic disasterin Quebec, it was invigorated within 2013, that a freight train carrying crude oil product, derailed and spilled over 5.56 million litres of oil (Dunford, 2017), which resulted to series of explosions, generating great fires that destroyed most of the town's, with over 30 buildings burn to ground and 47 persons killed. Within same year of Lac-Mégantic disasterin Quebec, a propane carrying train derailed near Gainford of Alberta, which results in explosions with no actual injuries or fatalities. Riedlhuber, (2013) The continual recordings of rail accidents promote the regulations and restrictions towards the use of rail as transportation means, especially for large volume crude oil, in most countries. Marine vessels and Barges are as well recorded of spilling so much crude oil on seas, promoting water pollution and which causes reduction in dissolved oxygen rate, thus effect in turn causes death to aquatics, and reducing capital and means of food to the aquatics dependable humans. The truth of all is that none of the applied means of transportation are risk free, including the use of Pipelines, for instance, Nexen pipeline in 2015, along the south of Fort McMurray, ruptured and leaked crude oil of over 5 million liters, covering approximately 16,000 m^2 of the company's Long Lake oil sands facility.(CBC, 2018).

Successful transportation of crude and its derivatives depends greatly on the product volume, nature and form, as well as the easiness and safety of the system. To avoid, reduce or eradicate risk of products lose and dead rate, one must be sensitive towards the type of transporting means applicable for a given crude oil type and its products. One of the key differences among the known transportation methods is the costs associated, but all are of their respective risk, which varies from one transportation method to other. Some of the greatest problems and challenges associated to the movement or transportation of petroleum products are pollution and products lost related. When crude oil gets into the environment (either via fugitive leakage, explosion and vandalization measures), it facilitates rapid unhealthiness of the ecology, on the bases that petroleum and its products are majorly hydrocarbon compounds (paraffins, aromatics and Naphthene’s) whose effects tends disastrous to both man, plants and microbes, promoting land / atmospheric pollution, agricultural soil nutrient degradation (Ugi *et al.*, 2023; Wordu *et al.*, 2023; Igwe *et al.,* 2026a; Igwe *et al.,* 2026b; Ogolo *et al.,* 2026; Nathaniel *et al.,* 2026). The degree of effects of hydrocarbons on an environment is a function of the toxic nature and concentration of the spilled hydrocarbons, which also serves as a promoter of atmospheric greenhouse gases (GHGs) whose contributions also enhance metallic corrosion (Ita *et al.,* 2026; Obeten *et al.,* 2017; Benedict *et al.,* 2021; Benedict, 2024; Benedict and Mbang, 2019; Ugi *et al.*, 2022; Ugi, 2014; Ugi and Magu, 2017; Ugi *et al.*, 2024; Ugi & Obeten, 2019; Ugi, 2018; Ugi *et al.*, 2016; Ugi & Obeten, 2019; Ugi & Obeten, 2019). So, adequate care is applied in crude oil transporting.

Numerous studies indicated the use of pipelines among other means of crude oil transportation as the best and safest means of moving oil and gas within distanced regions (Green & Jackson, 2015; Furchtgott-Roth, 2013), but despite all it seems, industries and some environments, still suffers greatly over products lost and spillage resulted from pipeline corrosion effects. Pipelines are classified in different ways, with each class having an area most fitted for application in the modern engineering world. Pipelines can be grouped by functions (gathering, transmission and distribution pipelines), by material type which it is transporting (water, effluent, oil/gas, slurry, Pneumatic & Capsule Pipelines), as well as by type of material which the pipeline is built of (Metal. Plastics and Composite pipelines), each playing essential role in today's societies. In the oil and gas sector, pipelines basically used are metallic, and their quality is based on the following classifications:

i. **American Petroleum Institute (API)**
ii. **American Iron and Steel Institute (AISI)**
iii. **Steel composites**

(a) (b)

Figure 5: Pipeline corrosion (b) with its easiness towards pipeline vandalization (a)

Steel based pipelines are those found in the oil and gas transporting sector, and the they are of thousands of grades, rated basically on their chemical composition, mechanical properties, and manufacturing processes. The four (4) main categories of steel used for materials building are Carbon Steel (A36, 1018, and 1045)**,** Alloy Steel (4130, 4140, and 4340)**,** Stainless Steel (304, 306 and 410), and Tool Steel (D2 and H13), of which out of the four (4) steel pipeline types, the **low-carbon steel (LCS)** and the **high-strength low-alloy (HSLA)** steel pipeline types are mostly used in transportation of crude oil, natural gas and petrochemicals. Though many believe that pipelines been thick as seen in various industries are made of high carbon steel (HCS), which is ideally wrong (Juad *et al.*, 2026; Ahmed *et al.*, 2020), for high carbon steels pipelines are not been used in oil and gas conveying process because they are too brittle and difficult to weld in the field (Juad *et al.,* 2026; Ahmed *et al.,* 2020). Low carbon steel (LCS) pipelines are most preferred for crude oil and natural gas transport on the bases that they are of:

i. Ideal carbon content (often 0.05% to 0.25% carbon content) which enhances the pipeline ductility and easiness to weld over a long distance of even thousand miles.
ii. Abilities of withstanding high internal pressurized pumped fluid as they are micro-alloyed with elements like manganese, niobium, and vanadium to boost their strength.
iii. Perfect balance tensile strength, fracture toughness, and affordability which makes them cost effective, cheap and affordable for a large quantity usage.
iv. Better or high corrosion resistance compared to the high carbon steel (HCS) which is susceptible to rust from moisture and the corrosive compounds in crude oil, hence pure carbon gets corroded faster than when in impure state.

Despite how resisting the LCS are to corrosion, the still gets affected overtime, proportional to the concentration of corrosion agents presents in the environment. Corrosion is the spontaneous and gradual degradation of metal materials due to electrochemical reactions between the metals and its environmnet (Benedict and Fredrick, 2023, Benedict *et al.*, 2022; Ugi *et al.,* 2023; Ugi *et al.*, 2026; Ugi *et al.*, 2021). In the case of pipeline corrosion which arises via the interactions between transporting fluid nature (internal factors) with the environmental or soil constitutes (external factors), corrosion promotes the easiness to vandalization as the process reduces the pipeline material strength (Mouneir *et al.*, 2026; Abdu *et al.*, 2023; Zhao *et al.*, 2024; Hussein *et al.*, 2023; Abdelkader *et al.*, 2024) as well thinning the pipeline wall, making it so easy towards penetration of pipeline with even the slightest direct impact force acted on the pipeline. Pipeline corrosion also enhances pitting, and catastrophic leaks, presenting severe financial and environmental risks. Metallic corrosion is a function of the environmental conditions, and on crude oil and natural gas transporting pipelines, which in most cases are buried or lay on surfaces of the soil are high exposed to different environmental conditions.

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Figure 6: The coastal mangrove swamp of the Okrika regions of River State

Within the Niger Delta regions of Nigeria, several reports have been recorded over the leakage of pipelines which 65% points to vandalization and the rest to corrosion with other anthropological phenomenon, making corrosion motoring and equipment's control an essential section of the oil and gas engineering. Crude oil and natural gas pipelines in the Niger Delta regions of Nigeria such as in River State are laid through coastal mangrove swamps of whose properties most times are acidic and with corrosion promotive conditions example are the soils of the Okrika, Bonny and Kalabari regions of River state. The Coastal ecosystems are dynamic, biologically rich environments where land and water meet, encompassing **mangroves**, **coral reefs**, **estuaries**, **salt marshes**, and **seagrass beds**. They are crucial hubs for **biodiversity**, driving global fisheries and sequestering massive amounts of carbon. Coastal mangrove swamps (which can be called just the mangrove swamps) are highly dynamic, transitional wetlands found in tropical and subtropical intertidal zones consisting salt-loving mangrove trees and shrubs. They are uniquely defined by salt-tolerant trees, waterlogged and oxygen-poor soils, fluctuating daily tides, and an extraordinary capacity to protect shorelines and act as major carbon sinks (Pieter, 1995; Singh, 2020).

Carbon steel crude oil conveyor pipelines durability within the mangrove swamps in Nigeria is greatly threatened by the soil properties and has facilitated lots of oil and gas leakage, products lose, engineering time consumption and delaines in oil and gas transmission. Corrosion assessment of the degree of carbon steel durability depletion as a factor of the soil type and properties will enhance the prediction of the surface pipelines lifespan as defines the possible period when maintenance is required to prevent fugitive leakages of oil and gas, saving both the industries, oil and gas producing sectors, as well as the environments.

1. Materials and Methods

In assessment of carbon steel crude oil conveyor pipelines durability within the mangrove swamps in Nigeria the following materials were considered:

i. **Three mangrove soil samples (Okrika, Kalabari and Bonny mangrove soils)**
ii. **Low carbon steel (LCS) non-coated pipelines**
iii. **Weighing balance**
iv. **pH, EC and DO tester**
v. **Computer**
vi. **Long Range Ultrasonic Testing (LRUT) equipment (MsSR3030R and Dry coupling tool)**

The above listed materials were adequately integrated for the assessment of pipeline durability through the coastal mangrove environments of Niger Delta regions of Nigeria. The Okrika, Kalabari and Bonny regions coastal mangrove are sampled for study in this work out of all the Ijaw ethnic group, and that is because they are known historically as coastal city-states located in the Rivers State region of the Niger Delta-Nigeria. The mangrove soil samples were collected as fresh wet soils from three different regions of the Niger Delta **(Okrika, Kalabari and Bonny)** in plastic vessels and stored at ambient temperature. Also, three (3) low carbon steel (LCS) non-coated pipelines; 45 inches (3.75 ft or 114.3 cm) long, 3.1 inch (0.258333 ft or 7.874cm) internal diameter, making the volume of 377.38 cubic inches (0.2184 ft^3); i.e. 6184.15021 cm^3. The initial weight of the pipelines was taken as well as the soils initial physiochemical properties (**pH, DO, and Conductivity**) where achieved. The pipelines were polished to remove all possible scales (using a sandpaper) and setting all the pipelines to same weight, then placed in three separate horizontally oriented plastic constructed hallows (6ft long each), before been covered with various soil samples collected from the coastal mangrove environments of the Niger Delta (Okrika, Kalabari and Bonny). Analysis of weight lost and soil physiochemical deviation ay variant time space were taken at every 7 days difference of 77days experimental assessment of the pipeline's response to the different coastal mangrove swamps. The corrosion rate of the assessed low carbon steel pipeline was determined using the corrosion rate model presented as equation (1)

$$Corrosion\ Rate\ (R_c) = \frac{K \times W_L}{DAT} \tag{1}$$

$$= \frac{\emptyset_I - \emptyset_f}{T} \tag{2}$$

Where;

K = A constant that defines the unit of the final corrosion rate (e.g., K = 8.76×10^4 for mm/year, or K = 5.34×10^5 for mils/year - mpy).

$\boldsymbol{W_L}$ = Weight loss of the metal specimen in grams (g).
D = Density of the metal in grams per cubic centimeter (g/cm^3)
A = Surface area of the metal sample in square centimeters (cm^2).
T = Exposure time of the metal sample in hours
$\emptyset_I$ *and* $\emptyset_f$ = Initial and final thickness (cm)
Where the surface area (A) is determinable as the internal surface area of the pipeline; which is 453.3475 square inches 3.1483 ft^2 or 2924.8169 cm^2), scaled on the bases of the pipeline cylindrical lateral surface area model equation (3), while the density is determined using the model equation (4) as 59.8424 g/cm^3

$$Lateral\ surface\ area = \pi dL = 2\pi r(r + L) \tag{3}$$

$$Density\ (D) = \frac{initial\ weight}{\pi r^2 L} \tag{4}$$

The internal corrosion of the pipeline was also determined using the Long Range Ultrasonic Testing (LRUT) equipment fastened on the pipeline surface before been buried in the coastal mangrove environment.

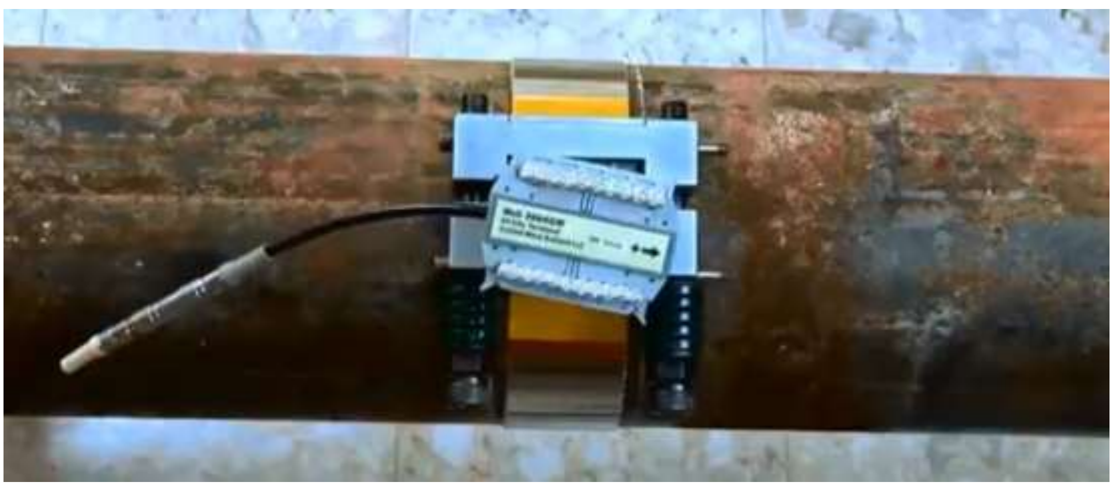


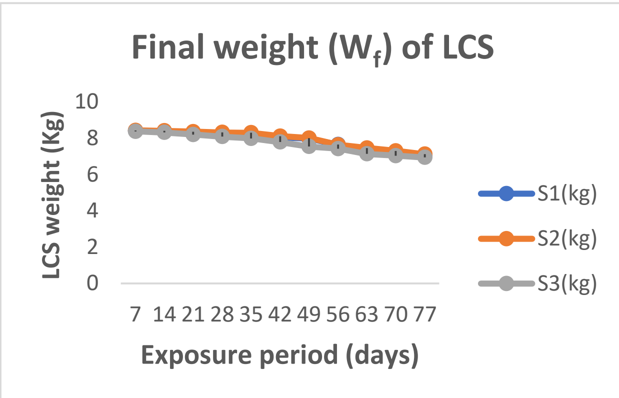
Figure 7: LRUT dry coupling on a pipeline

2. Results and Discussion

The corrosion response of low carbon steel in coastal mangrove environments of Niger Delta regions of Nigeria **(**Okrika, Kalabari and Bonny regions precisely**),** and the soil physiochemical deviations or response to LCS non-coated pipeline response, are recorded as presented at Table 1 and Table 2 (Appendix) as a function of the initial weight of the pipeline (8.46 kg), with S_1, S_2 and S_3 representing the Okrika, Kalabari and Bonny regions soils respectively.

3.1 LCS Pipeline Corrosion Response Analysis in Coastal Mangrove Environment

The weight lost analysis of the crude oil conveyor pipelines was able to identify coastal mangrove soils of Niger Delta regions (Okrika, Kalabari and Bonny) in Nigeria to be of a high corrosion enhancing efficiency on low carbon steel (LCS) non-coated pipeline used in conveying crude oil and natural gas through the route, applicable to both surface and subterranean conduits.



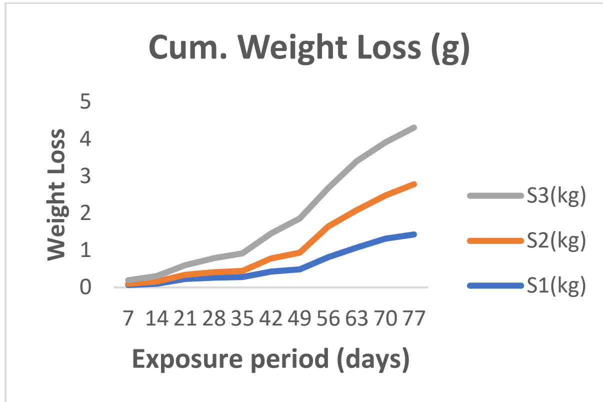


Figure 8: Weight loss of LCS non-coated pipeline in coastal mangrove environments of Niger Delta

As seen presented as Figure 8(a), the LCS pipelines experiences geometric decrease in their individual weights over the increase in their exposure time (days) subterranean in Okrika, Kalabari and Bonny Niger Delta coastal mangrove soils, such that the LCS non-coated pipelines of 8.46kg individual weights depleted to 7.032kg, 7.109kg and 6.934kg over 77 days exposure period in Okrika, Kalabari and Bonny coastal regions respectively. This act promoted the increase in the cumulative weight loss of the metals as seen at Figure 8(b), which depicts that the longer the LCS non-coated pipelines stays in the coastal mangrove soils the high they experience weight lost. Comparing the degree of corrosion enhancing efficiency of the three mangrove regions as seen at Figure 8, it can be seen that the Bonny coastal mangrove regions (S_3) are more corrosion enhancing compared to other two in the Niger Delta region of Nigeria, as the pipeline attain a cumulative weight loss of 1.526kg within the 77 days studied period, which is greater than that attained by Okrika (S_1) and Kalabari (S_2) as 1.428kg and 1.351 respectively.

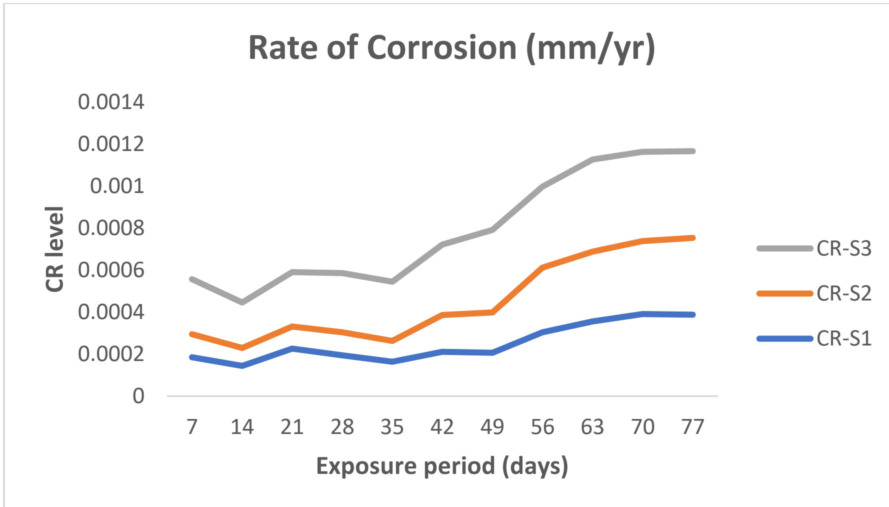


Figure 9: Rate of corrosion of LCS non-coated pipeline in coastal mangrove environments of Niger Delta

The rate of corrosion of LCS non-coated pipelines was also assessed and it shows an increasing rate of the pipelines corrosion in respective Niger Delta coastal mangrove soils as seen at Figure 9, with Bonny coastal mangrove soil (CR-S_3) taken the lead with a corrosion rate of 4.1328×10^4 mm/yr attained at 77 days exposure period, which exceeds that of the Okrika coastal mangrove environments (3.8674×10^{-4} mm/yr) as well as that of Kalabari (3.6589×10^{-4} mm/yr). The result shows also show that the system rate of corrosion is more experienced after 35 days exposure period, with the pipeline displaced within Bonny mangrove facing the greatest increase in the rate of corrosion.

3.2 Physiochemical Response of Coastal Mangrove Environments to LCS Pipeline Corrosion

3.2.1 Coastal Mangrove Environments pH Response to LCS Pipeline Corrosion

In assessing the coastal mangrove environments physiochemical response to corrosion of LCS non-coated pipeline, it was noticed that the Okrika, Kalabari and Bonny Niger Delta coastal mangrove soils pH reduces over time, making the soil acidity increasing proportional to increase in the pipeline corrosion rate. As seen at Figure 10 the pH of Okrica mangrove soil (5.9) tends to be greater compared to that of Bonny (5.4) and Kalabari (5.2) coastal environments.

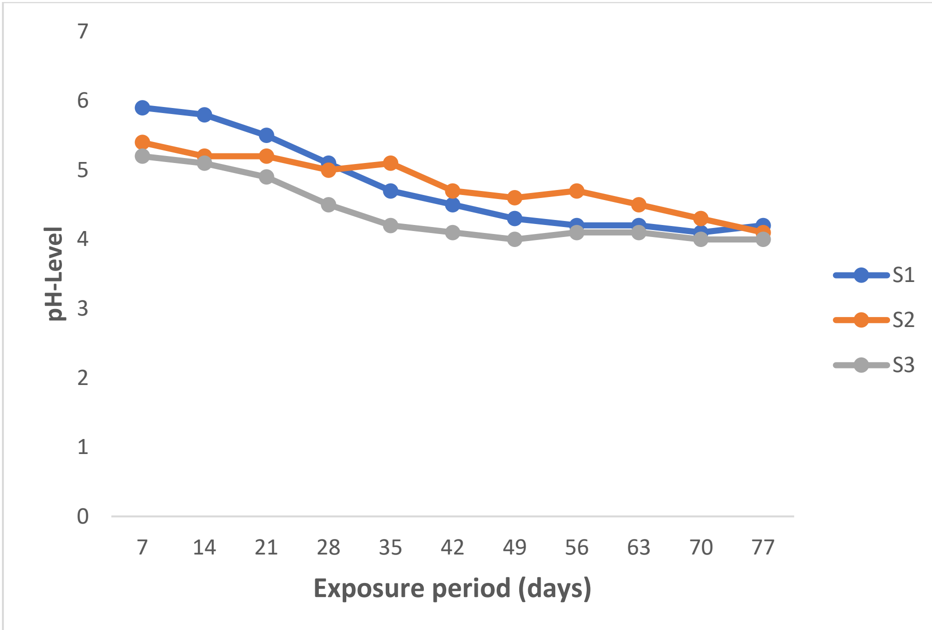


Figure 10: Niger Delta coastal mangrove soil pH behavior under LCS corrosion within specified exposure period

The result also shows that the Bonny and Okrika coastal mangrove environments pH response similarly over the pipeline exposure period, such that their pH drops rapidly from 5.2 to 4.0 for the Bonny environment, and from 5.9 to 4.2 for the Okrika coastal mangrove, before both linearly proceeded in their decreasing nature with respect to increase in the pipeline exposure period till 77 days was attend.

3.2.2 Coastal Mangrove Environments EC Response to LCS Pipeline Corrosion

The electric conductivity (EC) of the coastal mangrove environments of Niger Delta regions (Nigeria) was also assessed and the results as seen presented as Figure 11 shows just a little / slide increase in the EC from the initial points of 12975 µS/cm, 15897 µS/cm and 17847 µS/cm respectively for Okrika, Kalabari and Bonny Niger Delta coastal mangrove to 13257 µS/cm, 16296 µS/cm and 18165 µS/cm over the 77 days exposure period of the non-coated pipeline.

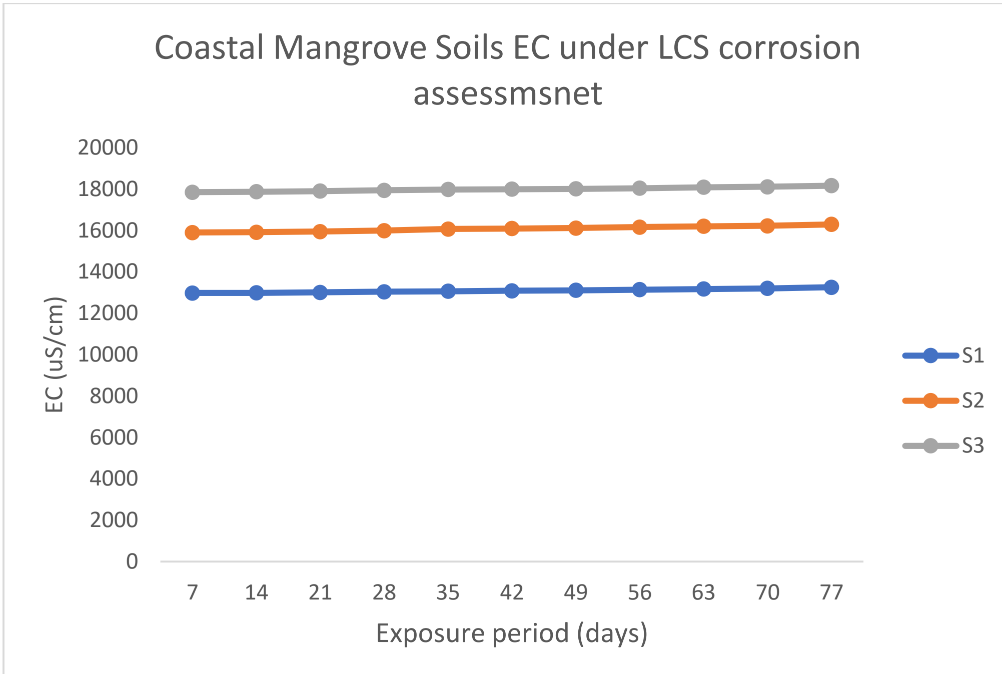


Figure 11: Niger Delta coastal mangrove soil EC behavior under LCS corrosion within specified exposure period

It was also identified that the Niger Delta mangrove soils are of a high EC level; > 12300 MicroSiemens per centimeter (µS/cm) which proves that there are indeed of salt water composites, according to (Zhang *et al*., 2024; Afefe *et al*., 2019; Bajahmoum and Almaghamsi, 2025; Kashif *et al.*, 2025), mangroves has the ability of retaining high amounts of salts and ionic composites, they can retain both autochthonous and allochthonous marine and/or terrestrial organic carbon (OC) in sediments as well, hence accounts for their high EC levels.

3.2.3 Coastal Mangrove Environments DO Response to LCS Pipeline Corrosion

In analyzing the behavior or response of the Niger Delta coastal mangrove environment dissolved oxygen (DO) in respect to increase in LCS pipeline exposure time, it was noticed that the Niger Delta mangrove environments were characterized with DO level 4.856mg/L, 4.186mg/L and 3.604mg/L for the Okrika, Kalabari and Bonny regions respectively as seen at Figure 12, which depicts the mangrove sediments to be anoxic (lacking oxygen), and the result is in agreement with that presented by Alex *et al*. (2024) which is that their assessed mangrove environment DO values ranged between 1 – 4 mg/L. Also, it was noticed that the EC increase very slowly throughout the exposure period. This is quarreled to the fact that some of the oxygen is utilized during the corrosion of the LCS non-coated pipeline.

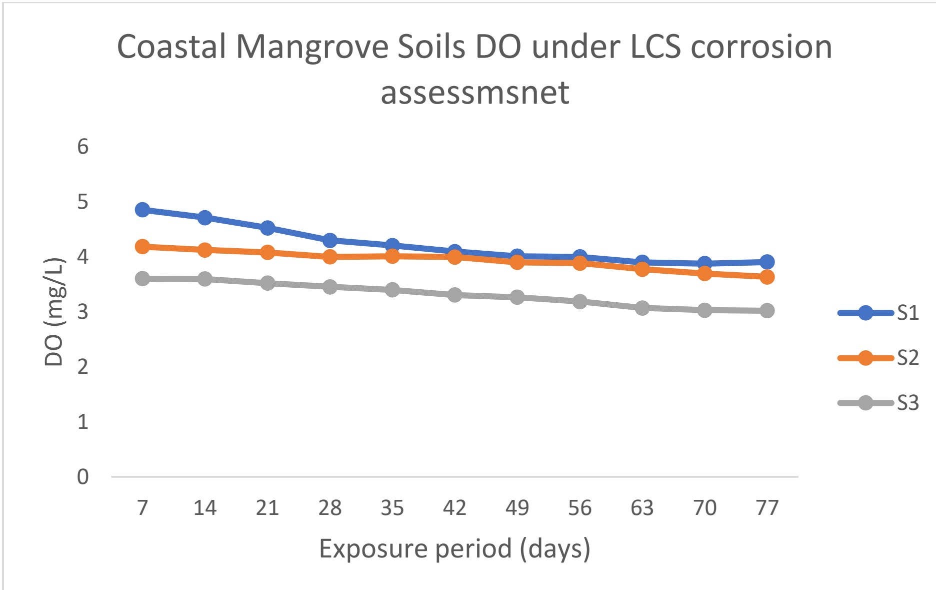


Figure 12: Niger Delta coastal mangrove soil DO behavior under LCS corrosion within specified exposure period

3.3 LCS Pipeline Hidden Corrosion Response in Coastal Mangrove Environment

In the screening of the pipeline for hidden corrosion and metal loss using the Long Range Ultrasonic Testing (LRUT) equipment which relies on using low-frequency guided waves (15 - 85 kHz) that can cover distance greater than 300meters (in all directions, it was detected that the pipelines buried within the coastal mangrove soils.

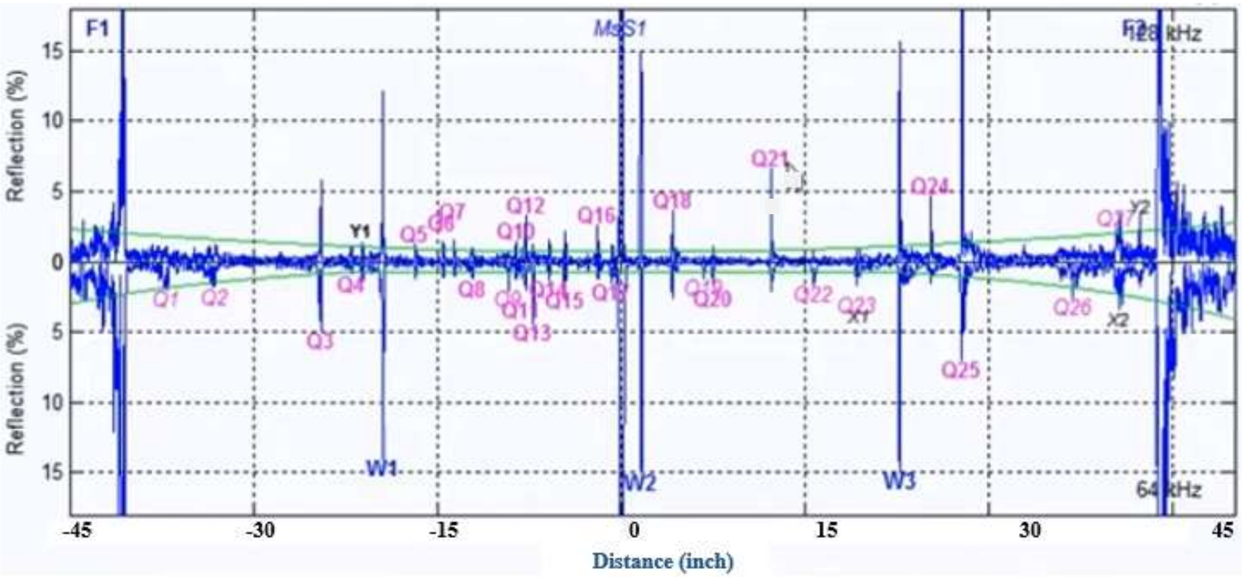


Figure 13: Time corrected gain (TCG) plot of the studied pipeline

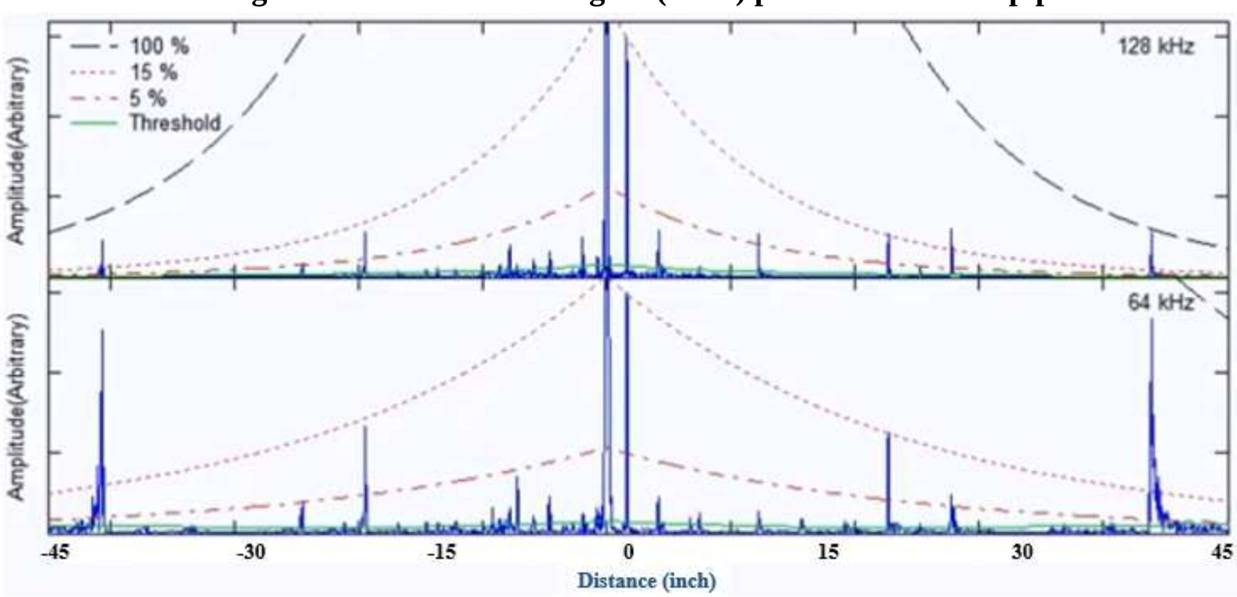


Figure 14: Distance amplitude correction (DAC) curve of the studied pipeline

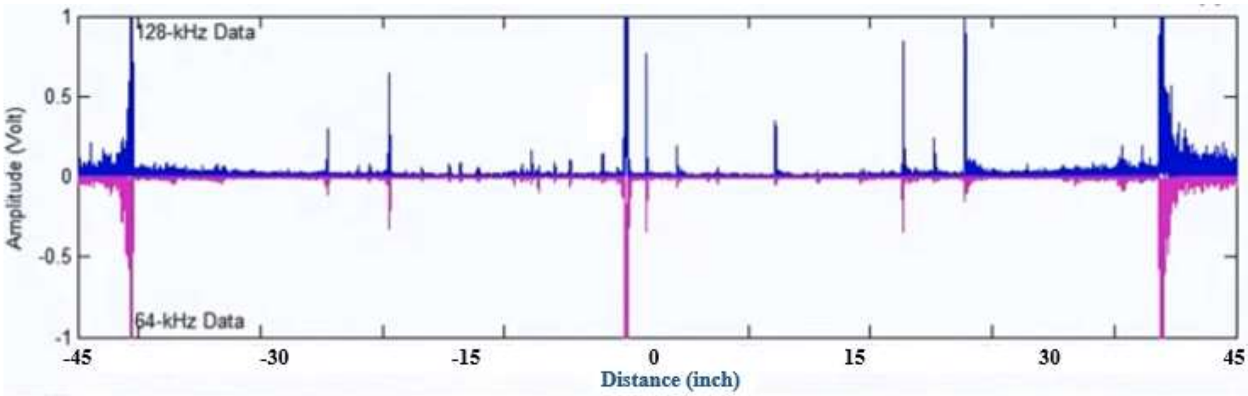


Figure 15: RF and Spectrogram plot of the studied pipeline

4 Conclusion and Recommendation

Conclusively, LCS metal used as conduit in mangrove region experiences fast and spontaneous degradation in a coastal mangrove region of Niger Delta, especially that of Bonny LGA, and the rate of corroding affects the environmental physiochemical properties. Hence, it's recommended that proper assessment of the pipeline should always be carried out to safe guide the transported fluid from been spilled over time, also, efficient coating/inhibition should be applied on the pipelines running through the mangrove regions as they get corroded fasted than expected.

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Appendix

Table 1: Weight lost and corrosion rate of the pipelines in Niger Delta coastal mangrove swamps

T(days)	T(hr)	Final Weight (W_f)			Weight lost (W_f)			Corrosion Rate		
		S_1(kg)	S_2(kg)	S_3(kg)	S_1	S_2	S_3	CR-S_1	CR-S_2	CR-S_3
7	168	8.398	8.423	8.372	0.062	0.037	0.088	0.00018471	0.00011023	0.00026216
14	336	8.364	8.402	8.315	0.096	0.058	0.145	0.000143	8.6394E-05	0.00021599
21	504	8.233	8.354	8.199	0.227	0.106	0.261	0.00022542	0.00010526	0.00025918
28	672	8.201	8.311	8.083	0.259	0.149	0.377	0.0001929	0.00011097	0.00028078
35	840	8.187	8.292	7.988	0.273	0.168	0.472	0.00016266	0.0001001	0.00028123
42	1008	8.035	8.108	7.786	0.425	0.352	0.674	0.00021102	0.00017477	0.00033465
49	1176	7.978	8.008	7.535	0.482	0.452	0.925	0.00020513	0.00019237	0.00039367
56	1344	7.645	7.633	7.425	0.815	0.827	1.035	0.0003035	0.00030797	0.00038542
63	1512	7.386	7.457	7.134	1.074	1.003	1.326	0.00035551	0.00033201	0.00043892
70	1680	7.148	7.294	7.032	1.312	1.166	1.428	0.00039086	0.00034736	0.00042542
77	1848	7.032	7.109	6.934	1.428	1.351	1.526	0.00038674	0.00036589	0.00041328

Table 2: Niger Delta coastal mangrove swamps physiochemical properties variation over time

T (days)	pH			DO (mg/L)			EC (µ S/cm)		
	S_1	S_2	S_3	S_1	S_2	S_3	S_1	S_2	S_3
7	5.9	5.4	5.2	4.856	4.186	3.604	12975	15897	17847
14	5.8	5.2	5.1	4.711	4.124	3.598	12986	15911	17871
21	5.5	5.2	4.9	4.525	4.081	3.521	13009	15946	17899
28	5.1	5.0	4.5	4.298	4.000	3.456	13034	15989	17938
35	4.7	5.1	4.2	4.205	4.010	3.399	13059	16065	17976
42	4.5	4.7	4.1	4.096	3.996	3.308	13083	16094	17992
49	4.3	4.6	4.0	4.011	3.901	3.267	13109	16112	18011
56	4.2	4.7	4.1	3.998	3.886	3.187	13142	16164	18042
63	4.2	4.5	4.1	3.901	3.774	3.072	13169	16198	18086
70	4.1	4.3	4.0	3.878	3.696	3.03	13197	16221	18110
77	4.2	4.1	4.0	3.906	3.635	3.021	13257	16296	18165