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Vandalism-Induced Corrosion: A Review of Oil and Gas Facility Protection Options

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ABSTRACT

Vandalism-induced corrosion poses significant challenges to the integrity of oil and gas infrastructure, particularly in oil-producing regions like the Niger Delta in Nigeria. This paper explores the mechanisms, impacts, and mitigation strategies for corrosion accelerated by deliberate damage to metal surfaces. This study also highlights how vandalism removes protective coatings, exposing metals to corrosive elements such as moisture and pollutants, thereby accelerating localized corrosion processes. Case studies, including incidents at the Nembe Creek Trunk Line, underscore the economic and environmental repercussions of vandalism-induced pipeline failures. Prevention and mitigation strategies, ranging from advanced coatings and surveillance technologies to mechanical protection systems like Anti-Tamper Lock (ATL), Sureguard®, and Interlocks, are discussed. Potential knowledge gaps/research needs are highlighted and future research directions, emphasizing interdisciplinary approaches are recommended to enhance understanding and management of vandalism-induced corrosion and improve the longevity and safety of critical infrastructure in the oil and gas sector.

1. Introduction

Every year, oil and gas operators all over the world lose millions of dollars because of corrosion, and corrosion management (Akpan, 2023; Izionworu et al, 2020a; 2020b; 2020c; NACE, 2016). While corrosion of oil and gas facilities can be attributed majorly to natural corrosion phenomenon and associated environmental issues (Etim et al., 2023), sabotage, operating violations, and activities related to crude oil theft through vandalized parts of a facility also lead to corrosion. Vandalism-instigated corrosion is a term used to describe the corrosion of metal surfaces that is accelerated or triggered by intentional damage or vandalism. When a metal surface is scratched, dented, or otherwise compromised, it creates areas where the protective coating or passivation layer (if present) is removed, exposing the underlying metal to environmental factors such as moisture, oxygen, and pollutants. This exposure can accelerate corrosion processes, leading to localized corrosion, that is pitting or crevice (filiform) corrosion or widespread deterioration of the metal surface. Corrosion caused by vandalism can happen in several places, including on cars, buildings, public properties, or oil and gas facilities like pipelines where metal surfaces are exposed to the weather.

While pipeline vandalism, leading to corrosion, is a cause for concern, it is equally worthy of mentioning that the resulting crude oil spill impacts negative ly on the economy and results in social and environmental pollution causing dangerous distortion of air and soil quality (Izionworu and Amadi, 2016). The negative effect of crude oil spill on biodiversity is a huge risk to land, sea, and sky mammals (Olujobi et al., 2022; Izionworu et al., 2021). These additional challenges present the need for control of vandalism and the associated corrosion. Prevention strategies often involve protective coatings, regular maintenance, surveillance, and public education to discourage vandalism and promote responsible behaviour. However, when vandalism occurs the effective management of corrosion caused by it requires that the culprit must be identified to prevent future occurrence. Sadly, there have been different opinions on the cause of failed oil and gas facilities. While Amnesty International blames oil and gas facility failures and the resulting spills on pipeline corrosion, maintenance issues, equipment failure, sabotage or theft, resulting from neglect by the oil and gas producing companies in developing countries like Nigeria, the producing companies have blamed more than 150,000 barrels of crude oil theft valued at $6billion and large-scale pollution on sabotage and the actions of vandals (Daniel, 2013; Olujobi et al., 2022).

The study of vandalism-instigated corrosion is critical since deliberate damage can have profound implications for corrosion processes, leading to faster degradation of metal surfaces than would occur under normal circumstances. However, there is lack of understanding of these processes, which are crucial for industries and sectors where metal structures or components are susceptible to vandalism. This will allow for the development of effective prevention and mitigation strategies. This discussion will cover mechanisms of vandalism-instigated corrosion, influencing factors, case studies, technological advances in prevention strategies against oil and gas facility vandalism, crude oil theft, and pipeline and other oil and gas facility corrosion management. Future research directions are also suggested.

2. Mechanisms of Vandalism-Instigated Corrosion

A notable primary mechanism of vandalism-instigated corrosion is the removal of protective coatings or passivation layers from metal surfaces. Vandalism, such as scratching or denting, can physically damage these protective layers, exposing the underlying metal to corrosive elements in the environment. Protective coatings, such as paints, sealants, or corrosion inhibitors play a crucial role in preventing corrosion by acting as a barrier between the metal surface and external factors (Fernandes and Montemor, 2015). When these coatings are compromised, the metal becomes more susceptible to corrosion leading to the exposure of the metal to corrosive elements. Corrosive elements in the environment, including moisture, oxygen, pollutants, and salts can penetrate the damaged areas and initiate different forms of corrosion processes like localized corrosion processes, where corrosion occurs preferentially at the damaged sites while the surrounding areas remain relatively unaffected (Fernandes and Montemor, 2015). This localized corrosion can manifest as pitting, crevice (e.g., filiform) corrosion, or galvanic corrosion, depending on the specific conditions and metal properties. This corrosion condition is usually exacerbated by the presence of moisture in the environment as it facilitates electrochemical reactions on the metal surface, leading to the formation of corrosion products like rust (Fernando et al., 2013).

Compared to uniform corrosion processes that occur over the entire metal surface at a relatively slow but steady rate, vandalism-instigated corrosion tends to lead to accelerated corrosion rates at the damaged sites. This acceleration is due to the localized nature of the corrosion and the increased exposure of the metal to corrosive elements. As a result, metal structures or components affected by vandalism may experience faster deterioration and reduced service life if the corrosion is not addressed promptly (APP, 2018).

Understanding these mechanisms is essential for developing effective prevention and mitigation strategies to combat vandalism-instigated corrosion. By addressing the root causes and vulnerabilities associated with intentional damage to metal surfaces, industries and sectors where metal structures or components are susceptible to vandalism can minimize the impact of vandalism on infrastructure, equipment, and public safety (APP Incorporated, 2018; Institute of Corrosion, 2024; Isaac, 2023).

2.1 Corrosion Implications for Crude Oil Pipeline

Research shows that when crude oil in pipelines flow under pressure, the possibility of corrosion attack is reduced (Wang & Zhang, 2016). Conversely, when the crude oil is stagnant, it increases the potential of brine- and CO_2-induced corrosion as well as microbiologically induced corrosion and other effects of stagnant debris that may result in localized pitting and thinning corrosion, ringworm corrosion, wormhole attack, and uniform corrosion (Wang & Zhang, 2016; Dennis, 2021; Izionworu *et al.*, 2020a).

CO_2-induced corrosion can occur in both overlapping and non-overlapping shallow pits and grooves. It can also manifest on the lower surface of a pipe when a distinct water phase is present or on the upper surface of a pipe in the presence of condensation within wet gas systems (Dennis, 2021). Delays in pigging or chemical injection – of biocides and inhibitors in such lines to allow for investigation over disputed cause of the facility damage – allow corrosion induced by CO_2 to prevail. Also, the control of variables including pH, temperature, and pressure is not possible because these variables ordinarily control CO_2 accumulation in the pipeline (Dennis, 2021).

Another dangerous corrosion situation that the vandalizing of oil and gas facility can create is the effect of sour corrosion caused by hydrogen sulphide (H_2S) produced by the crude oil from reservoirs or wells (Dennis, 2021). Stepwise, uniform and pitting corrosion can result when condensed water reacts with the H_2S to form weak acids (Dennis, 2021).

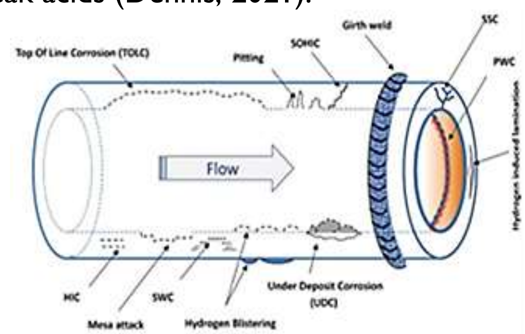

Figure 1: H_2S corrosion inside the pipe (Source: Denis, 2021).

3. Factors Influencing Vandalism-Instigated Corrosion

Denis (2021) identified the common factors that influence vandalism-instigated corrosion to include (but not limited to) moisture, oxygen, temperature, pollutants, pH, and the type of metal.

3.1 Moisture, Oxygen, Temperature, Pollutants, and pH

While moisture can aggravate the effects of deliberate damage by promoting the penetration of corrosive elements into the exposed areas, oxygen is a critical component in corrosion reactions, particularly in aerobic environments where it reacts with metal ions to form oxides or hydroxides, accelerating the corrosion process. Vandalism that removes protective coatings exposes the metal to oxygen, enhancing corrosion rates. Also, pollutants in the environment, such as sulfur dioxide, chlorides, or industrial emissions can exacerbate corrosion processes. These pollutants can react with moisture and oxygen to form corrosive compounds that attack metal surfaces. Vandalism-induced damage increases the susceptibility of metal surfaces to these pollutants (Wasim et al., 2018; SealXpert, 2017).

3.2 Type of Metal

Another factor is the type of metal involved. The type of metal involved plays a significant role in its susceptibility to corrosion. Some metals, such as steel, are more prone to corrosion than others. Factors influencing susceptibility to corrosion include the metal's composition, microstructure, and electrochemical properties (SealXpert, 2017). For example, stainless steel is more resistant to corrosion than carbon steel due to its higher chromium content, which forms a passive oxide layer that protects the underlying metal. However, even stainless steel can corrode if its protective layer is compromised by vandalism. The severity and type of vandalism can greatly influence the extent of corrosion damage to metal surfaces. Vandalism can take various forms, including scratching, denting, chemical damage, or deliberate removal of protective coatings to allow for hot or cold tappings. Scratching and denting as forms of physical damage to metal surfaces can remove protective coatings and expose the underlying metal to corrosive elements. Unintentional scratches and dents, and intentional scratches and dents to allow for cold or hot tapings to steal products of a pipeline provide localized sites for corrosion initiation and propagation, leading to accelerated degradation (SealXpert, 2017).

3.3 Chemicals

Vandalism involving chemical substances can directly attack metal surfaces, leading to corrosion. Chemicals such as acids or caustic solutions can rapidly degrade protective coatings and initiate corrosion reactions on exposed metal surfaces. Understanding these risk factors is crucial for assessing the risk of vandalism-instigated corrosion and implementing effective prevention and mitigation measures. By addressing environmental conditions, metal properties, and the nature of vandalism, industries and sectors where metal structures or components are susceptible to vandalism can minimize the impact of deliberate damage on metal infrastructure and equipment (Wasim et al., 2018).

4. A Case Study

A relevant case study illustrating the effects of vandalism on corrosion in the oil and gas industry in the Niger Delta region of Nigeria. In 2015, a major corrosion-related incident occurred on the 97-km, 150,000-barrels/day NCTL in the Niger Delta region, leading to a pipeline rupture. The rupture was primarily caused by corrosion and pipeline aging, which had weakened the pipeline over time. However, while corrosion played a significant role, there has been a widespread report in the media that the pipeline rupture was exacerbated by sabotage due to the nefarious activities of criminal groups and oil thieves in the region, which have cost Nigeria over $4 billion every year, equivalent to 10% of its annual budget (Victor, 2023).

5. Frequency and Causes of Pipeline Failures in Nigeria (2014 – 2018)

Figure 2 shows the frequency (number) and causes of pipeline failures from 2014 to 2018 in the Niger Delta region.

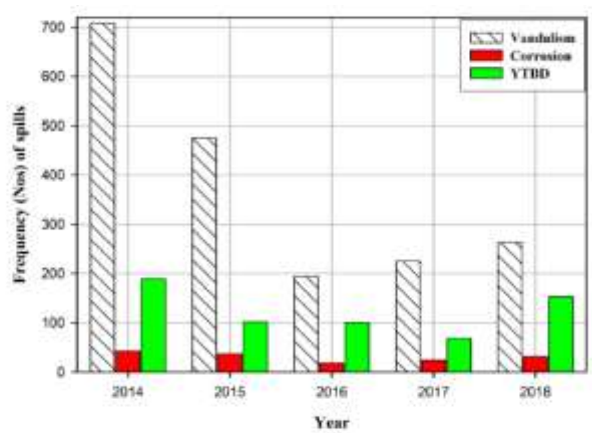

Figure 2: Frequency and Causes of Pipeline Failures 2014-2018 (Augustin et al., 2021).

Figure 2 shows that vandalism remains the major cause of spills. In 2014, there were the highest incidents of vandalism, followed by 2015, 2018, 2017, and 2016. Spills attributed to vandalism were 65.1, 63.0, 44.0, 52.4, and 46.2% of total spills for 2014, 2015, 2016, 2017, and 2018, respectively. The data demonstrate that vandalism is a major contributor to pipeline corrosion and failures in the Niger Delta region, with significant environmental and economic consequences for Nigeria. Addressing pipeline vandalism is critical to mitigating corrosion and ensuring the integrity of oil and gas infrastructure in the region (Agomuoh et al., 2021).

6. Pipeline Failure Prevention and Mitigation Strategies

Two types of technology-based innovations, namely hard technology and soft technology have been used over time to protect oil and gas facilities (ADF, 2023). Several researchers have explored various hard and soft technologies in safeguarding oil and gas facilities against vandalism.

6.1 Soft Technologies for Facility Protection

A microcontroller-based anti-pipeline vandalism system has been used for oil and gas facility protection (Ogujor *et al*., 2013). The system can send real-time alerts to operators in a control room, specifying the precise location of ongoing theft along the pipeline. To detect sabotage, this system integrates insulated copper cable sensors wound round the pipeline. When any interference is detected, the acquired data is displayed on the monitoring system. However, in this system, there can be short circuiting to allow for undetected vandalism during the cable repair if vandals impact multiple cuts on the insulated copper cable over varying distances.

An automated electronic pipeline vandalism detection and surveillance system with an intruder detection module has also been used (Obodoeze *et al*., 2014). This system integrates video cameras for surveillance and the capture of evidence related to criminal activity on oil pipelines. While proficient at identifying criminal identities, it lacked provisions for sabotage countermeasures. Consequently, a system for detecting pipeline vandalism, which transmits information to a control room through alarms and SMS notifications was developed (Ezeh *et al*., 2014). This system uses resistance sensors to maintain an uninterrupted electrical signal path. Any disruption in the signal path triggers alarms, illuminating light-emitting diodes (LEDs). However, this system lacks the ability to communicate over a remote network.

A similar approach was adopted by Igbajar and Barikpoa (2015), who proposed a microcontroller-based pipeline monitoring system. Igbajar and Barikpoa (2015) focused on the architectural design and modelling of oil spillage detection, incorporating real-life scenarios and simulations. Detection was based on imbalance between inflow and outflow pressures. Whenever a significant drop in outlet pressure was detected, the system triggers alarms and sends short notification messages to a dedicated control unit. However, this system is primarily effective in the presence of substantial oil leaks, as small leaks or punctures in the pipeline were not considered.

Franklin *et al.* (2016) presented a system like that of Ogujor *et al*. (2013) in which unit-by-unit simulations of the system components using procedural programming during the experimental phase were carried out. Meanwhile, Eluwande and Ayo (2016) adopted a more novel approach involving the use of Unmanned Aerial Vehicles (UAVs) for real-time monitoring and surveillance of pipelines in hazardous environments. This system utilizes quadcopters for live video streaming. However, its implementation and maintenance were cost intensive. More recently, Ajao *et al.* (2018) devised an anti-theft mechanism that employs Internet-of-Things (IoT) technology and incorporates ATmega328, GSM, and GPS for remote information monitoring.

6.2 Mechanical Facility Protection Tools

Hard technologies solely based on mechanical systems including Anti-Tamper Lock (ATL), Sureguard®, and Interlock have been used by oil and gas company operators to protect their facilities from intruders (Yang *et al*., 2021). Installation of mechanical locks has protected many operators' facilities from sabotage and theft over the years. The results over these years show that these unique facility protection systems have proved to be very useful in anticipating, managing, and ameliorating risks associated with vandalism, mechanical failure, technical performance, operational and maintenance issues.

6.2.1 Anti-Tamper Lock (ATL)

The ATL was developed in response to the challenges of unauthorized valve operation, which occurred during vandalization, product theft, sabotage, or human error. ATL is a simple-to-use locking device, which prevents accidental or unauthorized operation. It is designed to fit directly on valves, replacing the original operating hand-wheel and is compatible with all valve sizes (Figure 3a). It is keyed access (i.e., each valve has its own unique key). It freewheels when locked and has no visible screws. It is made of case-hardened material and epoxy resin coated for corrosion protection. The ATL provides vandal-proof protection against unauthorized operation or damage to valves, especially those installed in remote locations (Figures 3c and d). ATL has been effective in preventing valve tampering, product pilfering, and vandalism in many locations in the Niger Delta region of Nigeria. The ATL rotates freely when a valve is locked, eliminating the need to use force to attempt to operate a locked valve. The units can be uniquely coded or coded alike, depending on operational conditions and requirements. Lock-to-valve interfaces for all types of valves have also been designed and manufactured. To operate the lock, the unit is fitted to the valve shaft, the tamper-proof coded card key is inserted allowing valve operation. The valve can be operated to any position. Once the key is removed, the unit freewheels, preventing further valve operation.

ATL is recommended for critical valves on wellhead (Figure 3b) such as master and wing valves; and production pipeline valves such as isolation, mainline and bypass valves (Figures 3c and d). This mechanical device also has its downside, which is that vandals may cart away the ATL and the installed valves flanged on the facility.

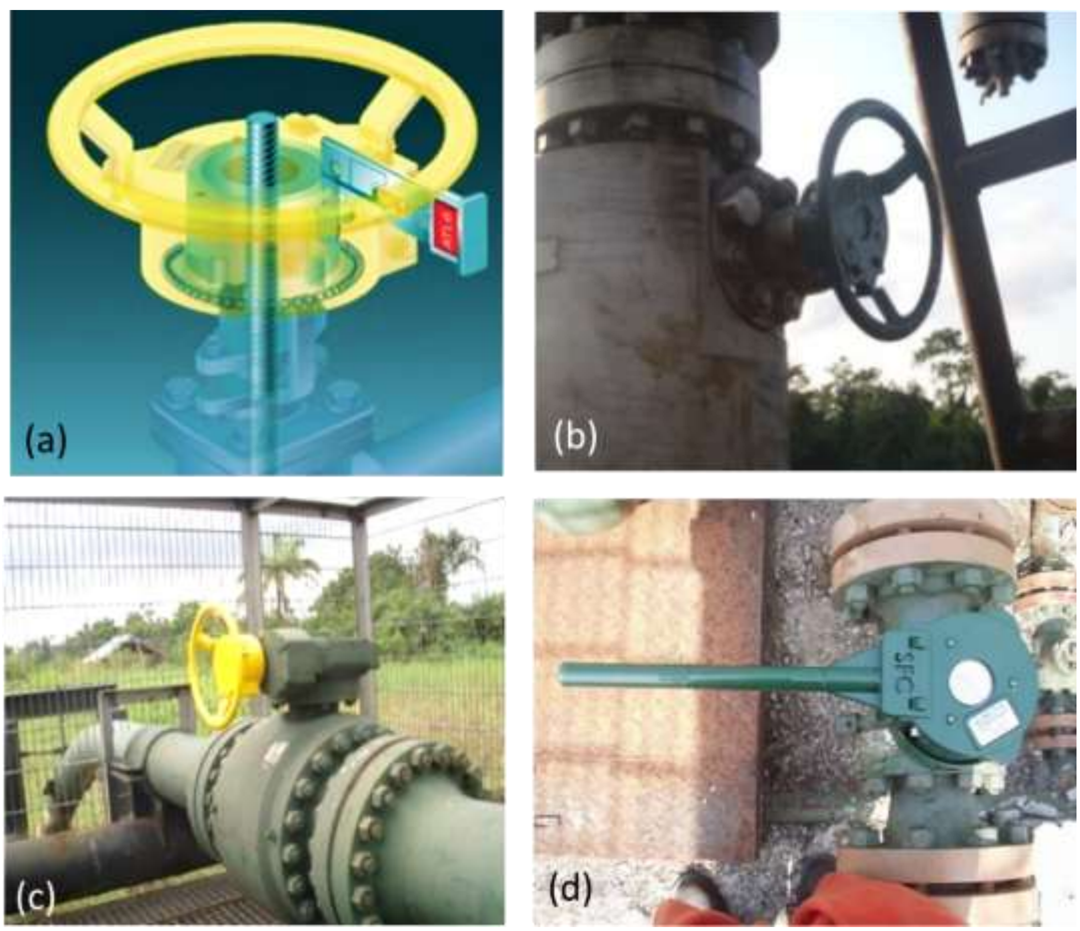

Figure 3: (a) Anti-Tamper Lock (ATL), (b) ATL installed on a wellhead, (c) and (d) ATL installed on Valves at remote locations (BGT, 2018).

6.2.2 Sureguard®

Since some vandals may decide to gain access to the products through the valve and cart away with the installed valves or other installed devices on the facility, Sureguard® was developed to deter the vandals. Sureguard® (Figure 4a) is a Flange and Nut anti-theft /anti-vandal protection device that protects bolts and nuts on flanges from unauthorized removal, tampering, and operation. It can be installed over new or existing nuts/bolts. Once installed, the nut cannot be unscrewed as the Sureguard® rotates freely and as such torque cannot be applied to remove the Sureguard® or the protected bolt. It can only be removed by authorized operators, using a special tool. No hot work is required during installation, and it requires little or no maintenance after installation. It is installed on flanges (Figure 4b) and wellheads (Figure 4c) in remote locations or at any location where unprotected nuts may be tampered with to access or impede the operation of the installation. This unique product has been installed by BGT in various oil and gas facilities and has been proven to be effective for over ten years. Some facility protection of this kind has obvious attack points and are easier to punch out with simple hand tools (punch & hammer). Sureguard® lock mechanism is well concealed, no obvious weak points to attack. Sureguard® freewheels when torque is applied.

Figure 4: Sureguard® (a) installed on flanges (b) and wellhead (c) in remote locations (BGT, 2018).

6.2.3 The Interlock

The Interlock shown in Figure 5a is another unique facility protection device, which corrects personnel operation error, unauthorized operation, product theft, and vandalism. When the lock is installed, a sequence is usually followed to operate the valves. When considering facility process safety, the Interlock is said to be the best, because the other locks can only be engaged and operated when the right key from the sequence is inserted into the Interlock's key slot. The keys are usually marked in alphabet or with numbers. The right key must be inserted into the lock with the corresponding mark. The lock, just like the ATL, is installed on the valve shaft in any valve assembly and is suitable for all valve sizes. The Interlocks can be fitted to the valve during live process without the need to shut down the system and do not compromise the certified pressure envelope of the system.

The Interlocks take care of the security of facilities or wellheads located in remote locations where personnel do not visit regularly. This device, when installed on remote facilities, reduces the risk of personnel exposure to volatile communities and saves the company huge costs that would have been used in stationing security personnel at the locations. It is imperative to adopt a multi-level protection system in order to achieve optimum security of oil and gas facilities. This requires securing more parts and components on pipeline and wellhead. This approach offers the most effective mechanical protection against vandals or thieves.

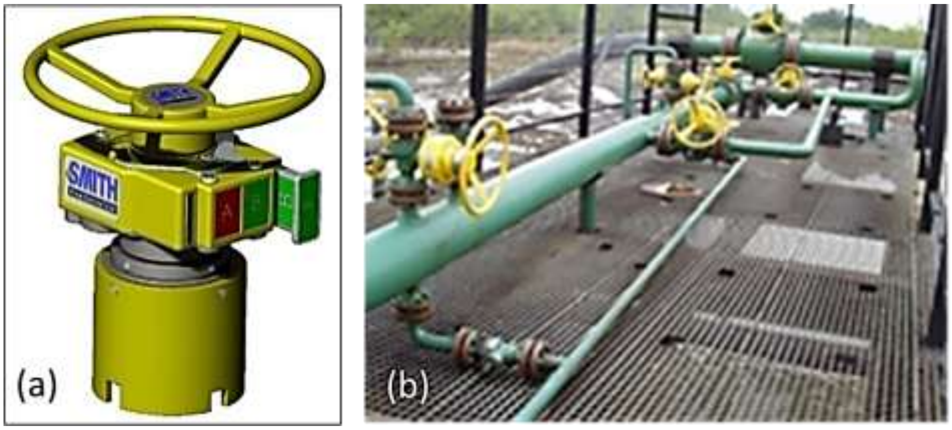

Figure 5: (a) Interlock (b) Installation of Interlocks on a typical Pigging barrel (BGT, 2018).

7. Knowledge Gaps/Research Needs

Vandalism-instigated corrosion, a form of corrosion that results from intentional damage to metal surfaces, is a growing concern. Deliberate damage such as scratching, etching, or the application of corrosive substances can significantly accelerate corrosion processes, leading to structural integrity issues and increased maintenance costs. To better understand and mitigate these effects, future research needs to address perceived gaps and adopt interdisciplinary approaches.

7.1 Knowledge Gaps

i. *Mechanisms of Vandalism-Induced Corrosion*
- *Localized Corrosion Processes*: Detailed studies on how localized damage, such as scratches, etchings, and hot/cold tapping initiate and propagate corrosion. Current understanding lacks specificity regarding different metals and environmental conditions.
- *Role of Applied Substances:* Research on the impact of various substances commonly used in vandalism, such as acids and salts, and their specific interactions with different metal surfaces is limited.

ii. *Material Response and Protection*
- *Surface Treatments and Coatings:* Development of advanced coatings and surface treatments that can either resist initial damage or self-heal after damage to prevent subsequent corrosion is lacking.
- *Material Science Innovations:* Limited exploration of new alloys or composite materials with enhanced resistance to both physical damage and corrosion (Cann *et al.*, 2021).

iii. *Environmental and Contextual Factors*
- *Urban vs. Rural Settings:* Comparative studies on the effect of environmental conditions, including pollution and humidity, on the rate of corrosion following vandalism is lacking.
- *Long-Term Exposure Studies*: Limited longitudinal research to understand the long-term effects of vandalism-induced damage under various environmental conditions (Bender et al., 2022).

iv. *Detection and Monitoring*
- *Non-Destructive Testing (NDT) Methods:* Lack of development of advanced NDT techniques to detect and quantify damage and early-stage corrosion that is not visible to the naked eye.
- *Sensor Technologies:* Limited studies on integration of smart sensors in metal structures that can detect changes in surface integrity and provide real-time data on corrosion progression (May *et al.*, 2022).

7.2 Research Needs

i. *Materials Science and Engineering*
- *Nanotechnology*: Application of nanomaterials and nano-coatings that can provide superior protection against both

physical damage and corrosion. Metallurgical studies present opportunities for collaboration with metallurgists to design metals and alloys specifically tailored to resist damage, hot or cold tapping, and corrosion. This opportunity looks quite promising (Cann *et al*., 2021).

ii. *Chemistry*

- *Corrosion Inhibitors:* Research on chemical inhibitors that can be applied to metal surfaces to prevent corrosion after vandalism (Izionworu *et al.,* 2020).
- *Surface Chemistry:* Detailed analysis of the chemical interactions between chemicals used for vandalization and metal surfaces (Onuegbu *et al.,* 2020).

iii. *Environmental Science*

- *Impact of Pollutants:* Future research on this broad area will need to narrow down to impact of pollutants. Studies on how urban pollutants exacerbate the effects of vandalization on corrosion.
- *Climate Impact:* Investigation into how various climatic conditions (e.g., coastal and inland environments) influence the corrosion process.

v. *Civil and Structural Engineering*

- *Design Innovations and Maintenance Strategy:* These are key future research interest areas. While designing structures with built-in redundancies and protective features to minimize the impact of vandalism-induced corrosion, the development of maintenance protocols that can quickly address damage before significant corrosion occurs makes this future research area a compact pack (Farh *et al*., 2023).

vi. *Data Science and Artificial Intelligence (AI)*

- *Predictive Modelling:* Use of machine learning and AI to predict the progression of corrosion based on initial damage patterns and environmental data (Hussain et al., 2024).
- *Big Data Analysis*: Analysis of large datasets from sensors and NDT methods to identify trends and early warning signs of corrosion (Arinze et al., 2024a; Arinze *et al*., 2024b).

vii. *Social Sciences and Public Policy*

- *Vandalism Prevention:* Research into the social and psychological factors behind vandalism to develop effective prevention strategies. This is highly desired in areas prone to metal structures attack for monetary gains or for religious considerations (Agomuoh *et al.,* 2021; Emelu *et al.,* 2021).
- *Policy Development:* Creation of policies and regulations that encourage the use of more durable materials and protective coatings in vulnerable structures (Emelu *et al.,* 2021).

viii. *Economics*

- *Cost-Benefit Analysis:* Economic studies to evaluate the cost-effectiveness of various prevention and mitigation strategies. Forecast in this area of research would look at funding models to drive development for public and private investments in anti-corrosion technologies and infrastructure. Research in this area would also focus on increasing metal fatigue life and their wear resistance (Cann *et al.,* 2021; Emelu *et al.,* 2021).

By addressing these gaps and leveraging interdisciplinary approaches, future research can significantly advance human understanding and management of vandalism-instigated corrosion. This holistic approach is essential to develop effective strategies for preventing and mitigating the impact of deliberate damage on metal surfaces, ultimately enhancing the longevity and safety of critical infrastructure.

8. Conclusion

Ensuring preventive intervention on oil and gas facilities considering the mostly remote environment where oil and gas production and transportation facilities are located is key to international oil companies (IOCs). It saves associated cost of vandalism such as the cost of corrosion management, loss of products, environmental damage, and risks to human life. The use of various monitoring electronic devices and mechanisms cannot be over emphasized, and ATL, Sureguard®, and Interlocks have proved to be successful tools to shut off vandals and thieves. The approach is cost saving and ensures efficiency of the facility under protection.

Every producing company requires these devices either on the pipeline valves or the wellhead assembly as a first-line deterrence/protection, preventive maintenance, or corrective approach. Up until now, several of these devices have been installed. More importantly, efforts have been to continually improve these products to meet the expectations of the IOCs in protecting oil and gas facilities, preventing corrosion, and protecting the environment. Although some manufacturers introduced the coded linear-key concept to the Interlocks, there is a need to monitor the security of installations in the industry to ensure that real-time feedback from security installations is automated.

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