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The Socio-Economic and Environmental Impacts of Petroleum Refinery Operations in the Niger Delta Region

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Abstract

The Niger Delta region, a crucial hub for Nigeria's petroleum resources, encounters significant socio-economic and environmental challenges stemming from both government-owned and artisanal oil refineries. The environmental impacts, particularly air pollution and its subsequent effects on public health and the local economy, remain a primary concern. Through a comprehensive analysis of over 110 sources, this review evaluates the contributions of refinery operations to air pollution and environmental degradation in the Niger Delta. Our findings indicate that emissions from these refineries not only contribute to significant ecological imbalances but also pose severe health risks to local communities. Furthermore, the inefficiencies in refinery operations, characterized by below-standard product output and frequent accidents, have profound economic ramifications, especially for communities reliant on traditional livelihoods. The review identifies critical gaps in environmental regulations and policy enforcement, necessitating an array of solutions, including technological enhancements for better operational efficiency, the development of modular refineries, and thorough policy reforms. The study advocates for a holistic approach to surmount the environmental and health adversities triggered by refinery operations in the Niger Delta. It is imperative to integrate technological advancements, eco-friendly practices, community engagement in governance, and stringent environmental policy implementation. These strategies are vital for diminishing pollution levels and propelling sustainable economic progress within the region.

Keywords: Niger Delta, Refinery Operations, Niger Delta, Environmental Impact, Public Health, Socio-Economic Challenges.

1. Background

Oil exploration in Nigeria commenced in 1908, spearheaded by the Nigerian Bitumen Corporation, a German company, in the Araromi area of Western Nigeria (Ikong, 2021). However, it was not until 1956 that commercial quantities of oil were discovered at Oloibiri in the Niger Delta, located 65 miles to the west of Port Harcourt (Adeola *et al*., 2022; Okotie, 2018). Following this discovery, the establishment of oil fields and wells commenced, aligning with the directives of the Petroleum Resources Department. By 1958, the inaugural oil field began its crude oil production operations (Jadhav, 2014). For more than fifty years, crude oil has been the cornerstone of Nigeria's economy, contributing to over 90% of its foreign exchange earnings (Sam & Zabbey, 2018; Tukur Umar & Hajj Othman, 2017). Nigeria ranks as the sixth largest crude oil exporter globally, with the Niger Delta region harbouring over 37.4 billion barrels of crude oil reserves and being home to one of the world's most diverse ecosystems (Albert *et al.,* 2018; Chikere & Fenibo, 2018; Sam & Zabbey, 2018). The Niger Delta, covering an area of about 75,000 square kilometres or 7.5% of Nigeria's total landmass, is home to around 31 million residents (Ite *et al*., 2013). This region includes nine states that are involved in oil production: Abia, Akwa Ibom, Bayelsa, Cross River, Delta, Edo, Ondo, Imo, and Rivers. These states are divided into 185 local government areas. The area is known for its extensive oil production activities, encompassing over 800 communities with more than 900 active oil wells and a variety of petroleum production facilities (Ite *et al*., 2013). Additionally, the Niger Delta is recognized for hosting the world's third-largest mangrove forest, encompassing vast areas of both freshwater and saltwater swamps. This unique ecosystem supports a diverse range of plant and animal life (Ogbeibu & Oribhabor, 2023).

The mangrove forest's resources have long served as a vital livelihood source for local residents, who rely on them for various needs such as wine, food, roofing materials, baskets, hats, mats, and firewood. These essentials are all derived from the by-products of the mangrove ecosystem (Numbere, 2018). Furthermore, swamp manure is utilized by farmers as organic fertilizer for their crops, and the abundant fishery resources in the surrounding waters provide a source of income for local fishermen. Yet, these vital resources from the mangrove and surrounding areas in the Niger Delta face the risk of depletion. Notably, about 50,000 acres of mangrove forest have already been lost (Numbere, 2019). Numerous acres of farmland have turned barren, and fish populations in several rivers have dwindled, intensifying the economic difficulties within the region (Umar *et al*., 2021). This looming threat primarily stems from persistent environmental pollution caused by various factors, among which the oil and gas exploration and refining activities in the region are the most significant contributors (Ewim *et al*., 2023).

The challenges linked to oil exploration and refining encompass a range of issues, including oil spills triggered by equipment malfunction, aging pipelines, and corrosion, as well as gas flaring and venting (Obi-udu *et al*., 2022). Additional concerns involve the discharge of chemical wastes derived from petroleum, pollution of water sources and soil, sediment contamination, operational discharges, and deliberate sabotage of petroleum facilities (Sojinu & Ejeromedoghene, 2019). According to a report by Jernelov (2010), the Niger Delta has experienced an estimated total oil spillage of 9 to 13 million barrels over a span of 50 years, averaging about 1.5 million tons annually. This volume is comparable to an Exxon-Valdez spill occurring every year for five decades (Nriagu *et al*., 2016). Additionally, unintentional leaks from neglected or improperly sealed oil wells have placed the Niger Delta among the top five most oil-affected regions globally (Ite *et al*., 2013).

The artisanal refining of crude oil in the Niger Delta has had significant implications for the environment, public health, and the overall well-being of the communities in the region. Studies have shown that artisanal refining activities have led to an increase in the toxicity levels of the soil, alteration of its chemical properties, and potential devastating effects on saltwater wetland ecosystems (Bebeteidoh *et al*., 2020; Ikezam *et al*., 2021; Onuh *et al*., 2021; Zaria *et al*., 2019). Moreover, the persistent shortcomings of environmental rehabilitation efforts in the Niger Delta are connected to the thriving artisanal crude oil refining industry in the area (Onakpohor *et al*., 2020). The rise in costs of processed petroleum products for domestic use in Nigeria has spurred the development of local refining technologies in certain areas of the Niger Delta (Obida *et al*., 2018).

Furthermore, the exposure of humans and the environment to oil pollution in the Niger Delta has been quantified using advanced geostatistical techniques, revealing the presence of chemicals such as polycyclic aromatic hydrocarbons (PAHs) and volatile organic compounds (VOCs) in crude oil, which have had negative impacts on groundwater quality in the polluted areas (Ite *et al*., 2018; Umar *et al*., 2019). The effects of oil leaks from artisanal refining on the ecosystem of the Oturuba River in the Niger Delta have been studied, underscoring the considerable environmental repercussions of these practices (Richard *et al*., 2022). Moreover, artisanal crude oil refining has been found to have implications for sustainable food production in the Niger Delta region, affecting arable land and agriculture (Ogele, 2022).

Legal and artisanal refining of crude oil has become a major source of greenhouse gas emissions, further exacerbating environmental challenges in the Niger Delta region (Chikere & Fenibo, 2018). This research aims to conduct a comprehensive evaluation of the environmental pollution resulting from both state-run and artisanal refineries in the Niger Delta region, and its subsequent impact on public health and the local economy. The study's objectives are to pinpoint the sources of emissions, assess their effects on both the environment and community health, and scrutinize the efficiency and quality of the output from these refineries. Furthermore, the research intends to develop viable strategies to alleviate these environmental issues and bolster the economic prospects for the communities in the Niger Delta.

While previous studies have explored the environmental impacts of refinery operations in the Niger Delta, this study aims to bridge critical gaps by offering a more inclusive and up-to-date analysis of air pollution and product output efficiency. It intends to undertake a comparative analysis of both government-owned and artisanal refineries, evaluate the combined environmental and public health effects, and investigate the economic consequences for communities reliant on traditional livelihoods, such as agriculture and fishing. This research is particularly vital as it incorporates recent data and accounts for the evolving practices and technologies in the refinery sector. Moreover, it provides a unique insight into the socio-economic drivers behind artisanal refinery operations and their environmental impacts. By addressing these gaps, the study significantly contributes to a deeper understanding of the complex challenges in the Niger Delta, thereby guiding more precise and impactful policy measures for environmental conservation, public health safeguarding, and the promotion of sustainable economic growth in the region.

Main Text

2. Methods

To ensure a thorough and multidimensional analysis, this study employed a comprehensive methodology that integrated empirical research, an extensive review of existing literature, and an analysis of grey literature. The research involved an in-depth assessment of peer-reviewed scientific papers obtained from several renowned electronic databases including Scopus, ScienceDirect, Springer, Wiley Library, PubMed, and Web of Science (version 3.5.0). The search utilized specific terminologies encompassing a wide range of topics: from the origins of oil and gas in Nigeria to the environmental impact of both government-owned and artisanal refineries, including their emissions and the government's response to these challenges.

The study's search criteria were strategically chosen to focus on relevant subjects. Key search terms included combinations like “origin of oil and gas in Nigeria”, “pollution from oil and gas activities in the Niger Delta”, “state of government-owned refineries”, “origins of artisanal refineries”, “emissions from government-owned refineries”, “pollution from artisanal refineries”, and “government response to refinery emissions”. The exclusion criteria were set to omit studies focusing on other forms of anthropogenic pollution and different pollution receptors, such as water and soil pollution.

Additionally, to capture a broader scope of information, documents published by authoritative organizations like the US Energy Information Administration (EIA), Nigerian National Petroleum Commission (NNPC), Partnership Initiatives in the Niger Delta (PIND), and various European and

US EPA organizations were also reviewed. The literature search was limited to English-language, peer-reviewed papers predominantly from the period 2000 to 2023.

Recognizing that air quality studies related to the oil industry might often be published outside traditional scientific journals, the study also incorporated a grey literature review. This was conducted using similar keywords through Google searches to encompass reports and studies not available in recognized scientific databases.

In total, this methodological approach facilitated the inclusion of over 110 peer-reviewed papers focusing on pollution from both conventional and artisanal oil and gas exploration, ambient emissions from refineries, and recommendations for environmental improvement. This comprehensive review strategy enabled a holistic understanding of the issues at hand and informed the development of targeted recommendations for mitigating the identified challenges.

3. Analysis of Nigerian oil refineries and associated environmental impacts

3.1 Overview of Nigerian oil refineries

Nigeria hosts four oil refineries, which together have a combined refining capability estimated at 445,000 barrels daily (Ogbuigwe, 2018). Within the Niger Delta, three out of Nigeria's four state-owned refineries are situated. Among these is the Port Harcourt refinery, the country's earliest and foremost refinery, established in 1965 as a basic hydro-skimming plant. Its initial capacity was 35,000 barrels per day. The capacity was later enhanced to 60,000 barrels per stream day (bpsd) in 1972 following the addition of a Naphtha Catalytic Refining Unit (CRU). This refinery was capable of producing all standard petroleum products required by the country, except for bitumen, which remained an import. The Port Harcourt refinery complex also encompasses a newer refinery, with a production capacity of 150,000 barrels per day (Elisha, 2020). The Warri refinery, inaugurated in 1978, initially processed 100,000 barrels of light crude oil per day. In 1986, its capacity was expanded to accommodate 125,000 barrels per day (Odekanle *et al*., 2021). Associated with the Warri Refinery are a polypropylene plant with a production capacity of 35,000 metric tons per annum (mtpa) and a carbon black plant capable of producing 18,000 mtpa (Ogbon *et al*., 2018).

Despite having established these refineries and possessing substantial oil reserves, as well as being a prominent member of the Organization of Petroleum Exporting Countries (OPEC), Nigeria continues to experience a scarcity of refined petroleum products (Itsekor, 2020). The production output of the aforementioned refineries is insufficient to meet the country's regular consumption needs (Nigerian National Petroleum Corporation, 2018; Ogbon *et al*., 2018). Figure 1 illustrates the rising trend in Nigeria's consumption of petroleum products, which is not matched by a similar increase in production. Remarkably, Nigeria is the only OPEC member that imports approximately 80% of its petroleum products to satisfy domestic demand (Ajia, 2023).

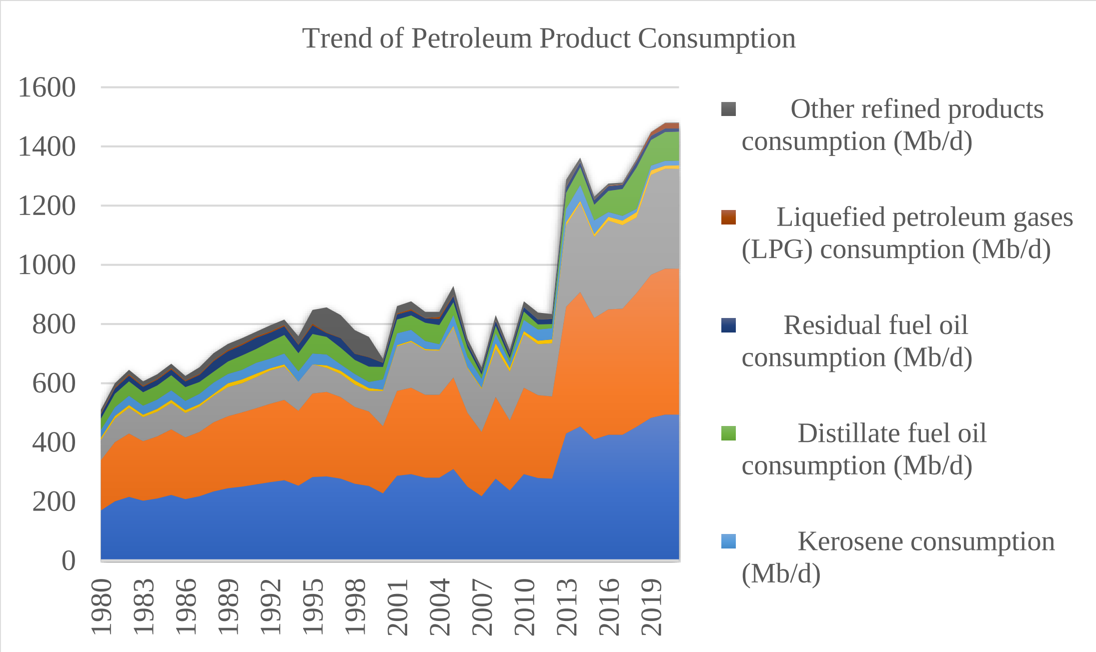

Figure 1. Trend of petroleum product consumption in Nigeria (1980-2021) (Adapted from U.S. Energy Information Administration, 2023).

3.2 Shortfalls of government-owned refineries

Inefficiencies mark the operation of Nigerian refineries, resulting in diminished productivity (Alaba & Agbalajobi, 2014). As a result, these refineries operate at merely around 30% of their capacity, producing only about 1.6 billion litres of Premium Motor Spirit (PMS) annually, which falls significantly short of the country's estimated annual requirement of over 18.8 billion litres of PMS (Ogbon *et al.*, 2018). The diminished productivity of the existing refineries has necessitated the importation of petroleum from overseas to meet demand (Udo, 2022).

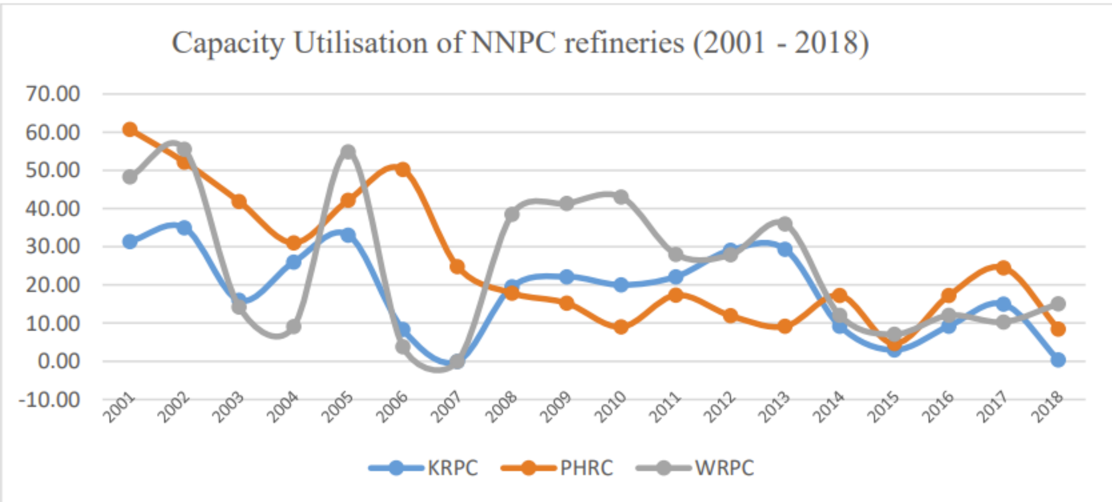

Figure 2. Refineries production decline 2001-2018. (Source: Nigerian National Petroleum Corporation, 2018).

Figure 2 depicts a downward trend in the production of refined petroleum products from 2001 to 2018. Iheukwumere *et al*. (2020) compared this data with the refinery performance of other African oil-producing nations with economies similar to Nigeria's, such as Egypt, Angola, and South Africa. Their analysis revealed that these countries have consistently maintained their refineries' performance at a minimum of 65% capacity from 2013 to 2018, further highlighting the underperformance and deterioration of Nigerian refineries. In his case study focusing on Nigeria's downstream sector, Wapner (2017) highlighted various reports by independent entities and the Nigerian Government that shed light on the fundamental causes of the inefficiencies in Nigerian refineries. Among these factors is the erosion of the Nigerian National Petroleum Corporation's (NNPC) autonomy. Originally established by a special act to function with corporate autonomy, akin to a National Oil Corporation (NOC), the NNPC was primarily managed by professionals from the private sector (Ogbuigwe, 2018). However, a pivotal change occurred in the early 1990s when the military government mandated the NNPC to relocate its financial holdings from commercial banks to the Central Bank, significantly impacting its operational independence (Ramon, 2022)

Another critical issue was the absence of regular turnaround maintenance (TAM), alongside outdated industrial practices and technological obsolescence (Alkassim, 2022). Between 1990 and 2000, the NNPC expended over 400 million dollars on the turnaround maintenance of refineries, yet this investment did not yield any improvement in production (Itsekor, 2020). Since 2008, no turnaround maintenance (TAM) has been undertaken in any of these refineries, with the most recent TAM at the Port Harcourt refinery occurring in 2000 (Agbakahi, 2022). This neglect contrasts with global industry best practices, which stipulate that turnaround maintenance (TAM) should be conducted every four years (Al-Marri *et al*., 2020). Wapner (2017) inferred from an interview with an NNPC expert that the primary reasons for the failure to conduct regular TAM were insufficient funding and protracted decision-making processes. The expert noted that obtaining approval for certain actions could require as many as 27 signatures.

Furthermore, the technical services departments within the refineries have been unable to offer sufficient support. Factors such as the utilization of substandard raw materials, exemplified by poor water quality in boiler equipment, have frequently led to boiler failures, often due to tube ruptures. Additionally, a lack of experienced personnel, attributable to suboptimal hiring practices or inadequate training, has resulted in poor oversight of refinery systems, thereby contributing to incidents of fire (Edeh, 2020). Fires at NNPC-operated refineries have been a recurring issue. A particularly devastating incident was the catastrophic pipeline fire at Atiegwo, near Jesse in Delta State, on October 17, 1998. This tragedy, involving a 16-inch petrol pipeline owned by the Nigerian National Petroleum Corporation (NNPC) that connected the Warri refinery to Kaduna, resulted in the loss of over 1,000 lives from the local community. The blaze persisted for approximately five days before it was finally extinguished by a team of American firefighters (Akande, 2018). In contrast to international standards where more than one or two fires per year are deemed a serious concern, NNPC refineries experience a significantly higher frequency of fire incidents. Figure 3 illustrates the rate of fires at various NNPC refineries over a span of nearly a decade, highlighting this alarming trend.

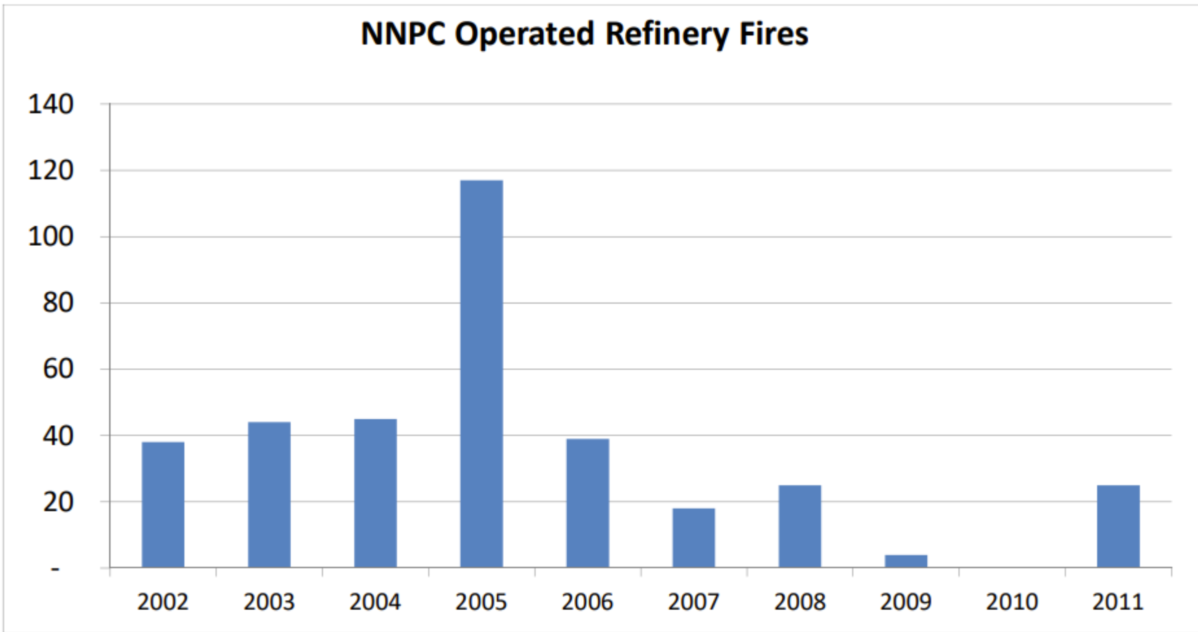

Figure 3. NNPC reported fires between 2002-2011 (Adapted from Nigerian National Petroleum Corporation, 2011).

Lastly, the pipelines that transport crude oil to the refineries and distribute products from them are frequently subject to vandalism. The theft of crude oil from these pipelines amounts to between 300,000 and 400,000 barrels per day, a significant portion of which is illicitly refined in the Niger Delta using artisanal methods. This illegally refined oil, including products like kerosene, diesel, and bitumen, is sold both locally and internationally (Campbell, 2015). This situation results in substantial revenue losses and exacerbates the issue of not fully recovering the costs associated with crude oil production (Agbakahi, 2022; Ogbuigwe, 2018).

3.3 Emissions from government-owned Nigerian refineries

In an effort to enhance its refining capabilities, the Nigerian government has issued licenses for the establishment of over twenty-two privately owned refineries. These new facilities, currently at various stages of completion, are intended to supplement the four existing, but struggling, state-owned refineries (Punch Newspapers, 2022). All twenty-two of the proposed refineries are situated in the southern region of Nigeria, with nearly eighty percent of them being located in the Niger Delta. This strategic placement is likely attributable to the abundant crude oil reserves found in the region (Fakinle *et al*., 2021; Odekanle *et al*., 2021). However, an increase in the number of refineries leads to higher emissions, posing greater risks to both health and the environment. This escalation in refinery activities could potentially result in the deterioration of air quality in the surrounding areas (Hasheminasab *et al*., 2020; Oladimeji *et al*., 2015; Thennakoon *et al*., 2021).

The process of refining crude oil to produce petroleum and its by-products generates various types of waste. A significant portion of this waste is emitted into the atmosphere as gases and particulate matter.

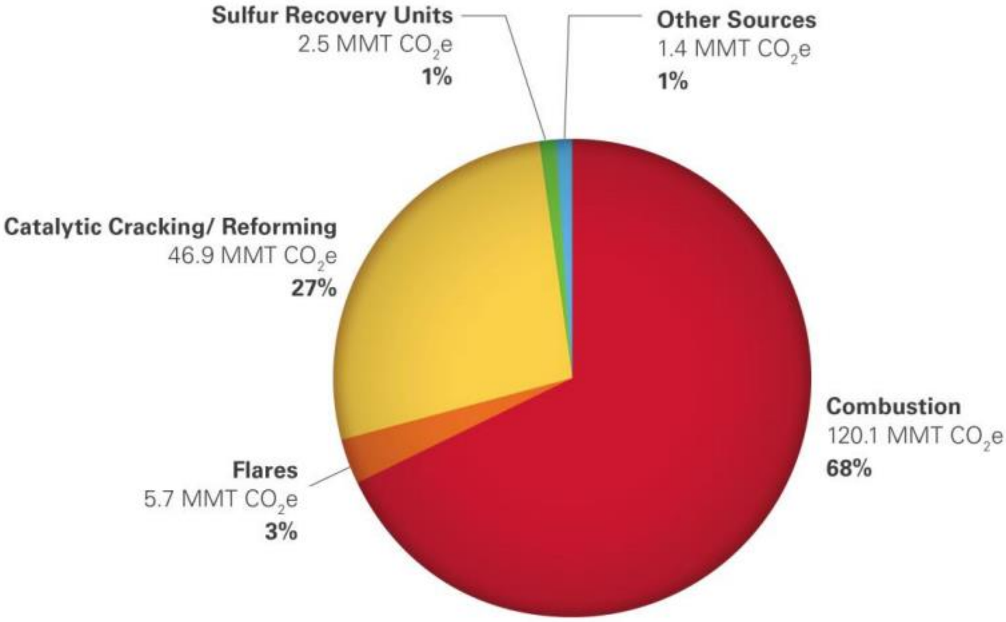

Figure 4. Petroleum refineries sector-emissions by source (Source: Environmental Protection Agency, 2013).

Figure 4 illustrates the diverse processes within a refinery that lead to emissions. This comprises operations in catalytic cracking units, high-temperature combustion in fuel burning, fluid and delayed coking units, storage tanks, coke calcining units, catalytic reforming, operations in sulphur recovery plants, asphalt blowing operations, product transfer, heating of steam and process fluids, equipment leaks, loading operations, blowdown systems, and flaring (Kamiński *et al*., 2021). Various refining operations, including separation, conversion, and treatment processes, result in the inadvertent release of pollutants into the environment. These emissions stem from equipment leaks involving valves, flanges, pump seals, compressor seals, and drains, as well as accidental releases or disruptions at plants (Al-Rubaye *et al*., 2023).

Sonibare *et al*. (2007) conducted comprehensive research on the impact of volatile organic compounds (VOCs) emissions from petroleum refineries on air quality in Nigeria. They assessed the emission potential of VOCs from both operational and proposed refineries, categorizing these emissions into point and area sources. The study found that annual point source emissions from the four operational refineries in Warri, Port Harcourt 1 and 2, and Kaduna were 147,212 tons, with area source emissions at 133,038 tons. Key point source emissions were from the fluid catalytic cracking unit (FCCU), vacuum distillation unit (VDU), and pipeline and pressure relief valves, while major area source emissions came from uncontrolled blowdown systems, process drains, pump and compressor seals, and fuel evaporation. The study projected an additional 389,503 tons per annum of VOC emissions from the proposed refineries. Rivers State, with a dense population and the highest number of refineries in the Niger Delta, was noted for the highest per capita emission distribution, indicating a significant risk of increased VOC emissions in this region.

In a related analysis, Oladimejii *et al*. (2015) investigated the environmental impacts of emissions from Nigeria's petroleum refineries. Utilizing AP-42 emission factors from the Environmental Protection Agency, they estimated the annual emissions of criteria air pollutants from point sources in the existing refineries. Their findings showed PM_{10} emissions at 1,217 tons/annum, SO_2 emissions at 45,124 tons/annum, NO_x emissions at 167,570 tons/annum, VOC emissions at 3,842 tons/annum, and CO emissions at 242,469 tons/annum. For the proposed refineries, the study projected additional emissions: PM_{10} at 1,082 tons/annum, SO2 at 168,944 tons/annum, NO_x at 688,687 tons/annum, VOC at 9,122 tons/annum, and CO at 569,975 tons/annum, highlighting the significant contribution of petroleum refineries to air pollution in Nigeria.

Balogun and Odjugo (2022) conducted research on air pollutant concentrations around the Warri Refining and Petrochemical Company (WRPC) in Delta State, Nigeria, aiming to determine a safe minimum distance from the refinery. They analyzed the spatial distribution of air pollutants and compared them to the World Health Organization's (WHO) regulatory standards. Their findings showed that the annual mean values of NO_2, $PM_{2.5}$, and PM_{10} exceeded WHO limits at all measured distances. For NO_2, annual mean values ranged from 0.11 ppm at 16,000 metres to 0.58 ppm at 4,500 metres; for $PM_{2.5}$, from 12.91 µg/m^3 at 16,000 metres to 42.71 µg/m^3 at 4,500 metres; and for PM_{10}, from 20.28 µg/m^3 at 16,000 metres to 109.99 µg/m^3 at 1,500 metres.

Similarly, Fakinle *et al*. (2021) evaluated the impact of hazardous air pollutants from Nigeria's petroleum refineries on ambient air quality, focusing on estimating benzene emissions using the emission factor approach. They gathered data from Nigeria's Department of Petroleum Resources covering both existing and proposed refineries. The study found that benzene emissions from these refineries significantly exceeded occupational exposure limits set by various health and environmental organizations in the United States. Additionally, when compared to studies in other countries, the benzene emissions from Nigerian refineries were considerably higher (Edokpolo *et al*., 2015). The study presented current measured emission values for existing refineries and projected benzene emissions for proposed refineries based on their operational capacities. Figure 5 presents the current measured emission values of the existing refineries as determined during the aforementioned research. Meanwhile, Figure 6 illustrates the projected benzene emissions from the proposed future refineries, estimated based on their operational capacities.

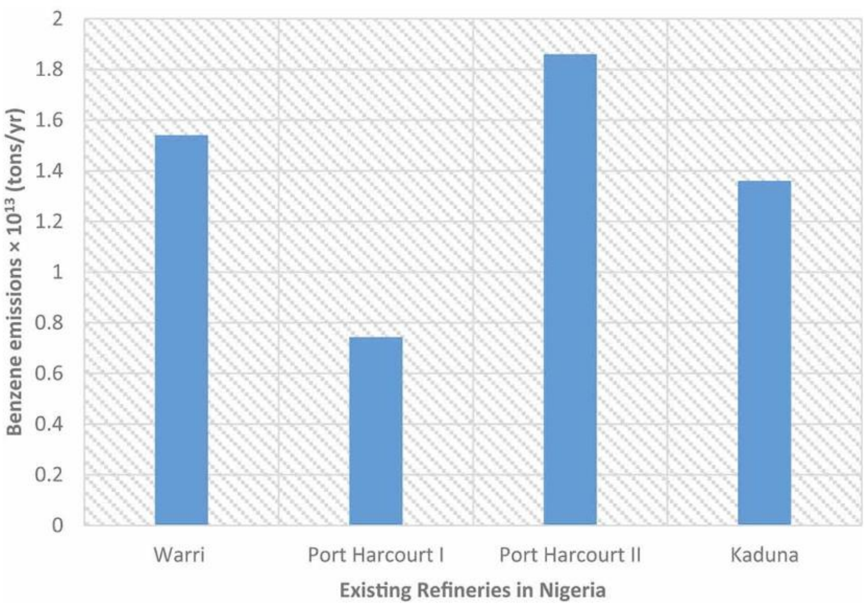

Figure 5. Aggregate benzene emissions from Nigeria's current refineries (Based on Fakinle *et al*., 2021).

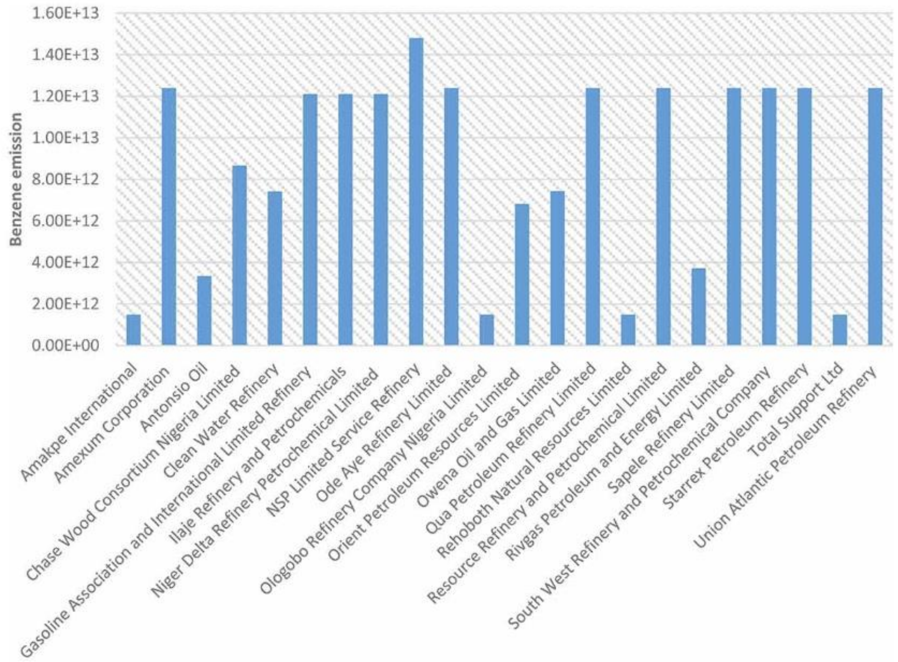

Figure 6. Overall benzene emission estimates for each proposed refinery in Nigeria (Derived from Fakinle *et al*., 2021).

To further understand the sources of air pollution in Nigeria, Okedere *et al*. (2021) conducted a comprehensive review. Their analysis, which included examining a range of previous studies, identified refineries as major sources of anthropogenic air emissions in the country. This array of research collectively underscores the critical need for effective strategies to mitigate the environmental impact of refinery emissions and improve air quality in Nigeria.

3.4 Environmental impact of refinery gas flares

In addition to the emissions previously highlighted, oil refineries are notable for their high energy consumption and substantial contribution to greenhouse gas emissions. These refineries are recognized as key energy-intensive sectors within the scope of the EU Emission Trading System (Jia *et al*., 2020). The refining process produces a significant quantity of co-generated gas, which, often flared as a by-product, contains high concentrations of H_2S and other detrimental by-product species (Chen *et al*., 2022; Hajilary *et al*., 2020). Nonetheless, CO_2 is the most prevalent greenhouse gas emitted from petroleum refineries, comprising nearly 98% of all GHG emissions in these facilities. In comparison, CH_4 emissions stand at 4.7 million metric tons, representing 2.25% of the total emissions from petroleum refineries (Orugba *et al*., 2019). The levels of CO_2 and CH_4 emissions from a refinery are influenced by the specific types of process units and other characteristics of the facility. Refineries lacking catalytic cracking units and hydrogen plants typically release a larger proportion of their total greenhouse gas emissions as CH_4 (Orugba *et al*., 2019). The main sources of greenhouse gas emissions in refineries are from stationary combustion equipment such as process heaters, boilers, combustion turbines, and other similar apparatus.

As a member of the non-Annex 1 countries under the Kyoto Protocol, Nigeria does not have a defined limit on its greenhouse gas emissions, which contributes to a more adverse emissions profile (Ede & Edokpa, 2015). In 2021, Nigeria ranked seventh among the top 30 countries for gas flaring, contributing to over 40% of Africa's total annual gas flare with 6.6 billion cubic meters of gas flared (Abu *et al*., 2023). Despite being among the top seven countries in gas flaring, Nigeria has managed to cut down its gas flaring activities by 70% over the last 15 years. Between 2012 and 2021, there was a 31% reduction in gas flaring in Nigeria, although the country saw a 10% rise in flare intensity during this period (World Bank, 2022).

Considering that the Niger Delta hosts three out of four government-owned refineries and about 80% of the licensed private refineries, it's expected that this region is the most impacted by emission flares. The daily gas flaring in the Niger Delta leads to the discharge of about 45.8 billion kilowatts of heat from 1.8 billion cubic feet of gas into the atmosphere of the region (Bodo & Gimah, 2020). Furthermore, the ineffectiveness of Nigeria's legal framework on gas flaring is largely due to weak enforcement and minimal financial penalties. The current penalty, a mere ₦10 or approximately 1/10th of a dollar per thousand standard cubic feet for violations, fosters non-compliance and undermines the law's efficiency in addressing gas flaring issues (Olujobi, 2020). Consequently, the current situation calls for a critical re-evaluation and strengthening of Nigeria's gas flaring regulations to ensure more stringent compliance and effective environmental protection.

4. Artisanal refineries: Operations, efficiency, emissions, and product quality

4.1 Emergence of artisanal refineries

The rise of artisanal crude oil refining in the Niger Delta region is often linked to economic and social factors. This industry has become a coping mechanism in response to environmental degradation, insecurity, and poverty in the area (Odubo & Odubo, 2022). It is paradoxical that the Niger Delta, often likened to a goose that lays golden eggs, has reaped minimal benefits and instead bears the brunt of the environmental degradation resulting from these industrial processes (Collins, 2018). Additionally, inexplicably, these regions endure the harshest effects of fuel shortages, even though they are surrounded by both crude oil and refined products. Confronted with these circumstances and with few alternatives following the disruption of their traditional farming and fishing livelihoods by oil exploration, the coastal communities, once sustained by their ecosystem, now find themselves compelled to engage in unauthorized oil extraction and refining (Onyena & Sam, 2020). In this review, the term "artisanal refining" will be used instead of "illegal," owing to the contentious debate surrounding the latter term. While some classify these activities as illegal, others argue that they represent a legitimate means of utilizing resources found on local land for survival. This perspective takes into account the prevailing environmental and economic conditions that have left artisanal refiners with few alternatives (Amah, 2020; Mai-Bornu, 2019; Niworu, 2017; Okwelum 2021, Umukoro, 2018).

The concept of artisanal refining is not a new idea. Across different continents, local inhabitants have traditionally engaged in manual or small-scale processing of natural resources. Examples of this include small-scale gold refining activities in Myanmar, Indonesia, and Ghana (Arifin *et al*., 2020; Emmanuel *et al*., 2018; Soe *et al*., 2022). Apart from Nigeria, Venezuela, Mexico, Iraq, Russia, Indonesia, and Brazil also grapple with illegal oil refining, often linked to organized crime, economic crises, and theft from pipelines (Akpomera, 2015). Nigeria incurs an estimated loss of approximately US$1.5 billion each month as a result of pipeline tapping, artisanal refining, and various other intricate schemes (Aqrawi-Whitcomb, 2018). In regions where artisanal activities emerge, a consistent pattern is observed: these areas typically experience a shortfall in both infrastructural and human development, alongside significant environmental degradation.

As previously mentioned, while the practice of artisanal refining is not new, the specific method of pipeline vandalism to acquire crude oil for refining is a relatively recent development in the Niger Delta. This activity gained momentum following the 2009 Presidential Amnesty Program (PAP), which marked a period of relative peace in the previously restive region. The PAP offered a state pardon to armed militias who had been aggressively advocating for more inclusive oil governance and development in the oil-rich area (Onuh *et al*., 2021). The militant youths of the Niger Delta perceived this act as a form of self-compensation, addressing the exploitation, environmental pollution, marginalization, impoverishment, unemployment, and underdevelopment they experienced in the region (Adunbi, 2020).

4.2 The artisanal refining process

The process of artisanal refining involves small-scale or subsistence distillation of petroleum, typically conducted outside legal regulations. This method entails boiling crude oil at atmospheric temperatures, then condensing the vapours and collecting them in tanks, primarily for local automotive fuel use (Udo *et al*., 2020). The procedure starts by tapping crude oil into drums, with the tapping point either on dry land or underwater. This operation is usually executed over several nights by a small team of three to six skilled welders, often from the local community. They work on the approximately 1650 km of crude oil pipelines crisscrossing the Niger Delta (Onuh, 2021). After establishing the tap, the oil is drawn into reservoirs utilizing the existing oil pressure and a rubber hose. Alternatively, some artisanal refiners opt to skip the tapping phase and instead purchase pre-tapped crude from bunkering agents for storage in their reservoirs (Suku *et al*., 2023). However, the lack of requisite training in the process can lead to imprecise distillation, heat requirements, and the production of products with impurities (Igbagara, 2021). The materials required for artisanal refining are obtained locally from nearby towns and cities. Local welders fabricate the reservoir drums, and once filled, these drums are transported using speed boats or locally constructed canoes, often called 'Cotonou boats,' made by indigenous carpenters. These boats have the capacity to transport between 100 to 600 drums in a single journey (Agheyisi, 2023). The boats carrying the crude oil distribute their loads to oil tankers stationed off the coast and to camps typically located along the riverbanks. The riverside location of these camps facilitates easy access to water, which is essential for the cooling process in artisanal refining (Richard *et al*., 2023a).

In the camps, where a typical one employs 12–20 individuals and larger ones considerably more, workers handle the received crude oil, transferring it into zinc-fabricated reservoirs or into pits lined with polythene or similar materials to prevent seepage into the ground, as shown in Figure 7. The refining method used is a basic type of fractional distillation, modified from the local distillation techniques of gin (kai-kai) and palm wine (ogogoro), for which the region is well-known. Ovens, constructed from 2–3 mm metal plates, are set over fire pits fuelled by dry wood and raw crude, as shown in Figure 8. These ovens are connected to a galvanized pipe that carries the vaporized product to a cooling drum (condenser) filled with water from nearby rivers. This process yields various products, including premium motor spirit (PMS), diesel, bitumen, kerosene, and some waste products (Anifowose *et al*., 2012). The duration of the fractional distillation process ranges from 6 to 9 hours, varying based on the volume of raw crude being refined and the intensity of the heat produced by the fire.

Figure 7. Zinc reservoir for storage of raw crude (Source: Adunbi, 2022).

Figure 8. Artisanal refinery site (Source: Stakeholder Democracy Network, 2020).

4.3 Efficiency of artisanal refineries

The efficiency of artisanal refineries is crucial for ensuring the quality of the refined products and minimizing environmental impact. Understanding the physicochemical properties of the refined products, optimizing the distillation process, and controlling emissions are essential factors in improving the efficiency of artisanal refineries. Moreover, addressing the lack of training and implementing measures to enhance the precision of the distillation process can contribute to improving the overall efficiency and sustainability of artisanal refining practices (Oyewale *et al*., 2023).

From an economic standpoint, establishing such an operation is relatively cost-effective, given that all processing equipment and facilities are locally sourced. The management of these refineries can be streamlined with a minimal number of staff, depending on the business acumen of the investors and the processing capacity of the refinery. The low cost of starting and running this business, owing to the employment of non-professional staff and simple equipment, has made it an attractive option for local individual investors (Asuru & Amadi, 2016). Consequently, there has been a notable rise in the number of artisanal refinery sites, with private companies establishing over 20,000, taking advantage of the region's availability of inexpensive labour and raw materials (Onakpohor *et al*., 2020)

The economic analysis conducted by Roy *et al*. (2022) provides a detailed insight into the financial dynamics of artisanal oil refineries in Nembe, Bayelsa State, and Bolo, Rivers State. This analysis, grounded in the assumption that these refineries operate three days a week and four weeks a month, with equipment costs renewed biannually, offers a comprehensive view of the cash flow within these operations. In Bolo, Rivers State, the study illustrates that the most significant income comes from the illicit sale of crude oil, generating a staggering $480 million in revenue with a profit of $430.4 million after accounting for various operational costs like wages, equipment, and community fees. In contrast, refining purchased crude oil into fuels yields a smaller, yet substantial, profit of $11.55 million. Transporting refined fuels by boat is another lucrative activity, with a monthly income of $120 million and a profit of $118.14 million. The data, however, does not capture the volumes or profits from marketing refined fuels to consumers. The situation in Nembe, Bayelsa State, shows a different economic landscape. The sale of stolen crude oil here amounts to a revenue of $85 million and a profit of $64.45 million. The refining process, involving kerosene, petrol, and diesel sales, yields a total profit of $29.62 million. While the study doesn't record specific income from transporting refined fuels to markets, it notes substantial costs associated with this activity. The marketing of refined fuels to consumers brings in a profit of $592,200 from kerosene and petrol sales. Additionally, the study observes ancillary activities such as catering services, prostitution, and hotel operations, which contribute to the local economy, with profits ranging from $96,000 to $480,000 in various sectors.

These findings highlight the substantial economic impact of artisanal oil refining activities in these regions, not only through direct operations but also through ancillary services that support the local economy. The substantial profits from these activities underscore their allure and potentially explain their prevalence in these regions despite their illegal nature and environmental impact. This analysis by Roy *et al*. (2022) offers a crucial perspective on the financial incentives driving artisanal oil refining in the Niger Delta, illuminating the complex interplay between economic gains and regulatory challenges.

Ikezam *et al*. (2022) conducted a detailed analysis of the economic feasibility and costs associated with artisanal oil refining in the Niger Delta, revealing its potential profitability despite significant health and environmental risks. Their research showed that in Bayelsa, most refining camps were set up within two weeks, indicating a rapid establishment process. In contrast, Delta predominantly saw a three-week setup period, while Rivers State exhibited a varied timeframe, with many camps also completed within two weeks. This demonstrated the operations' quick adaptability to market needs. In terms of costs, Bayelsa's camps generally required moderate investments, mostly within the 201-300 thousand Naira range. However, Delta and Rivers experienced a wider range of expenditures, with numerous camps in Rivers necessitating higher investments, especially in the 301-400 thousand Naira bracket. Financially, Bayelsa's local refineries usually earned between 101-200 thousand Naira daily, with international sales being more profitable. Delta exhibited a more even distribution of revenue, whereas in Rivers, a substantial part of local refineries earned between 201-300 thousand Naira daily, with international sales also yielding high returns. The study highlighted a lucrative yet risky business environment within the Niger Delta's artisanal oil refining sector. Despite significant investments in time and money, the operations offered substantial financial rewards, especially from international markets.

Artisanal refining, however, carries significant risks. Owing to its rudimentary and unregulated methods of operation, it is prone to explosions and unexpected fire outbreaks (Izionworu *et al*., 2021). A recent catastrophic incident involving one of these refineries occurred on April 23, 2022, near the Ohaji-Egbema local government area in Imo State, close to the border with Rivers State. This explosion resulted in the tragic loss of 100 lives, injured several others, and also led to extensive damage to vast areas of the surrounding forests (GardaWorld, 2022). In their research, Abu & Orisa-Couple (2022) examined the relationship between energy poverty and burn incidents among residents in low-income suburbs of Port Harcourt, Nigeria. This study was based on an analysis of patient records at the University of Port Harcourt Teaching Hospital Burns Centre. The investigation, which spanned from 2015 to 2021, focused on various factors such as age, gender, mortality rates, causes of injuries, and residential areas. It was found that home-stored fuel for power generators and flames from sites of artisanal oil refining were responsible for 113 cases, constituting 17% of the incidents. Consequently, this subsection emphasizes the profound and often tragic human impact of artisanal refining practices and energy poverty, calling attention to the necessity of targeted interventions and policy reforms to mitigate these risks and enhance community safety.

4.4 Emissions from artisanal refineries

The emissions generated at different temperatures during the refining process can impact air quality and environmental monitoring (Bolliet *et al*., 2015). The environmental risks associated with crude oil have been a subject of concern for some time, but alarm intensified when emissions escalated to the extent that visible soot began to coat every exposed surface in Port Harcourt, a major city in the Niger Delta. These aerosols, consisting of tiny particles approximately 2.5-10µm in diameter, linger in the lower troposphere. They not only hinder cloud formation but also pose long-term environmental and health risks to the inhabitants of the area (Giadom, 2019). The agglomerated aerosols include contaminants like Nickel, Cobalt, Lead, and Polycyclic Aromatic Hydrocarbons in sizes that can be both inhaled and respirable. Laboratory tests of the particulate matter (soot) conducted by the Rivers State Ministry of Environment indicated that these particles originated from petroleum combustion (Yakubu, 2017).

Onwuna *et al*. (2022) conducted a study to assess air quality at artisanal crude oil refinery sites in Igia-Ama, Tombia Kingdom, Rivers State, Nigeria. The study aimed to measure concentrations of various pollutants, including NO_x, VOC, CH_4, CO, CO_2, O_3, different particulate matter sizes (PM_1, $PM_{2.5}$, PM_4, PM_7, PM_{10}, TSP), SO_x, NH_3, H_2S, as well as relative humidity and noise levels. Utilizing air quality sensors for physicochemical parameters and settle plate exposure for microbial parameters, they monitored these elements during both dry and wet seasons. Their findings indicated that SO_x and NO_x levels at the impacted site were higher than those in pristine environments (control sites) and exceeded the limits set by the Federal Ministry of Environment.

In their study, Michael and Joepen (2021) analyzed pollutant emissions from artisanal crude oil refining in Port Harcourt, focusing on Eagle Island as a case study. They employed the Gaussian dispersion model and an ADM 106 (particulate mass monitor) to measure concentrations of particulate matters (PM_1, $PM_{2.5}$, PM_{10}). An Aerqual 300 device was used for assessing levels of NO_2, VOCs, and SO_2. Additionally, temperature, humidity, wind speed, and direction were recorded using a Portable Extech 45156 weather station and a compass, with experimental data gathered over two days, both in the morning and at night. The findings indicated that the artisanal refining activities emitted harmful substances like NO_2, CO_2, CO, VOCs, PM_1, $PM_{2.5}$, and PM_{10}, with high concentration levels even at greater distances from the source, influenced by wind speed and direction. The study concluded that the operations of artisanal refineries significantly contribute to environmental degradation and pollution in Port Harcourt city.

Similarly, Onakpohor *et al*. (2020) investigated air emissions from artisanal petroleum refineries in the Niger Delta, Nigeria, using an E8500 Portable Combustion Analyzer to directly measure emissions at the source. Their approach involved categorizing refineries based on oven sizes and processing capacities to estimate emissions accordingly. The findings indicated significant variation in pollutant emissions across different unit operations, with higher emissions observed in operations with larger processing capacities.

The study revealed that emissions of CO, NO_x, and SO_2 often exceeded the daily limits established by the Environmental Guidelines and Standard for Petroleum Industry in Nigeria (EGASPIN). When evaluated against the Federal Environmental Protection Agency (FEPA) standards for stationary sources, emissions of HC and CO were found to be above the permissible thresholds. Although SO_2 and H_2S emissions were above their lower limits, they stayed within the upper limit. In contrast, NO_x emissions remained within the prescribed limits. The research presented in Figure 9 details emissions from the crude boiling units, differentiated by their refining capacities. Similarly, Figure 10 showcases emissions from the refined product collection unit, also categorized according to the oven refining capacities. This comprehensive study provides crucial insights into the environmental impact of artisanal petroleum refining activities in the region, highlighting the need for regulatory measures to mitigate pollution and adhere to environmental standards.

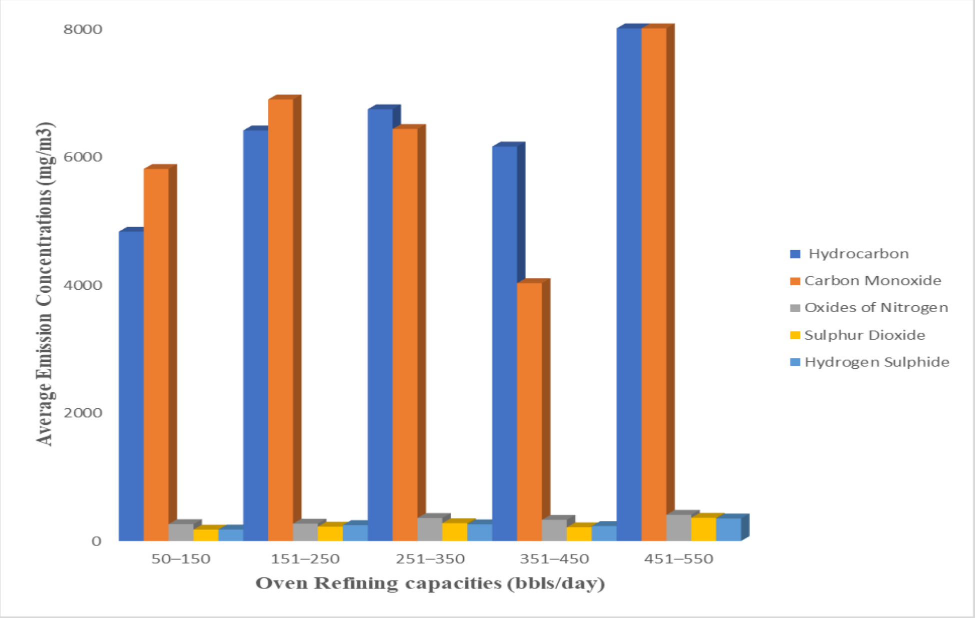

Figure 9. Emissions originating from the heating of ovens and the boiling of crude oil units (Adapted from Onakpohor *et al*., 2020).

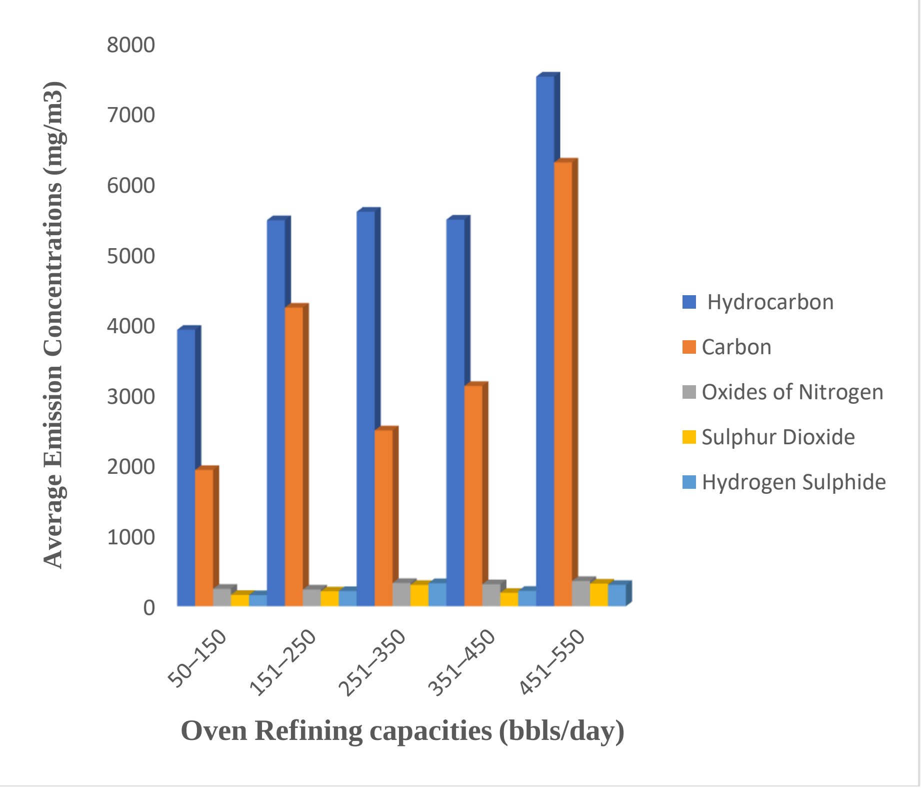

Figure 10. Emissions stemming from the unit where refined products are collected (Adapted from Onakpohor *et al*., 2020).

In a similar vein, Ukaegbu *et al*. (2020) conducted a detailed spatiotemporal study of air quality in various local government areas across Rivers State, focusing on the Port Harcourt metropolis. The research aimed to assess the spread of air pollutants over time and space in areas characterized by intense industrial activities, heavy traffic, and dense population. Air samples were strategically collected at nine different locations within the study area during peak hours—8 am and 4 pm—using the Aerocet-531 Met One Instrument and Drager X-am 5000 handheld gas analysers to measure concentrations of $PM_{2.5}$, PM_{10}, CO, SO_2, and NO_2. They employed a Germin-300 GPS device to record the coordinates of these sampling points, which aided in generating spatial interpolation maps using ArcMap software. The findings from this study indicated that air quality levels in these areas surpassed the limits set by both the World Health Organization and the Federal Ministry of Environment, reflecting a significant concern regarding air pollution in the Port Harcourt metropolis. This analysis provides critical insights into the spatial and temporal dynamics of air quality in Rivers State, emphasizing the need for targeted environmental policies and interventions.

4.5 Product quality from artisanal refineries

The artisanal crude oil refining industry in the Niger Delta region of Nigeria has raised concerns about the quality of its products and the environmental impact of its operations. Studies have shown that artisanal refineries produce crude oil with a sulphur content of less than 0.5%, which is classified as sweet crude (Luke & Odokuma, 2021). On the end products itself there seems to be an argument as to the quality of the products when compared with those obtained from the conventional government owned refineries. Studies have also shown that the physicochemical properties of the products from artisanal refineries fall short of the standards for crude oil used in conventional refineries, as they contain impurities. In a study carried out in Akwa Ibom State, Niger Delta, Nigeria, Udo *et al*. (2020) compared the characteristics of Artisanal Refined Gasoline (ARG) from Eastern Obolo Creek and Mkpat Enin with Regular Automotive Gasoline (RAG), focusing on their physicochemical properties and conformity with the American Society for Testing and Materials (ASTM) standards. The research aimed to evaluate the similarities and differences between these gasoline varieties and their adherence to established ASTM specifications. The findings revealed that Regular Automotive Gasoline generally met ASTM standards in several aspects, including research octane number, motor octane number, Reid vapor pressure, sulphur content, and specific gravity. However, it fell outside the ASTM's prescribed range for the initial boiling point and flash point. On the other hand, Artisanal Refined Gasoline conformed to ASTM standards only in terms of atmospheric distillation and sulphur content. Critical properties such as research octane number, motor octane number, Reid vapor pressure, and specific gravity did not meet the ASTM criteria. This discrepancy indicated that artisanal gasoline might be under-refined or adulterated, posing potential risks to automotive engines. The study suggested that the quality of artisanal gasoline could be enhanced by improving refinery operation conditions and incorporating appropriate gasoline additives. This research highlights the importance of developing local technology in Nigeria's petroleum sector to achieve self-sufficiency and ensure the production of quality fuel that meets international standards.

Ojirika *et al*. (2019) also undertook a study to assess the environmental impacts and product quality of artisanal petroleum refining in Rivers State, Nigeria. Their goal was to analyze the quality of petroleum products produced by artisanal refineries, a common practice in the Niger Delta region, including Rivers State. The study involved laboratory analysis of artisanal petrol, kerosene, and diesel, following American Standards for Testing and Measurements (ASTM) procedures and international best practices, to evaluate their quality. The findings indicated that most parameters analyzed (including specific gravity, flash point, pour point, fire point, and viscosity) from the artisanal refineries did not align with industry standards, unlike those from government refineries. Moreover, artisanal refineries typically skip preliminary refining processes like dewatering, desalting, and desulfurization, which are crucial for removing impurities before refining. The study concluded that the products from artisanal refineries were of inferior quality compared to industry standards.

Roy *et al*. (2022) carried out a study comparing the quality of fuel from artisanal refiners in two communities with that from local filling stations. Their aim was to evaluate the fuel's quality, composition, and pollutant levels, focusing specifically on hydrocarbon composition characteristics using Nigerian laboratories. Adhering to the European Commission's best-practice Petroleum Liquids Sampling Approach, they collected a total of 33 samples to ensure precision and avoid contamination—24 from artisanal refineries and 9 from official filling stations. The analysis revealed that both types of fuel typically contained high levels of long carbon chains, which increased fuel viscosity. This had implications for the temperature at which the fuel burns and the completeness of its combustion, leading to 'sooty' burning that adversely affects engine performance and emissions. Furthermore, the study found high sulphur content in all fuel samples, a major factor contributing to particulate matter and soot emissions. Interestingly, these sulphur levels, significantly exceeding national standards, were consistently higher in the samples from official sources than those from artisanal refineries. This study sheds light on the fuel quality produced by different sources within the communities and underscores the need for regulatory oversight and quality control in fuel production.

Oyewale *et al*. (2022) carried out a study to measure the sulphur content in diesel and kerosene produced by thirty local refineries in the Niger Delta region of Nigeria. Their objective was to evaluate whether these combustion products complied with the minimum quality standards set by the Standard Organisation of Nigeria (SON) and the Department of Petroleum Resources (DPR). For this purpose, they employed the gravimetric method using Eschka's mixture to determine sulphur content. The findings of the study indicated that the sulphur levels in the products met the standards specified by the SON and DPR.

5. Government response to both (regular and artisanal) refinery emissions.

Government's response has been to saddle agencies such as the special security task forces with the responsibility to protect national resources and prevent the continuous oil theft, by identifying and destroying illegal artisanal oil refineries and their storage tankers via burning, in addition to the arrest of suspected illegal refinery operators as well as dealers in illegally refined petroleum products (Partnership Initiatives in the Niger Delta, 2022). These responses have only resulted in double pollution burden, which not only increase in air pollution and its associated health hazards in the region, but results in the spread of the artisanal refining sites, as the refiners will simply count their losses and move on (Richard *et al*., 2023b). In addition, there is substantial evidence indicating that certain corrupt individuals within the Joint Task Force (JTF) are actively involved in and benefit financially from oil theft and illegal oil refining activities (Ogele & Egobueze, 2020). The current approach portrays artisanal oil refining as a security problem rather than as a symptom of economic deprivations and governance dysfunction (Partnership Initiatives in the Niger Delta, 2022).

Fig. 11 Burning of an artisanal refinery by security forces (Source: Taylor, 2013).

6. Recommendations for tackling emissions from both conventional and artisanal refineries

Policies are all well and good, but Nigeria do not suffer from the lack of policies and regulations, but from the lack of infrastructural presence on which these already established policies can function. Some of these infrastructures which would aid in the execution of these policies include:

- The existing refineries should be refurbished with the latest technology targeted at not just increased production only, but also for energy efficiency and emission prevention.
- The government's involvement in the refineries by their current 100% ownership, makes them unable to conduct the proper checks and balances as it relates to environmental regulations. The refineries ought to operate under a fully commercial governance structure, wherein decision-making authority resides with the Board of Governors of the facilities, who should also maintain complete control over their financial resources.
- Modular refinery model adoption should be implemented, in conjunction with the relevant stake holders of the Niger Delta region. The government should set up these refineries in the Niger Delta region and grant licenses to Niger Delta indigenes to not only own and operate it, but also grant them access to direct purchase of the crude and refining it for profit. This will not greatly reduce the need for pipeline vandalism, but also the spills and environmental degradation that occurs as a result.
- The government should also employ and hone the skills of The Niger Delta indigenes already involved in artisanal refining activities to compete with modern quality and safety operating standards.
- The government should review some of the regulations as they apply to air quality, and their limitations for improvement. In addition to the empowerment of the relevant air pollution regulatory agencies like National Environmental Standards and Regulations Enforcement Agency (NESREA), with the necessary technologies, training and mobilities to carry out their functions appropriately.
- Awareness should be raised by government bodies such as the National Orientation Agency (NOA), amongst the inhabitants in the region on the hazards associated with activities of artisanal refining, awareness and training should also be conducted amongst the various security outfits on the proper measures to be undertaken when in contact with artisanal refining sites as opposed to the present measures of burning and bombing which only results in further damage to the environment. Instead, they should rather evacuate products from such sites and hand it over to the relevant authorities.

7. Conclusion

This paper has systematically addressed the significant gaps in our understanding of the socio-economic and environmental consequences of refinery operations in the Niger Delta. By conducting a comparative analysis of government-owned and artisanal refineries, this study has not only highlighted the environmental and public health challenges but also elucidated the economic impact on local communities reliant on agriculture and fishing. Our findings underscore the urgent need for interventions that consider the evolving practices and technologies within the refining sector. Most notably, the research indicates that artisanal refinery operations, while economically beneficial to some extent, pose substantial environmental risks. It is imperative to harmonize the economic benefits with environmental sustainability, calling for robust regulatory frameworks and the adoption of cleaner technologies. The insights gained from this study pave the way for crafting more nuanced and impactful policies that could foster economic development while safeguarding the health of the ecosystem and the communities of the Niger Delta.

List of Abbreviations

ASTM – American Society for Testing and Materials
CRU – Catalytic Refining Unit
DPR – Department of Petroleum Resources

EIA – US Energy Information Administration
EGASPIN – Environmental Guidelines and Standard for Petroleum Industry in Nigeria
FCCU – Fluid Catalytic Cracking Unit
FEPA – Federal Environmental Protection Agency
GHG – Greenhouse Gas
NOA – National Orientation Agency
NNPC – Nigerian National Petroleum Commission
NOC – National Oil Corporation
NOx – Nitrogen Oxides
NESREA – National Environmental Standards and Regulations Enforcement Agency
OPEC – Organization of Petroleum Exporting Countries
PAP – Presidential Amnesty Program
PAHs – Polycyclic Aromatic Hydrocarbons
PIND – Partnership Initiatives in the Niger Delta
PMS – Premium Motor Spirit
SON – Standard Organisation of Nigeria
TAM – Turnaround Maintenance
VDU – Vacuum Distillation Unit
VOCs – Volatile Organic Compounds
WHO – World Health Organization
WRPC – Warri Refining and Petrochemical Company

Declarations

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Authors' contributions:

PGS was pivotal in conceptualizing and designing the study. She spearheaded the project's methodology, conducted an extensive literature review, synthesized the findings, and was chiefly responsible for writing the original manuscript. EU played a significant role in the study's conceptualization and methodology design, offering supervision and guidance as PGS's PhD advisor, and was instrumental in the manuscript's review and editing process. OFO was responsible for interpreting the reviewed data, crafting impactful data visualizations, and also contributed to refining the manuscript. DREE provided critical intellectual oversight, ensuring the work's scientific rigour and merit, and participated actively in manuscript editing. All authors collectively approved the final manuscript version for publication and share responsibility for the work's overall integrity, committed to addressing any questions regarding its accuracy or integrity.

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