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Review Article

Environmental Influence of Gas Flaring: Perspective from the Niger Delta Region of Nigeria

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Gas flaring (GasF) is an important aspect of the combustion mechanisms in the burning of related, undesirable, or surplus fluids (gases in particular) that are released during the ordinary or unexpected overpressuring process in several industrial activities, specifically in the petroleum resource (PTR) industries. It is also one of the major sources of greenhouse gas emissions which cause climate change (CMC). In addition to the generation of noise and heat, it makes substantial adjacent areas uninhabitable and, hence, causes detrimental consequences to the entire ecosystem as well as waste energy and results in economic losses. Reducing GasF is a critical issue due to its ensuing complications; consequently, there is a tenacious need to measure GasF via the study of its composition, distribution, and capacity, as well as the utilization of appropriate GasF recovery/removal procedures. The present review study will, thus, attempt to assess the impacts of GasF on the environment vis-à-vis the possible nexus between GasF/CMC using the perspective of the Niger Delta region of Nigeria which is rich in PTR, with relevant information drawn from existing publications. The roles of government, policymakers, and relevant stakeholders as well as suggestions and recommendations that will assist in the extenuation approaches and technologies of the influence of GasF on the environment are also discussed.

1. Introduction

At present, one of the foremost difficulties confronting humanity is the environmental impact resulting from gas flaring (GasF) [1, 2]; heavy metals [3–5]; dyes [6–10]; particulate matters [11]; petroleum or oil spills, toxic gases, and agricultural, domestic, and industrial chemicals/composites [12, 13]; and other human-induced conditions [14]. These emissions are ordinarily found in the atmospheric environment (air), terrestrial environment (soil/land), and aquatic environment (water), and if not appropriately checked, their ensuing effects are generally disadvantageous [15, 16].

The focus of the present review study is the GasF which is the release of a substantial volume of associated natural gas (ANG) into the atmosphere via vertical and horizontal flaring stacks [17]. GasF is one of the utmost processes of burning off allied fluids (gases in particular) from petroleum wells, hydrocarbons (HC) such as methane, ethane, and carbon dioxide (CO_2) processing refineries or plants, either as a measure of dumping or as a safety means of discharging pressure. Presently, GasF is recognized as one of the foremost environmental problems which is a significant source of anthropogenic CO_2, together with spillages ensuing mostly from the activities of petroleum resources (PTR). About $1.50 \times 10^8\,m^3$ of natural gas (NGas) that is flared globally is attributed to PTR activities, and this is infecting the entire ecosystem with about 4.00×10^2 Mt CO_2 annually [16, 18, 19]. The global GasF that is linked to activities of PTR (especially petroleum gas) is a possible emission source of particulate matters, and this has been prominent in some particular areas that are in crucial need of extenuation. Particulate matter released from GasF is primarily in the form of black carbon which is a strong fleeting climate change (CMC) forcer, although black carbon from GasF has been ignored in some international/local emission catalogues and is hardly considered by climate scientists during climate modelling [20–22].

One of the most significant sources of GHG emissions in the environment is the flaring of associated gas from PTR as well as from petroleum wells and surplus gas from gas processing facilities and oil refineries [23]. Burning flare gases with high heating values has an adverse effect on the environment in addition to causing significant economic losses [14, 23]. GasF wastes energy and results in economic losses as well as result in other environment issues through its greenhouse gas (GHG) emissions [24]. GasF is accountable for about 1.50% of the total industrial GHG emissions. Moosazadeh et al. [24] reported that the increasing role of low-carbon hydrogen in the energy sector has led to state-of-the-art approaches and technologies for GasF utilization and exploitation. Consequently, they proposed a net-negative and self-sufficient multigeneration system for converting gas into hydrogen and deploying captured CO_2 for enhanced oil recovery. For the petroleum (oil and gas) and petrochemical industries to operate in a safe and dependable manner, the flaring network is an essential component [25]. According to Khalili-Garakani et al. [25], in the past ten years, many methods have been developed to collect and use gas in the upstream and downstream oil and gas (petroleum) sectors, as gas causes considerable GHG emissions and economic loss. Not all GasF recovery and utilization solutions are always practical and economically justifiable due to the vast range of GasF and related gas requirements [25].

Despite the ensuing economic, social, and political influence on the international community as well as other benefits of PTR [16, 26], its activities have been a source of some extremely negative implications for human and the entire ecosystem especially the spillages and GasF issues [16]. The "2021 Global Gas Flaring Reduction Partnership Multi-Donor Trust Fund of the World Bank" is reflective of the fact that since the launch of the first of 2 satellites in the year 2012, Russia, Iraq, Iran, USA, Algeria, Venezuela, and Nigeria remain the topmost 7 GasF nations for the last 9 years consecutively (Figures 1 and 2). These 7 nations produce 40.00% of the world's petroleum annually amounting to at least 1.00×10^6 barrels per day (bpd). But they face different challenges to address the issues of GasF and account for about 65.00% of GasF globally [27].

Consequently, nations with conflict-affected, fragile, and insecure issues flared more gas per barrel of petroleum in the year 2020 than other nations, signifying a failure and deficiency of capacity to operate facilities efficiently and to deal with the problems of GasF. The 2021 statistics from the World Bank indicates that the total volume of GasF between 2016 and 2020 was 726 billion cubic meters (bcm) [27].

It is observed that Nigeria has remained the 7th-largest GasF nation in the world with a total volume of GasF of 37.43 bcm between 2016 and 2020. However, the country has progressively reduced its GasF by up to 70.00% over the last one and a half-decade. GasF has reduced from more than 25.00 bcm in the year 2000 to about 7.00 bcm in the year 2020, while the production of PTR has remained at a basic level of approximately 2.00×10^6 bpd (Figure 3). In the last few decades, there have been several research studies undertaken on the environmental impact assessment and the environmental hazards caused by PTR and activities in the NDN. Shown in Figure 4 are the various publications in indexed journals obtained from the Scopus database using the phrase "environmental impact of PTR in the NDN" over the last three decades (1985 to 2021).

A large part of these studies has revealed that there are enormous adverse physical, economic, social, and environmental consequences of the activities of PTR leading to the destruction of living organisms as well as the reduction in agricultural yields particularly to the host communities where these PTR activities are undertaken [16, 28–30].

The NDN is among the top twenty nations with GasF [31]. Hence, there is a need to regularly assess the already carried out studies on cases of the PTR activities (particularly spillages and GasF) in the NDN vis-à-vis GHG emissions which invariably cause global warming (GW) as well as the ensuing incessant CMC issues for environmental sustainability and safety (ESS). However, the issue of petroleum spillages and the ensuing environmental consequences in the NDN was intensively dealt with in our recently published article [16]. Therefore, the utmost emphasis of this present review study will be on assessing the impacts of GasF on the environment vis-à-vis the possible nexus between GasF

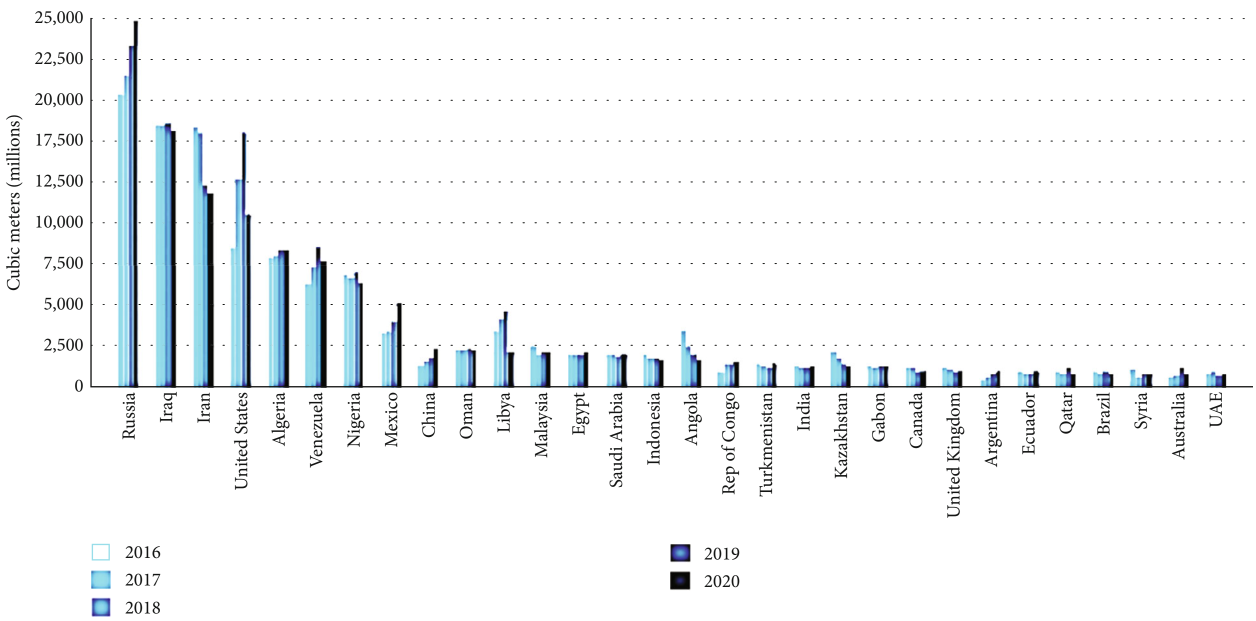

Figure 1: GasF volumes for the topmost 30 GasF nations between 2016 and 2020 [27].

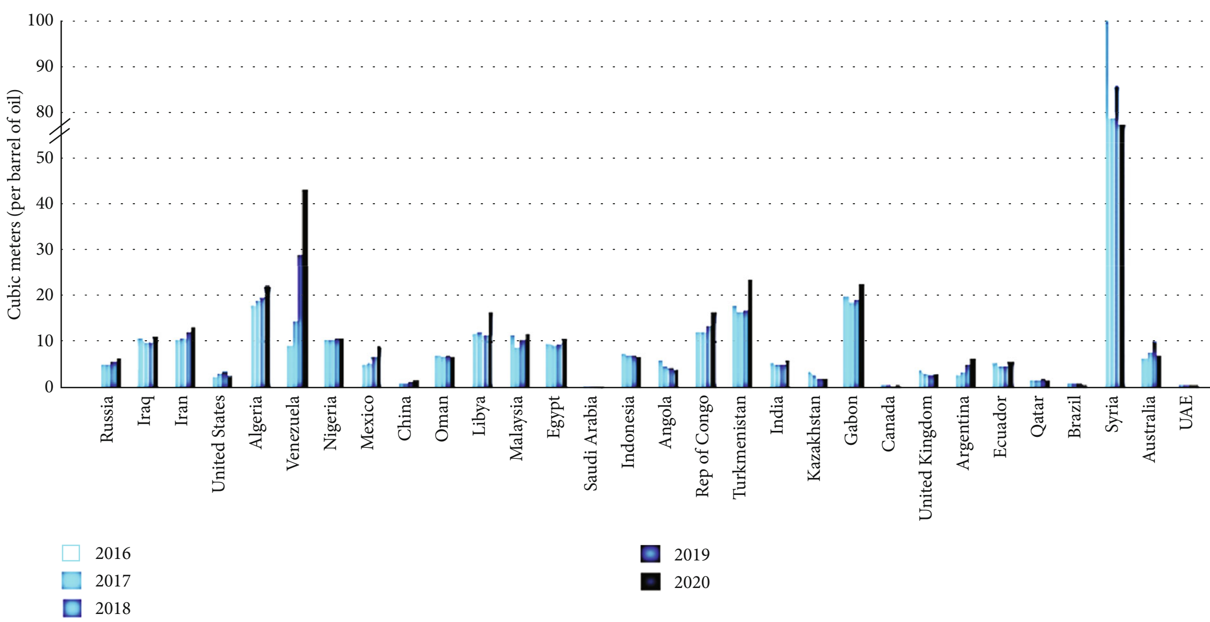

Figure 2: GasF intensity for the topmost 30 GasF nations between 2016 and 2020 [27].

and CMC using the perspective from the NDN drawn from existing publications as illustrated in Figure 5 (graphical abstract showing the emphasis of this present review study and illustrating that petroleum activities in the NDN have two major aspects, namely, economic benefits and environmental implications; the economic benefits are in the form of income, jobs, and international influence, while the environmental implications are due to climate change, environmental pollution, agriculture and vegetation obliterations, and health problems. These environmental implications occur mainly from GasF and petroleum spillages, which are caused by sabotage, operational, and other factors. The figure also captured other aspects of the study, which include reduction approaches and technologies, the role of government, policymakers, and relevant stakeholders, global experts' perspectives, and the legal framework, as well as conclusions and recommendations). Some keywords and phrases, such as "GasF, impacts of GasF, and environmental impact of PTR in the NDN," from databases such as Scopus, Google Scholar, Researchgate, and Google Search Engine from both review and research publications as well as grey literature on the subject matter were utilized using a facile systematic approach in the selection of the most relevant publications that reflect the state-of-art knowledge on the

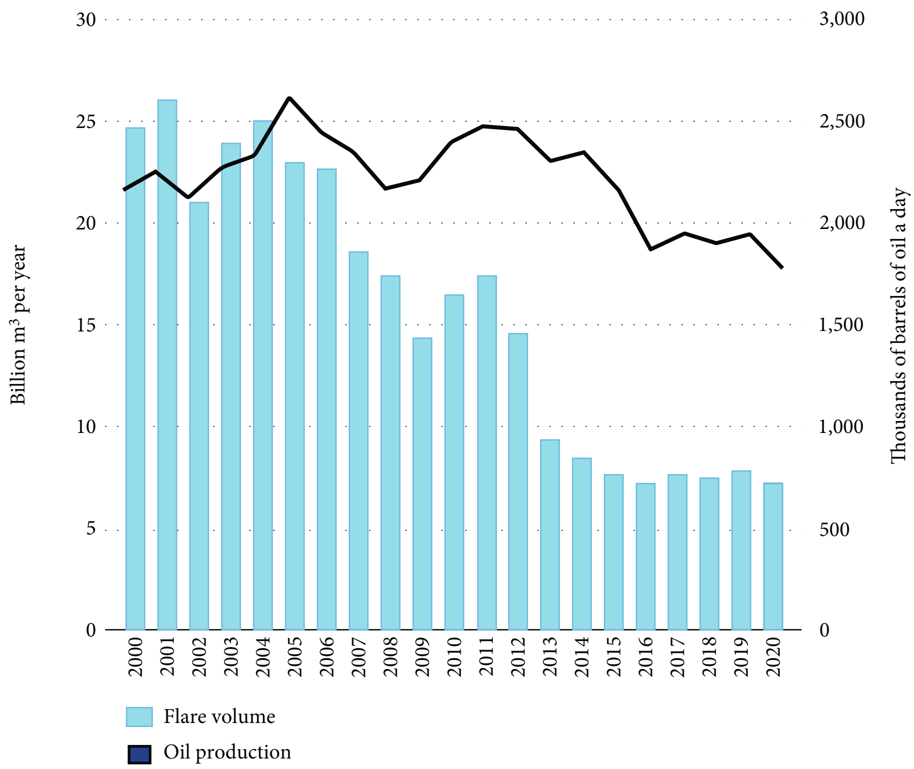

Figure 3: GasF in Nigeria in volumes and PTR production between 2000 and 2020 [27].

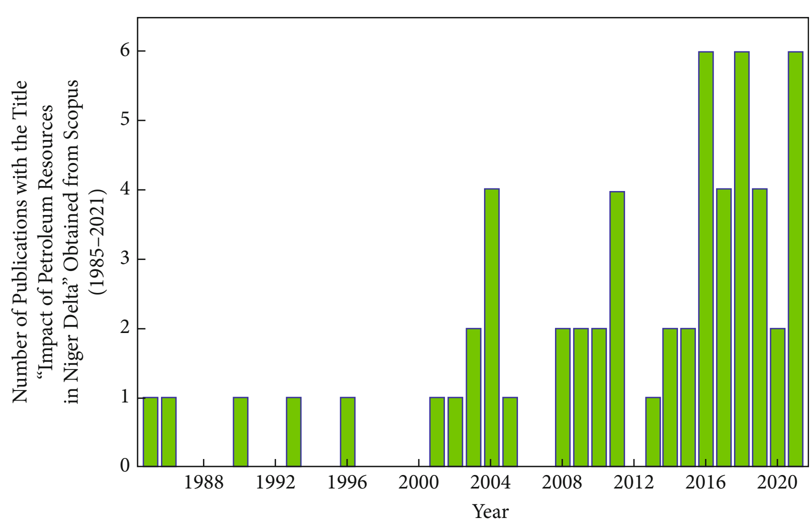

Figure 4: The number of publications obtained from the Scopus database using the phrase "environmental impact of PTR in the NDN" over the last three decades (1985 to 2021).

subject matter. The added value of this study comprises an all-inclusive, facile approach, more scientific solutions, suggestions, and recommendations for addressing the complex issues of GasF and CMC in data-sparse NDN, and this will serve as a basis for other environments with similar consequences.

2. GasF and Its Causes in the NDN

A variety of factors influence the combustion efficiency of GasF, including the composition of the flare stream and the presence of flare gases. These factors can be grouped as technical reasons, economic reasons, political reasons, etc. As stated earlier in the introduction section, the release of a significant volume of ANG into the atmosphere via vertical and horizontal flaring stacks is known as GasF, in the oil and gas industry during the production and processing of crude oil [32]. GasF during the production process of PTR harms the environment, the national economy, and the health of Nigerians living in the NDN. A total of 9.17×10^2 bcm was flared in 2017 [33].

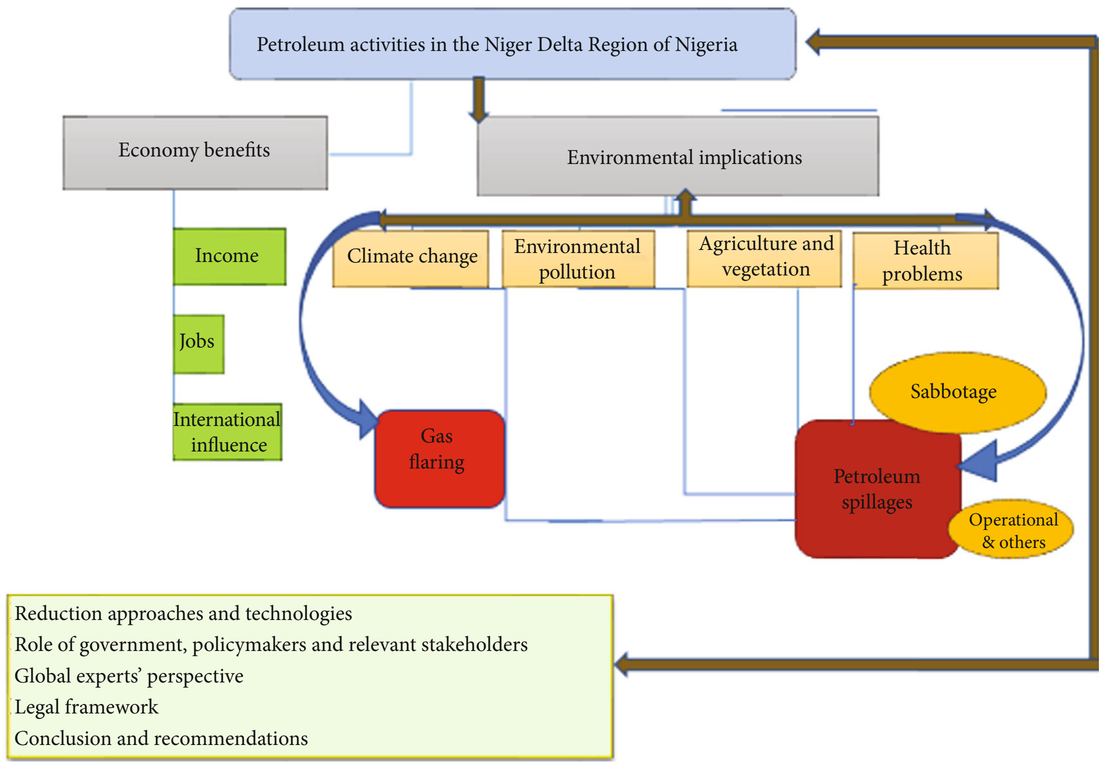

Figure 5: Graphical abstract.

Historically, GasF started in the NDN as early as 1956 [16]. The NDN has been regarded as one of the world's most vulnerable ecosystems because of GasF and other processing activities of PTR. In that, the emission of GasF contributes remarkably to GW, and they are generated when surplus gases are burned off during the oil drilling procedure [34]. Also, GasF is extremely hazardous to the life of humans (see Table 1 for the various gases and their harmful effects). The residents in the NDN observed noticeable gases oozing from the various production sites of PTR. Evidence of acute and chronic toxicity demonstrates the potentially hazardous and unfavourable effects of PTR-derived pollutants on the tropical environment, which has direct consequences for the socioeconomic well-being, human health, and environment of the surrounding people as in the case of the NDN.

Alarmingly, the production sites of PTR have become a part of the landscape of the NDN [35]. The global annual volume of flared and vented ANG in 2011 was sufficient to supply both Germany and France's annual NGas consumption, double Africa's annual gas consumption, and was enough to supply the entire world with gas for around 20 days [36–38].

CO_2 emissions from GasF contribute significantly to environmental GHG levels [2]. Rising temperatures have a detrimental influence on humans and their environment, particularly on human economic activities [39]. The emissions of PTR-related waste in the NDN have contributed to the regional and global pollution, having adverse health effects on both the environment and mankind [40]. Not only does GasF squander a potentially valuable source of energy, but it also releases substantial amounts of HC into the atmosphere. Furthermore, because of its links to asthma, cancer, chronic bronchitis, and other illnesses, GasF has a significant impact on human health [41]. Furthermore, GasF contributes to the earth's heating and intensifies the GHG effect. GasF activities in the NDN have consistently created fumes, particles, noise, and heat, all of which have affected both people and the environment [42].

The environmental impact of GasF activities in the NDN is quite clear in terms of its negative impact; in the cases of Umutu-Ebedei communities, it involves an increase in the environment thermal gradient and a decrease in agricultural efficacy. The socioeconomic problems and environmental degradation of the local and bordering communities' lands have been vastly documented. Some of the Umutu-Ebedei gas plant's GasF effects include decreased growth and red leaves in cassava, palm trees, plantains, and other crops placed within the flared areas [43].

As stated by the newspaper *Daily Independent*, "multinational oil companies operating in Nigeria's multibillion-dollar industry are in a race to beat the 2012 deadline to stop GasF. Nigeria has fixed 2012 as the new deadline to stop GasF after several years of foot-dragging from the January 1, 1984 date provided in the principal act which was later amended to December 31, 2008" [44, 45].

In 2005, local communities from the NDN filed lawsuits in Nigeria against the Nigerian government and the PTR companies—"NNPC, Total, and other local subsidiaries of SPDC, Chevron, and Agip," claiming that the companies' continuous practice of GasF (burning off NGas in oil production) instigated environmental damages and desecrated their right to life and human dignity. The lawsuits adopted different strategies. Otiotio [38] looks at a lawsuit filed

Table 1: A summary of pollutants, allowable air quality levels, and health problems of GasF.

Pollutants	Allowable air quality levels	Health problems
Nitrogen oxides	32 ppb (annual mean value)	Lung exasperation reduces the function of the lungs and rises vulnerability to allergens for asthmatics
Sulphur oxides	57 ppb (daily mean value)	Adverse influences on humans' respiratory systems due to exasperation and airway impediment
Carbon monoxide	5 ppm (daily mean value)	Nausea, headache, potential lasting health influences, and weakness
Benzene	0.096 g/m^3 (annual mean value)	Aplastic anaemia, leukaemia, leukocytes, thrombocytes, and pancytopenia
Toluene	120 ng/m^3 (daily mean value)	Potent central nervous system toxicant resulting in narcosis, coordination, emotional liability, and subjective symptoms like fatigue and headache
Xylenes	0.12 ng/m^3 (daily mean value)	Unambiguous developmental toxins, leading to deferred development, diminished fetal body weights, and reformed enzyme activities
Styrene	Not reported	Irritant of the skin, eyes, and mucous membranes and a central nervous system depressant
Naphthalene	96 ng/m^3 (daily mean value)	Destroying the membrane of the red blood cells with the liberation of haemoglobin, irritating the eye
Black carbon	3.5 mg/m^3 (1/3 daily mean value)	Caused accretion of dust in the pulmonary system and pneumoconiosis
Formaldehyde	0.75 ppm (1/3 daily mean value)	Irritation of lungs and mucous membranes causes naso/pharyngeal cancers and possibly leukaemia
Methane	1,000 ppm (0.10% for 1/3 daily mean value)	It is nontoxic and generates no hazard when inhaled in limited quantities. However, if large quantities of methane or other NGas are allowed to displace air, deficiency of oxygen might result in suffocation, and this could result in variations in mood, slurred speech, vision complications, loss of memory, facial flushing, nausea, vomiting, and headache. In some severe cases, there could be variations in breathing and heart rate, balance problems, unconsciousness, and numbness
	5,000 ppm (0.5% CO_2 in air averaged over 1/3 daily mean value)	Headaches, dizziness, restlessness, a tingling or pins or needles feeling, difficulty breathing, sweating, tiredness, increased heart rate, elevated blood pressure, coma, asphyxia, and convulsions
HMs	Depending on the category of HMs	Could cause gastrointestinal, dysfunction of the kidneys, disorder in the nervous systems, lesions in the skin, vascular impairment, dysfunction of the immune system, birth defects, and cancer

against the SPDC and the NNPC in the Nigerian federal court. GasF (the practice of burning off NGas associated with oil production) has been illegal in Nigeria since 1984. Companies may only flare if they have ministerial consent. The Nigerian government has imposed several deadlines for phasing out the practice, none of which has been met.

On November 30, 2005, Jonah Gbemre (representing the Iwherekan community) filed a claim in the Federal Court of Nigeria's Benin Judicial Division against the SPDC and the NNPC. The complainant claims that GasF infringes both the Nigerian constitution's and the African Charter's guarantees of life and human dignity. GasF, according to the plaintiff, has a negative impact on human health, the environment, food, water, and housing. The defendants filed several motions to halt the proceedings [38].

Furthermore, the lawsuit argues that GasF is harmful to human health, the environment, food, water, and housing. Several motions to stay the proceedings were made by the defendants. The court ruled on November 14, 2005, that GasF is a violation of a person's right to life and dignity. The defendants were ordered by the court to take urgent action to cease GasF in the community. The defendants filed an appeal against the decision. Contempt of court charge was filed against the SPDC and the NNPC on December 16, 2006. The SPDC said it was not in contempt of court since it has multiple appeals pending in the case [46].

Court cases and reports on GasF in the NDN:

(i) "Nigeria's gas profits 'up in smoke,'" Andrew Walker, BBC News, 13 January 2009

(ii) "The Nigerian Court Gives the SPDC One Year to Stop Gas Flaring," Environmental News Service, 11 April 2006

(iii) "Judge Orders GasF to Stop Immediately," Jim Lobe, IPS News, 14 November 2005

(iv) "The SPDC faces flaring lawsuit," Terry Macalister, Guardian (UK), 31 June 2005

According to Guardian reporter Ratcliffe [47], GasF, which releases NGas linked with PTR production into the environment, has polluted the air and resulted in acid rain. Eradiri community says, "It's extremely revealing on the people." Three-quarters of Bayelsa's in the NDN estimated 2.00×10^6 residents rely on fishing or farming for their livelihood. "Those communities are experimenting with other means of survival. And that's why there's been a spike in illegal activity as well as artisan refining."

Flaring is a widespread practice in the PTR industry all over the world. Libya, for example, flares about 21.00% of its NGas, compared to 8.00%, 5.00%, and 20.00% flared by Canada, Algeria, and Saudi Arabia, respectively. Nigeria burned over 76.00% of its ANG in 2002, indicating that it has one of the highest rates of GasF in the world [48]. Despite the reduction in GasF by 70.00% in the last decade, the NDN continues to suffer from pollution-related PTR extraction and production activities. Nigeria is ranked the top seventh in countries with GasF issues, accounting for 40.00% of global PTR output and 65.00% of global GasF [49]. Since 2002, the percentage of GasF in Nigeria has been reducing and stood at about 10% in 2018, in terms of volume of GasF.

Flaring and venting of ANG in the NDN release around 3.50×10^7 metric tons of CO_2, CH_4, a huge number of HC, and other GHGs into the atmosphere each year. CH_4, for example, makes up around 86% of ANG, and because GasF has a low burning efficiency, a higher percentage of the related gas emitted is CH_4, which has a higher GW potential. The GHG concentrations in the atmosphere rise as a result of these emissions, contributing to GW. Due to the high concentration of HC in the NDN atmosphere, there are numerous possible reactions in the region's photochemical smog, and emissions from flare and vent systems have implicated the regional and/or global environment [33, 50]. However, the country still ranks in the top 10 among global gas countries, with approximately 0.21 billion cubic meters (bcm) in 2018 [49].

According to recent data from the NNPC ASB [51], approximately 77.29 bcm of ANG was produced in 2020. This shows a decline of 4.74% when compared with 2019 production (81.135 bcm). Of the quantity produced, 71.819 bcm (92.92%) was utilized, while 5.47 bcm (7.08%) was flared. The ANG is composed of two HC, carbon, and hydrogen. The flaring of gas is motivated by multiple factors such as the following:

(i) The removal of excess HC and waste pressurised gases from refinery pipelines to reduce the buildup of gaseous pressures in the PTR pipeline venting is devised as a measured release [52].

(ii) The gases released from PTR processing are toxic and harmful to the entire ecosystem, thereby burning of such gases induces these quantities into the atmosphere. The issue of GasF has been a foremost environmental worry for the world; its influence is both local and global in nature. In other words, it is a multimillion-pound waste, as well as an environmental calamity

(iii) The flaring of gas was restricted in Nigeria in the late 1970s with a financial penalty put in place. However, PTR companies involved in GasF weigh the cost of flaring compared to investing and developing more social and environmental solutions to ridding the production lines of the excess gas produced, where the cost of flaring (related penalty) is less than investing and developing an ecosocio-economic strategy; gas is flared since paying the fine is more profitable than not flaring gas into the atmosphere

(iv) With the lapse in the enforcement of the law regarding anti-GasF-related activities, some government agencies and officials fail to enforce laws and duly report offenders due to the level of compromise that has/still takes place. Environmental contamination occurs as a result of insufficient environmental management practices used by the PTR sector, as well as the failure of Nigeria's environmental regulations

(v) Acts of receiving and accepting kickbacks, bribery, and other unethical practices have been alleged by some research. The "Petroleum Act of 1969 and the Gas Re-injection Act" examine the enactment and execution of GasF laws, concentrating on important legislative events from Nigeria's independence in the 1960s to the present. This chronology is crucial for understanding the roadblocks to end GasF [53].

(vi) Weak legislation and government policies are some of the major factors why GasF still occurs at the level it does in the NDN. The PTR firms failed to follow the regulations outlined in the 1984 deadline, arguing that reinjecting gas was too expensive; as a result, approximately 55.00% of oil fields were excused from engaging in gas reinjection, and a minor penalty was levied on oil fields where gas flared [53].

(vii) The political will of a region or country contributes to the ongoing issues of GasF. Environmental contamination, human health risks, safety and the environment, and negative socioeconomic consequences of most GasF pollution around the world are all influenced by the event, the geographic setting, the characteristics of the regional population, the corporate governance system, and the political economy, where for political or financial gain, the executive arms of government are unwilling to pass stricter bills or amend weaker ones, which have also been cited as leading causes of GasF

(viii) Lack of infrastructure, an associated cause of substantial GasF as in the case of the NDN, is the unavailability of the economic, physical facility, financial, and policy enablers in Nigeria to drive the development of a gas industry [54]

(ix) The benefits of such products are constantly absent in these growing economies, while the consequences remain to the extent of crippling the security, livelihood, and health of the underprivileged, as evident in the NDN. Such is an interrelated cause of continuous antienvironmental activity such as GasF

(x) The multinational PTR companies such as Exxon Mobil, Agip, the SPDC, Texaco, and Chevron in harmony with NNPC are responsible for the constant act of GasF in NDN. In most developing countries with regard to PTR production, GasF is one of the foremost routines owing to its financial affordability

(xi) GasF is used as a safety precaution to protect vessels or pipelines from overpressure when ANG is properly exploited. However, in areas where there is insufficient infrastructure to extract NGas, GasF is employed as a safety precaution to protect vessels or pipelines from overpressure [52, 54].

(xii) GasF has been a serious environmental issue in Nigeria. The World Bank advises that there is a need for long-term efforts to reduce GasF. High concentrations of pollutants from GasF have an effect on the environment, and the resultant products and reactions of pollutants in the atmosphere are a result of the concentration from the initial source. GasF is a highly oxidised technique utilized in scorching flammable elements, primarily HC from industrial waste gases

(xiii) The combustion efficiency of GasF is affected by many factors, as well as the composition of the flare stream and the prevalence of flare gases. In the course of upstream PTR activities, GasF is typically used for the removal of ANG for safety. While venting may appear to be a better option due to the foreseen destruction of NGas, this process results in a variety of air pollutant emissions [38]. Nevertheless, venting causes the release of methane, which is converted into CO_2 via flaring (combustion reaction).

GasF is a locally and universally substantial source of atmospheric contaminants, and several techniques have been developed for its detection, especially via satellite remote sensing. Undesirably, GasF influences the immediate environments via the generation of noise, heat stress visual effluence, and emission of GHGs and contaminants as well as acid rain. Allegedly, from 2003 to 2012, GasF generated about 0.60% of the annual global anthropogenetic emission of CO_2. The recovery of GasF can play a pertinent role in ESS as well as in meeting emissions goals [31].

Caseiro et al. [55] calculated the global GasF volume and black carbon emissions in 2017 by employing a previously established hot spot detection and characterization procedure for all observations of the "sea and land surface temperature radiometer" device which involved the Copernicus satellite Sentinel-3A in 2017 (Figure 6). They also applied recently established filters to identify GasF and modifications for estimating GasF volumes (in bcm) as well as the black carbon emission estimations. This study again affirmed the fact that Nigeria remained the 7th-largest GasF nation in the world.

3. Possible Nexus between GasF and CMC in the NDN

A continuous increase in the burning of fossil fuels as well as the modifications in land use due to the actions of PTR (GasF and petroleum spillages) has instigated an increase in the amount of radiant energy deposited in the atmosphere, which is astronomically emitted back [56–58]. GHG emissions and the consequences ensuing from the radiation have caused CMC [59]. Nevertheless, other human activities such as the burning of bushes, consumption of some crucial creatures, and the use of vegetation (deforestation) have also led to the intensification of the CO_2 level in the atmosphere, which sequentially causes GW [60–62].

With the progressively adverse impacts from the activities of PTR (such as GasF and petroleum spillages), it is assumed that with a meter increase in the mean sea level (MSL), the NDN could misplace around $1.5 \times 10^4\,km^2$ of their land possessions by the year 2100, and if critical action is not undertaken to address these issues, approximately 80.00% of the residents of the NDN will be entirely displaced. Sequentially, this would cause countless other environmental dereliction owing to GasF and petroleum spillages [63–65].

There are a thousand cases of GasF from PTR activities that have occurred in the NDN since the first noted case of GasF in 1956 [36, 66–68]. These GasF and others from PTR and activities have continued to affect the entire ecosystems of the NDN. Additionally, quite a lot of PTR well locations owing to burning linked with PTR from spill locations have flares [68]. The GasF ensuing from these PTR come with a huge amount of heat, and this will invariably have a proportionality with the temperature. Consequently, there is an increase in the temperature of the neighboring environments, discharging close to 5.00×10^7 tons of CO_2 and approximately 2.00×10^7 tons of CH_4 per annum [49, 69].

This, in turn, generates sulphuric acid and consistently led to the obliteration of the wetland organisms, shrubs, and forest ecosystem. Allegedly, these flares adulterate rainwater by engendering acid rain that contributes to regional CMC [70]. As rightly noted by Zabbey et al. [30], once an area is contaminated by these PTR, it is hard to confiscate without instigating additional obliteration of such ecosystem.

4. Impacts of GasF

The GasF is categorized as multibillion-dollar waste but is a solvable energy problem [71]. The 2011 statistical estimates intimated that 140 bcm of gas globally flared. This corresponds to 5.00% of NGas produced globally, a loss of 10 billion United States dollars (USD) in revenue which is

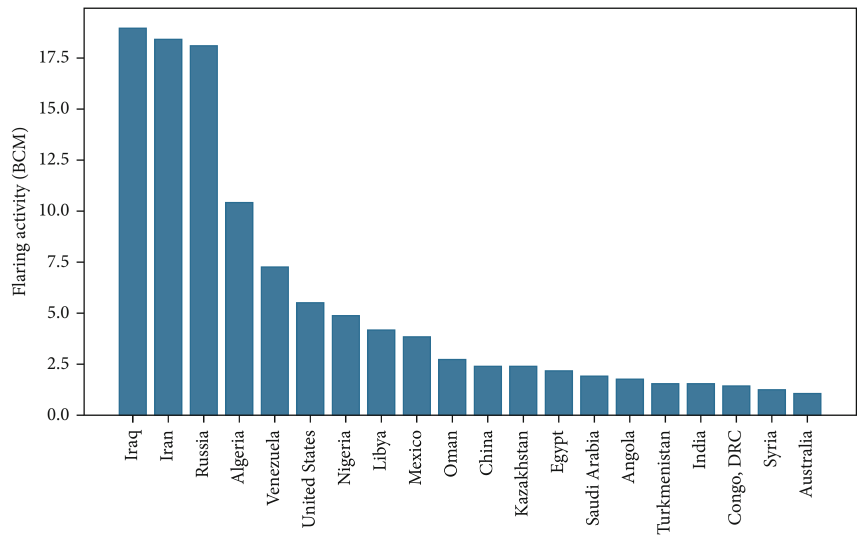

Figure 6: GasF activities in various nations using the sea and land surface temperature radiometer show the topmost twenty nations during 2017 [55].

equivalent to a 2.40×10^6 bpd loss. In clear perspective, 4.00×10^8 tons per year of CO_2 is equivalent to the following:

(i) Emissions from 7.70×10^7 cars annually

(ii) 2.00% emissions of CO_2 globally from energy sources per annum

(iii) 6 billion USD carbon credit at 15 USD per metric ton

(iv) 20.00% emissions of CO_2 from the steel industry

(v) 35.00% emission of CO_2 from the cement industry

(vi) Combined output from 125 medium-sized coal plants with 63 gigawatts of rating [71, 72].

Environmentally, GasF results in the emission of carbon, volatile organic compounds (VOCs), polycyclic aromatic hydrocarbons, noxious waste substances (NO_x, SO_x, H_2S, etc.), and inorganic contaminants and is accompanied by great heat and particulates, thus greatly impacting human and environment.

In the NDN, several GasF-related problems on vegetation and physical damage to infrastructures include dilapidation of roofing sheets, development of diseases, and health anomalies which include gastrointestinal problems, cancer, cardiovascular dysfunction, respiratory diseases and complications, bronchitis, and asthma oedema. Equally, the production of acid rain leads to the cause of lung diseases and poses a great danger to aquatic lives, wildlife, and vegetation. Finally, the ensuing noise pollution affects the humans residing or working around or near the flaring areas [42].

4.1. Formation of Acid Rain. The combustion of flared gas in a humid environment especially offshore leads to the formation of acid rain. The corrosive nature of acid rain means extensive harm to the environment, distressing effects on the vegetation, and pollution of surface water [41]. It has been noted that acid rain has significant effects on freshwater, coastal, and mangrove environments [73]. A study conducted by Uyigue and Enujekwu in the NDN shows that at 50.00 m and 200.00 m from the GasF point, the rainwater collected was acidic with pH values of 5.20 and 6.47, respectively [74]. These results are in good agreement with those of Efe [75] on research conducted in petroleum-producing regions where pH values in the range of 4.98 to 5.15 with a mean value of 5.06 was recorded. The results further confirmed that the acidity decreases with an increase in the distance further from the flaring sites.

The impact of GasF (in addition to oil spillage) on rainwater for domestic usage has been conducted in Okpai and Beneku areas, Delta State. Its color, temperature, conductivity, taste, and alkalinity were found to be altered when compared to allowable limit levels for drinking water by WHO and the "National Agency of Food and Drug Administration and Control" [76]. Also, acid rain has been linked to increased corrosion of galvanized iron sheets. In the study by Ite and Ibok [73], a comparative study of the corrosion of corrugated iron sheets revealed that a maximum loss of weight of 7.62 mg and 4.23 mg was recorded for 500.00 m and 1000.00 m away from the flare site with a weight loss of 1.17 mg witnessed on nonflaring area, thus confirming the effect acid rain [77].

4.2. Thermal Pollution. Elevated temperatures are associated with unfavorable chemical, physical, and biological conductions which are detrimental to human health, vegetation, and soil microbial. The thermal effect from flared sites conducted in the Ebedei community in Delta State during wet and dry seasons has been investigated. The temperature measurements were conducted by varying the distance from flaring sites, and the results showed that thermal pollution was experienced within a distance of 2.15 km and 2.06 km for wet and dry seasons, respectively [78].

By employing a global position system, thermometer, and fibrous meter tape, the location of longitudes, latitudes, and distance from the flaring site was established during surface temperature measurements [43, 78]. Within a radius of 210 m, an elevation of temperature of nearly 9.1°C above normal temperatures and a 0.05°C/m temperature gradient was observed with a recommendation that residential constructions be located approximately 210 m away from flaring centers [79].

4.3. Health Problems of GasF. Based on the length of exposure, considerable human health problems such as chronic obstructive pulmonary diseases, respiratory diseases, breathing difficulties, cardiovascular diseases, asthma, wheezing, cancer, stomach ulcers, and leaching of mucous membrane are witnessed among humans living close to or around flaring sites [73, 80]. These problems are a result of drinking contaminated water and ingestion and inhalation of particulate and toxic gases suspended in the air. For instance, the harvested rainwater usage exposes a huge number of people living in rural set-ups to toxic metals (precisely vanadium), petroleum hydrocarbon pollutants, and polycyclic aromatic hydrocarbons [73].

A study conducted by Nwankwo and Ogagarue [41], on the effect of GasF on the quality of groundwater in Delta State, revealed that the GasF site had higher concentrations of metals like barium, selenium, chromium, iron, cyanide, copper, and manganese when compared to nonflaring location. Also, a high content of iron and lead in the ground and surface water has been noted in Irri town and its neighboring areas with GasF cited as the cause [81].

Air quality concentration of SO_2, NO_2, H_2S, CO, VOC, etc. in radial distances from GasF sites (20, 35, 50, 100, 500, and 100 m) have been investigated. For example, the concentration of SO_2, NO_2, and CO at 20 m from the flaring point was found to be 26.9, 42.8, and 18.80 $\mu g/m^3$ compared to <0.01 $\mu g/m^3$ for each concentration at 700 m. The result shows low quality of air and high-risk factors of pollutants for humans and animals around the flaring locations [74]. Table 1 presents a summary of pollutants, allowable air quality levels, and health problems of GasF [72].

4.4. Impact of GasF on the Environment. Agricultural plants act as the main source of essential nutrients like proteins, carbohydrates, vitamins, lipids, and other minerals required by human bodies. Apart from being food for livestock particularly omnivorous animals such as cows, goats, rabbits, and grass cutters, vegetation is also a source of habitat for numerous wildlife species. Near the flaring site, the soil has often been used as a sink for disposing contaminants from PTR such as benzene, ethylbenzene, and toluene [72], thus affecting the productivity and growth of plant species [17].

A decrease in the length and weight of cassava coupled with an increase in its sugar contents and amino acid relative to a decrease in distance to the flaring area has been noted [82]. Further, a correlation was drawn between a decrease in flaring distance and a decrease in starch content and ascorbic acid. Similarly, it has been established that flaring affects food crops like okra, cassava, potatoes, plantain, and yam in the Ebedei community in the NDN [83].

Thermal pollution from flaring adversely affects microbial pollutions which are essential for the decomposition of organic matter and the nitrogen fixation process leading to declining soil fertility and biogeochemical nutrient cycles [72]. Research indicates that soil quality parameters such as temperature, microbial population, soil moisture, and bulk density significantly change near flaring areas in the NDN [84].

Crops whose response to high-temperature variation is poor should not be planted in those areas [78]. Using Ovade flare in the NDN as a case study, Odjugo and Osemwenkhae [48] noted the influence of the microclimate effect on maize yield. The results indicate that the rise in the air and soil temperature in the GasF area leads to a decrease in relative humidity, soil chemical, and soil moisture, thus harming maize yield. The authors affirm that the production of maize within 2.00 km of the flaring area is not economically viable.

Some substantial portions of the mangrove ecologies of NDN have been devastated due to PTR [85]. Due to the ensuing adverse effects of PTR (petroleum spillages and GasF), there is a steady reduction in the rainforest's landmass of the country which occupies an estimated area of 7,400 km^2, and this is instigating acid rain.

The petroleum spillages at Bomu in the NDN which happened in July 2001 affected the ecosystem of the NDN, especially the land that is even presently not able to be utilized for agricultural tenacities. As observed in the study of Amaize [86], there is a possible relationship between GasF and petroleum spillages. The study shows that the effect of incessant GasF in the NDN has led to the reduction in the size (weight and length) of the cassava tubers produced with a corresponding and proportional increase with distance from the flare.

In their study, Motte et al. [87] quantified the global and regional effects of GasF on human health utilizing spatial differentiation. The GasF produced about 350 million tonnes of CO_2 emissions globally in the year 2018. Together with CMC, this practice of burning GasF has other adverse consequences for humans (such as respiratory complications) and the ecosystem. Their findings quantified the effect of GasF on human health at the global and national levels by estimating the number of disability-adjusted life years caused by the burning of ANG. They also found that GasF emissions were linked to ensuing pointers such as CMC in life cycle assessments for all of the countries studied.

Owing to the abovementioned impacts of PTR (GasF) on the environment, Egbo et al. [88] noted that the dispersion of degradable hydrocarbon microorganisms around the NDN would assist in entailment of the vision of the UNDP for keeping and accomplishing the MDGs and SDGs. The application of these degradable hydrocarbon microorganisms for the accomplishment of a friendly environment in the NDN is attainable since these microorganisms have shown high proficiency, efficiency, and great economic possibilities, ecofriendliness, and acceptance by the general public [16].

After having looked at the devastating and increasingly accumulating evidence of the environmental and climatic dilapidation due to the activities (exploration and exploitation) of GasF in NDN, we now highlight a thorough outline of the supposed efforts in the management and mitigation of the aforesaid derelictions both by the government and other policy players.

5. Role of Government, Policymakers, and Relevant Stakeholders on GasF Problems in the NDN

Section 20 of the Nigeria Constitution (which is the utmost document concerned with the rules and regulations of the country) states that "the state shall protect and improve the environment and safeguard the water, air, land, and forest wildlife of Nigeria" [89]. This section is the first legislation concerned with the control of the effect of PTR on the environment. The section also provides the basis of all other rules for environmental regulation and management in Nigeria [90].

Nevertheless, the weakness of the Nigerian constitution in overseeing environmental justice and in restoring the resources (PTR) control to the immediate residents of the NDN has been one of the most critical restraining factors to the development of the region, as no aspect in the constitution permits the citizens of the communities of this region to have full control of the PTR from their communities [16].

The Nigerian constitution allows the states and the PTR industries to have complete control of the regional PTR [91–93]. However, this privilege has been suggestively abused by the representatives of the government, due to their continuous diversion of the incomes to other regions of the country from the NDN, with little or no significant improvement of both the lives of the people and the environment of NDN [94], and this has caused economic and environmental frustration to the people of the NDN [95–97].

Given some of the challenges inherent in the various GasF laws in Nigeria, the Nigerian policymakers have been pressured to amend or reenact an effective legal framework regulating the flaring of gas in Nigeria. Concerning this, there are several GasF bills still pending on the table of the Nigerian policymakers to decide on to become an Act. One of such bills is the GasF Bill, 2019. The bill sorts to regulate PTR companies involved in PTR production to adopt a sustainable method that is economically and environmentally friendly. The Nigerian policymakers must ensure that they enact a standard GasF law in curtailing and combating the GasF.

6. Global Experts' Perspective on GasF Problems in the NDN

The human existence and the climate of the earth are under serious threat of degradation arising from gas flares in the industrial activities of PTR companies [98]. The scientists predicted that the continuous GasF within the global environment will wreak catastrophic havoc (CMC and GW) on the ecosystems [99–101].

To curtail the danger posed to the global environment caused by the emission of GHGs associated with GasF, the global community under the organization of the United Nations formulated and strategized an international legal framework for preserving the environment from incessant GasF pollution. There have been unceasing efforts from relevant global experts in evolving and preserving the environment, for example, the 1972 extraordinary global landmark event titled "The Human Environmental Conference." As a continuation of evolving AES and CMC, the United Nations established 17 SDGs which are aimed at protecting, restoring, and promoting sustainable use of natural resources (such as vegetation, PTR, and wildlife), combating environmental adulterations, halting soil degradation, and managing the defacement of biodiversity [102–104].

However, it suffices to state that CMC is a global issue. In this regard, Nigeria is also faced with a GW threat [105, 106]. Although Nigeria is a party to the global ecological treaties, declarations, conventions, and protocols that required the reduction of GHGs, however, in NDN, there is still an incessant high rate of GasF [107]. A study in Nigeria has shown that Nigeria is one of the countries in Africa with the highest GHG emissions arising from the flaring of gas [108]. This is based on the fact that Nigeria has over 122 sites in NDN whose operation often led to GasF [109]. The study also shows that in the NDN, about 45.8 billion kilowatts emission of heat arises from GasF, as a result of about 1.8 bct of gas being released in the atmosphere [110]. To further compound the problem and challenges of most communities in the NDN, Marcus et al. [111] study on GasF further reveals that most GasF sites are very close to the residences, farmlands, rivers, and lakes of most communities in the NDN.

Given the level of GasF in the NDN as revealed by various studies, Raji and Abejide's [112] study on GasF in NDN further reviews that the major environmental problem affecting the NDN is GasF. They stated that the industrial activities of most multinational and foreign companies within the NDN are often the causes of land and water pollution within the NDN communities. Pollution arising from GasF often leads to health challenges, losses, and damages to subsistence and commercial farmlands, rivers, and lakes in the NDN.

Although there are national laws and international environmental legal frameworks that tend to regulate and curtail the incessant GasF, however, there has been a nonchalant attitude toward compliance with the existing international and national environmental legal framework [113]. Also, a study has revealed that poor and ineffective law enforcement institutional structure is a major cause of the continuous GasF in the NDN [114]. For example, the Ogoni community in the NDN that was severely polluted, given the flaring of gas, was awarded an environmental clean-up worth billions of dollars but has still not yielded any positive result [115].

Concerning the above, various environmental scholars have advised the Nigeria government, policymakers, and various stakeholders that there is a need to establish an effective GasF regulation and a good structure enforcement institution to coordinate the effective implementation of environmental law [108, 114]. Furthermore, it is also required that the Nigerian constitution should be revisited for an amendment to incorporate the enforcement of environmental rights as a core and fundamental right in Nigeria [116].

Therefore, appropriate action to avoid, diminish, and mitigate GasF will enhance AES, water safety, and an improved healthy environment. Also, this would contribute substantially to the adaptation and mitigation of CMC, the loss of biodiversity, and a decreased migration and conflict. Eventually, this is critical in meeting most of the MDGs and SDGs as stated in the Agenda 2030 for SDGs. In mitigating and reversing the present propensities in GasF, there is a prompt necessity to improve national capacities to assume computable assessments and steadily map the ensuing consequences, as required by the SDGs [103].

The World Bank, on its part, is working closely with the various governments and PTR companies in the areas of accessible technologies, developmental strategies and guidelines, and building of capacity to eliminate routine GasF by the year 2030. Also, they are continuing to secure commitments for the "Zero Routine Flaring by 2030" initiative, consolidating on the 78 various governments and PTR company advocates that, together, account for about 60.00% of global GasF. Eliminating routine GasF is critical if various governments and PTR companies are to deliver their products in the cleanest means possible, meet "zero emission" goals, and sustain their license to work, particularly in developing nations like Nigeria. The World Bank is committed to working in collaboration with the various governments and PTR companies to develop all-inclusive strategies and guidelines that will put a total end to GasF activities and practices [27].

7. GasF Reduction Approaches and Technologies

GasF is unavoidable in any chemical process owing to safety and control assessments. Hence, a substantial quantity of GasF has been experienced in several petroleum exploration regions globally. Various technologies and approaches, such as reinjection, power generation, pipeline NGas, liquefied petroleum gas, liquefied NGas, NGas hydrates, gas-to-liquid, compressed NGas, methanol and ammonia production, and the comparison of technology options, were noted for transforming the flare and other ANG into beneficial products [117]. These technologies and approaches, as well as the decision drivers for their selections, were painstakingly reviewed. The power generation appears to be a viable option for use in GasF recovery. Thus, this should be given the necessary consideration.

However, the main challenges in the application of these GasF recovery technologies are the economic limitations as well as structural and institutional difficulties. By mitigating these challenges and executing these GasF recovery technologies, regions such as the NDN can meaningfully decrease their environmental emissions and gain significant economic benefits.

The technologies for addressing the issues of GasF are presently in existence, and the required policy regulations are generally understood [23]. Despite some research, an estimated 150 bcm of NGas are flared globally each year, polluting the environment with approximately 400 million tons of CO_2 [117]. Having the required technologies and identifying the framework of the problem, what then stands as a storming block to taking this enormous and hitherto easy step in reducing these emissions? It appears like the universal community is still not doing the required homework when the key to such a prominent problem is so apparent, but is that the case? To this end, as suggested by Motte et al. [87] and Khalili-Garakani et al. [25], future research should similarly aim at the benefits of GasF reduction approaches and technologies to aid in the selection of the most auspicious approaches and technologies for the mitigation of GasF and its effects.

The increasing role of low-carbon hydrogen in the energy sector has led to innovative approaches for utilizing gas. Hence, a net-negative and self-sufficient multigeneration system for converting gas into hydrogen and deploying captured CO_2 for enhanced PTR recovery was recently proposed by Moosazadeh et al. [24]. Furthermore, they performed a comprehensive global comparative analysis for the three GasF-to-hydrogen generation set-ups in addressing the effect of CO_2 emission policies: autothermal reforming with CO_2 capture, autothermal reforming with CO_2 capture and enhanced oil recovery utilization, and autothermal reforming. Their results disclosed that the autothermal reforming with CO_2 capture and enhanced oil recovery utilization set-up is an auspicious carbon-reduction alternative, indicating an over 70% CO_2 capture rate. They concluded that the deployment of autothermal reforming with CO_2 capture in regions with high PTR could meaningfully diminish carbon emissions as well as the generation of hydrogen. Expectedly, the prevalent utilization of gas-to-hydrogen systems will assist in the mitigation of anthropogenic CMC. They, however, suggested that further studies should be conducted to explore the industrial feasibility plan.

8. Conclusions and Recommendations

This review study has attempted to evaluate the impacts of GasF on the environment vis-à-vis the possible nexus between GasF and CMC using the perspective from the NDN drawn from existing publications. Certainly, the continuous activities of PTR in the NDN are causing biodiversity loss, food shortage, health issues, GasF, petroleum spills, critical health issues, and other environmental complications which are believed to be instigating CMC. These concerns pose a great threat to humanity and deficiency to other natural resources and the entire ecosystem. The additional value of this review study comprises an all-inclusive, facile approach, suggestions, and recommendations toward addressing the complex issues of GasF and CMC in data-sparse NDN.

At present, the possibility of a permanent and perceptible solution to these consequences ensuing from the continuous activities of PTR in the NDN seems very slight. Although responsiveness is a fundamental groundwork for its extenuation, this will help in pushing for improved management of PTR in addition to the mitigation of the ensuing negative influences of GasF. Hence, investigating and releasing enhanced, biotic, and abiotic stress resilience as well as appropriate diversities across the ecosystem are two of the furthermost mitigations and adaptation strategies for CMC influences that need to be adopted globally. Consequently, diversities that could resist both biotic and abiotic stresses, as well as CMC, should be accessible on a large scale with suitable finance, strategy, and policy assistance. Also, employing cultivation procedures that raise agricultural productivity and ESS is required.

Additionally, more effective and advanced research on ecological necessities, vegetation, soil microorganisms, climate-smart agriculture, climate-resilient machineries, bioenergies, ecosystem-based CMC mitigation prospects, and adaptation traces, as well as the emphasis on the synergetic relationships between the host community and government/other stakeholders in the PTR business is critical. Also, research on public health evaluation on the contaminations caused by PTR as well as the wide-ranging utilization and application of bionanotechnological remediation (bioremediation) techniques should be regularly undertaken.

However, mitigating the cause of the flaring itself would be a better option. Hence, stopping flaring will be more effective than trying to clean the surrounding of the flare. The government and other stakeholders in the PTR business within the NDN need to put in more efforts that will support robust adaptation, pacification, and management of these negative consequences from PTR. Also, it is recommended that more reviews of successful mitigation cases worldwide should be undertaken in future research studies of this nature.

Conclusively, investment in how to keep reducing GasF is a necessity. GasF reduction plans and ventures could take years to get the required results, so plans that are presently undertaken will not bear the immediate required results. Hence, the time to take the necessary action is now; awareness alone is no longer sufficient. There must be a genuine drive from the seven topmost GasF nations to realize a dramatic change. Also, the national PTR companies should advance their efforts and determination, like those of the international PTR companies. To achieve this, there should be a test and scale-advanced approaches, while bearing in mind innovative solutions that treat ANG as a beneficial asset. Such advanced approaches should be tailored to the unique conditions and framework of a particular nation or even a precise PTR production location. Therefore, there should be a collaboration with the various governments and PTR companies in developing all-inclusive strategies and guidelines, putting into consideration a range of incentives and consequences in the form of penalties, for example, CO_2 and other gas emission taxes, that will put an end to the GasF issues.

Abbreviations

AES: Agricultural and environmental sustainability
ANG: Associated natural gas
bpd: Barrels per day
bcm: Billion cubic meters
CMC: Climate change
DPR: Department of Petroleum Resources
ESS: Environmental sustainability and safety
GasF: Gas flaring/gas flare
GW: Global warming
GHGs: Greenhouse gases
HC: Hydrocarbon
MSL: Mean seal level
NGas: Natural gas
NDN: Niger Delta region of Nigeria
PTR: Petroleum resource.

Data Availability

Completely, data produced or investigated during this work were involved in this submitted article.

Conflicts of Interest

There is no conflict whatsoever to declare.

Authors' Contributions

Ukhurebor, K.E., Aigbe, U.O., and Onyancha, R.U. were responsible for the conceptualization, investigation, methodology, project administration, resources, supervision, validation, writing—original draft, and writing—review and editing. Athar, H. was responsible for the supervision, validation, and writing—review and editing. Okundaye, B., Aidonojie, P.A., Siloko, B.E., Hossain, I., Kusuma, H.S., Darmokoesoemo, H were responsible for the writing—original draft and writing—review and editing. All authors contributed significantly to this review study.

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