A holistic study of the sustained impact of non-standard refined diesel fuel on the Niger Delta Region of Nigeria

Thesis by

Oyinkepreye Lucky Bebeteidoh

for the degree of Doctor of Philosophy

Faculty of Science, Agriculture & Engineering

School of Engineering

April 2022

Declaration

I declare that the contents of this thesis are my original work and have not been presented elsewhere for any other award.

Abstract

The non-standard refining of crude oil in the creeks of the Niger Delta Region of Nigeria has come to be a profitable business. The monetary benefits this brings to the refiners are obvious, nevertheless the host communities are relentlessly hit by their activities. This research investigates the sustained impact of the activities of the non-standard crude oil refiners on their host communities. The research will take a social study approach, with result from the social study fed into a scientific study, which will in turn be fed into an engineering study. This approach involves all stakeholders and makes for necessary feedback.

The results revealed that farming areas and fishing routes have been impacted by the activities of the non-standard refiners. The usage of the non-standard refined diesel fuel oil was found to be damaging to engines contributing to huge expense in their maintenance. The physiochemical properties of the non-standard refined diesel fuel oil revealed that the pour point, flash point, and water content showed differences to ASTM designated standard D975. The Gas Chromatography Mass Spectrometry (GC-MS) analysis revealed significant differences in the BTX concentration of the non-standard refined diesel fuel oils as compared to the control sample. The engine performance and emission analysis revealed high levels of oxides of nitrogen (NO_x) and carbon monoxide emissions from the non-standard refined diesel fuel oil coupled with high peak cylinder pressure.

This study provides evidence-based recommendations that the government should do more to discourage the citizens from establishing non-standard refineries. It also suggests that government agencies like the military given the responsibility of destroying the non-standard refineries must do so in a sustainable manner. The National Orientation Agency must do more to enlighten the public on the dangers of establishing non-standard refineries and purchasing refined products from non-standard refineries.

Dedication

To the almighty God, for his protection, guidance, and favour all through my PhD programme. He alone be praised.

To my wife, My Mummy as she is fondly called, Mrs Bosindoh Sarah Bebeteidoh that gave me the best children in the world. You stood by me all through my PhD journey, thank you.

To the memory of my late father, Chief Luckie Akpolagha Bebeteidoh and my beloved mother, Madam Florence Williams for bringing me up the right way and for investing in my early education.

To the 487 respondent who gave their consent and partook in this study, their contributions produced this thesis.

To the people of the Niger Delta Region of Nigeria who through no fault of theirs suffer daily from the activities of the non-standard crude oil refiners.

Acknowledgements

I would like to thank, Professor Samuel E. Edonmiekumoh the Vice Chancellor of Niger Delta University, Wilberforce Island, Bayelsa State, Nigeria, Professor Stanley Ogoun, the Director of Linkages and Advancements and the Tertiary Education Trust Fund (TETFund) for funding this research study without which my dream of a PhD would not have been possible.

My sincere gratitude goes to Dr Rose Norman and Dr Kayvan Pazouki my supervisors for their guidance, mentoring, constructive feedbacks, and patience although my PhD study. The feed backs I received at our biweekly meeting were very helpful in shaping this research. The feed backs from my panel members at every annual progression is also highly appreciated. I also want to extend my sincere appreciation to Rob Dixon, Paul Donhoe, Dr Rachel Dack, Phil Letouze, Ian Howard-Row and Thomas Knight all laboratory technicians who were all of great assistance. I would like to say thank you too Mr Paul Kennett, Mr Anthony Littlefair and Mr James Amero all of Intertek UK for their support. I would like to express my gratitude to the school administrators, school manager, deputy director and director of postgraduate studies in the School of Engineering for their support. Special thanks to the Academic staff of the Marine, Offshore and Subsea Technology Group for their support at one time or the other during my period of study.

I would like to say thank you to Mrs Ifiemi Tulagha-Ocholi and Mr Frank Briseimo for their support and assistance during the field work. Dr and Mrs Seimokumo Samuel Angaye, Mr Benjamin Joffa, Professor Ezenwa Ogbonnaya, Mr Edward Omemu, Mr Otigha Miriki, Miss Theodora Ovuru and all members of Nah We Bi Dis group for their financial support and prayers. I must thank my fellow PhD students in the Marine, Subsea and Offshore Technology Group, Mr Joshua Abam, Ms Tamara Topic, Mr Chen Li, and Mr Steve Ayodele Ebifemi for their valuable and worthwhile discussions we had during the period of this research.

Contents

Declaration ii
Abstract iii
Dedication iv
Acknowledgements v
List of publications xi
List of tables xii
List of figures xiv
List of acronyms xvi
Chapter 1 Introduction 1
1.1 Background of study 1
1.1.1 Scarcity of petroleum products in Nigeria 4
1.2 Statement of the problem 5
1.3 Scope of the problem 7
1.3.1 Environmental impact 8
1.3.2 Health impact 9
1.3.3 Economic and Community impact 10
1.4 Aim of study 12
1.4.1 Objectives of the study are: 12
1.4.2 Research question 13
1.5 Justification of the study 13
1.6 Achieved thesis objectives 13
1.7 Thesis structure 14
Chapter 2 Literature and Critical Review 16
2.1 Introduction 16
2.2 Crude Oil 16
2.2.1 Crude Oil in Nigeria 19
2.2.2 Crude Oil Refining in Nigeria 21
2.2.3 Non-Standard Refining of Crude Oil in Nigeria 21
2.2.4 Perspective of the Non-standard Refiners 22
2.2.4.1 Unemployment 23
2.2.4.2 Claim to oil resource 24
2.2.4.3 Relationship to community and other stakeholders 26
2.2.4.4 Economic model 29
2.2.5 Drivers of Non-Standard Refineries 29

2.2.6 Impact of Non-Standard Refining of Crude Oil in Nigeria 31
2.2.7 Crude oil Pollution 33
2.2.8 Regulation and Policy 37
2.3 Fuel Adulteration 39
2.3.1 Diesel Fuel Adulteration and Recent Detection Methods 41
2.3.1.1 Physicochemical properties 42
2.3.1.2 Chromatographic analysis 44
2.3.1.3 Infrared spectroscopy analysis 46
2.3.1.4 Sensor based techniques 48
2.3.1.5 Nuclear magnetic resonance spectroscopy 49
2.3.1.6 Other Related Adulteration Detection Methods 50
2.3.2 Effects of Fuel Adulteration on Engines and the Environment 52
2.4 Summary 53
Chapter 3 Research design 55
3.1 Introduction 55
3.2 Research gap 55
3.2.1 Novelty of the Research Study 56
3.2.2 Contribution to knowledge 58
3.2.3 Data sources 58
3.3 Study area 59
3.4 Data collection process 60
3.4.1 Questionnaire development 61
3.4.2. Pilot study 61
3.4.3 Administration of questionnaire instrument 62
3.4.4 Diesel fuel oil samples 65
3.5 Data analysis 65
3.5.1 Demographics 65
3.5.2 Summary statistics 65
3.5.2.1 Statistical Package for Social Sciences (SPSS) 66
3.5.3 Physicochemical properties analysis 67
3.5.3.1 Fourier Transform Infrared Spectroscopy (FTIR) 67
3.5.3.2 GC-MS analysis 67
3.6 Summary 68
Chapter 4 Sustained Impact Assessment of the Activities of the Non-standard Crude Oil Refiners on their Host Communities 69
4.1 Introduction 69

4.2 Study methodology ... 69
4.2.1 The questionnaire instrument ... 69
4.2.3 Environmental impact statements ... 70
4.2.4 Implementation and participants in the study ... 71
4.3 Results ... 72
4.3.1 Demographics of the respondents and survey responses ... 72
4.3.2 Response to the six environmental questions, S1 to S6 ... 74
4.3.3 Responses to the six usage questions, S7 to S10 ... 75
4.3.4 Factor analysis ... 75
4.3.5 Association between demographic factors and environmental impact statements ... 81
4.3.6 Association between demographic factors and usage impact statements ... 81
4.3.7 Correlation (Spearman rho) amongst environmental impact and usage impact statements ... 84
4.4 Discussion ... 86
4.5 Summary ... 88
Chapter 5 Analysis of Physicochemical Properties of Non-standard refined diesel fuel oils ... 90
5.1 Introduction ... 90
5.2 Significance of physicochemical properties ... 90
5.3 Experimental methods ... 91
5.3.1. Test fuels ... 91
5.3.2. Density measurement ... 91
5.3.3 Kinematic viscosity measurement ... 92
5.3.4 Flash point measurement ... 92
5.3.5 Pour point measurement ... 93
5.3.6 Water content ... 93
5.3.7 Cetane index ... 93
5.3.8 Distillation curves ... 94
5.3.9 Calorific value ... 94
5.4 Results ... 95
5.4.1 Fuel properties ... 95
5.5 Discussion ... 101
5.6 Summary ... 103
Chapter 6 Gas Chromatography Mass Spectrometer and Fourier Transform Infrared Spectroscopy ... 104
6.1 Introduction ... 104

6.2 Experimental methods 104
6.2.1 Test Fuels 104
6.2.2 Gas chromatography Mass spectrometry (GCMS) analysis 104
6.2.3 Quantification of Volatile Organic Compounds (VOCs) 106
6.2.4 Fourier transform infrared analysis 110
6.3 Results 110
6.3.1. GC-MS Analysis 110
6.3.2 FTIR analysis 117
6.4 Discussion 120
6.5 Summary 123
Chapter 7 Performance and combustion characteristics 124
7.1 Introduction 124
7.2 Experimental methods 124
7.2.1 Experimental setup and procedure 124
7.3 Results 128
7.3.1 Brake thermal efficiency (BTE) 128
7.3.2 Brake specific fuel consumption (BSFC) 130
7.3.3 Cylinder pressure 131
7.3.3.1 Maximum cylinder pressure 134
7.3.4 Exhaust gas temperature 135
7.3.5 Oxides of nitrogen (NOx) emissions 136
7.3.6 Carbon monoxide emissions (CO) 137
7.3.7 Carbon dioxide emissions (CO_2) 138
7.4 Discussion 139
7.5 Summary 143
Chapter 8 Conclusions, Recommendations, and Future Research 144
8.1 Introduction 144
8.2 Novelty of the study 144
8.3 Summary of findings 145
8.4 Recommendations 146
8.4.1 Remediation of affected soil, water 147
8.4.2 Fish restocking and water supply 147
8.4.3 Enforcement and funding 148
8.4.4 Public enlightenment 148
8.4.5 Establishment of mini refineries 149
8.4.6 Legal Framework 150

8.4.7 Revamping and construction of more floating fuel stations ... 150
8.4.8 Maintenance of existing refineries ... 150
8.4.9 Infrastructural development of the Niger Delta ... 150
8.5 Further research ... 151
8.5.1 What is the level of VOCs in the exhaust emission from engines? ... 151
8.5.2 What is the ambient level of VOCs around the host communities? ... 151
References ... 152
Appendix A: Study questionnaire ... 186
Appendix B: Study questionnaire ... 187
Appendix C: Diesel Fuel Oil ... 198
C.1 Diesel Fuel Physical and Chemical Properties ... 200
C.1.1 Density ... 202
C.1.2 Kinematic Viscosity ... 202
C.1.3 Cetane Number ... 203
C.1.4 Pour Point (PP) ... 203
C.1.5 Flash Point ... 204
C.1.6 Water Content ... 204
C.1.7 Calorific Value ... 205
C.1.8 Distillation Range ... 205
Appendix D: Diesel Engine Analysis ... 206
D.1 Engine analysis ... 206
D.1.1 Brake Specific Fuel Consumption ... 206
D.1.2 Brake Thermal Efficiency ... 206
D.1.3 Cylinder Pressure ... 207
D.2 Emissions ... 208
D.2.1 NO_x Emissions ... 208
D.2.2 Carbon Monoxide ... 209
D.2.3 Carbon Dioxide ... 210
D.2.4 Exhaust Gas Temperature ... 210

List of publications

This thesis has been carried out at the Marine, Offshore and Subsea Technology Group of the School of Engineering, Newcastle University, United Kingdom.

The Publications includes:

Peer Reviewed Journals

1. Bebeteidoh, O.L., Pazouki, K., Norman, R., 2020. An experimental investigation of the physio-chemical properties of locally refined diesel oil. Sustainable Chemistry and Pharmacy 15, 100200. https://doi.org/10.1016/j.scp.2019.100200

2. Bebeteidoh, O.L., Kometa, S., Pazouki, K., Norman, R., 2020. Sustained impact of the activities of local crude oil refiners on their host communities in Nigeria. Heliyon 6, e04000. https://doi.org/10.1016/j.heliyon.2020.e04000

Publications Under Review

1. Diesel Fuel Adulteration Issues in Nigeria (Scientific African Journal, Elsevier)

Conference Attendance with Presentation

1. 5^{th} Edition of the Global Conference on Catalysis, Chemical Engineering and Technology, London. September 16-18, 2019

List of tables

Table1-1: Refineries in Nigeria……………………………………………………………4

Table 2-1: Crude oil fractions……………………………………………………………18

Table 2-2: Critical air pollutants in the Niger Delta Region of Nigeria………..….20

Table 2-3: Contaminants associated with crude oil production and their potential health effects………………………………………………………………………………37

Table 4-1: Demographics of respondents.………………….……………………….73

Table 4-2: Effect of non-standard crude oil refiners on the environment……..…77

Table 4-3: Summary statistics of the six environmental statements……………..78

Table 4-4: Effect of non-standard crude oil refined diesel fuel on machine/engines……………………………………………………………………………79

Table 4-5: Summary statistics of the four usage statements……………………...80

Table 4-6: Chi-Square association between demographic factors and environmental impact statements……………………………………………………….83

Table 4-7: Chi-Square association between demographic factors and usage impact statements…………………………………………………………………………………84

Table 4-8: Correlation matrix of environmental impact statements……………….86

Table4-9: Correlation matrix of usage impact statements…………………………86

Table 5-1: Specification of a KEM DA 500 automatic density meter…………….92

Table 5-2: Seta flash Series 3 Flash Point Tester………………………………….92

Table 5-3: Physiochemical properties of the diesel fuels…………….……………97

Table 5-4: The percentage difference in the water content……………………...101

Table 6-1: Infrared vibrational groups of diesel fuel………………………………110

Table 6-2: List of BTX (Benzene, toluene, and xylenes), n-Alkanes, and their concentration in $\mu g\ g^{-1}$…………………………………………………………………118

Table 6-3: The percentage difference of BTX between the non-standard refined diesel fuel oils and the control sample……………………………………….……….122

Table 7-1: Specification of the test engine……………………………………...126

Table 7-2: Specification of the Kistler 5018A single-channel charge amplifier...127

Table 7-3: Specification of the GDS-1102A-U Digital Storage Oscilloscope…..127

Table 7-4: Specification of Testo 350 exhaust gas analyser…………………….128

Table 7-5: % BTE at full load……………………………………………...……..130

Table 7-6: Brake specific fuel consumption at all load conditions………………131

Table 7-7 Exhaust gas temperature at full load…….…………………..………136

Table 7-8: NO_x emission at full load in ppm………………………………………137

Table 7-9: CO emission at part load (0.12kW) and full load (1.71kW) in ppm…138

Table 7-10: CO_2 emission at part load (0.12kW) and full load (1.71kW) in %....139

Table 7-11: The percentage difference in NOx emission at full load condition…141

Table 7-12: The percentage difference in CO emission at initial load condition of 0.12kW……………………………………………………………………………142

Table C1-1 Various grades of distillate fuel oil…………………………………….199

Table C1-2 Key properties of standard diesel fuel oil…………..………………..201

List of figures

Figure 1-1: Cross section of a non-standard crude oil refinery……………………2

Figure 1-2: Customers queuing to buy petroleum products as a result of product scarcity in the Federal Capital Abuja, Nigeria……………………………………......4

Figure 1-3: Petroleum scarcity; Large queues at retail outlets and black-market trade………………………………………………………………………………………5

Figure 1-4: Yields from non-standard crude oil refineries…………………………...6

Figure 2-1: A typical example of a non-standard refinery…………………………..22

Figure 2-2: NNPC floating Mega station…………………..………………………....30

Figure 2-3: A labourer feeds a fire with crude oil at a non-standard refinery…….32

Figure 3-1 Proposed method………………………………………………………….57

Figure 3-2: Research study approach………………………………………………..58

Figure 3-3: Crude oil installations in the Niger Delta………………………………..60

Figure 3-4: States of the Niger Delta…………………………………….…….….….60

Figure 3-5: Ologbobiri community in Southern Ijaw Local Government Area of Bayelsa State, Nigeria…………………………………………………………….....64

Figure 3-6: Akinima and Okarki communities in Ahoda-West Local Government Area of Rivers State, Nigeria……………………………………………………….....64

Figure 4-1: Scree plot of eigenvalues against all the factors………………………76

Figure 5-1: Density of test fuel samples……………………………………….......98

Figure 5-2: Kinematic viscosity of fuel samples…………………………………....98

Figure 5-3: Pour point of test fuel samples…………………………………………99

Figure 5-4: Cetane index of test fuel samples…………………………….……….99

Figure 5-5: Water content of test fuel samples with the red line representing the ASTM 975 limit of 200 mg kg^{-1} ……………………………………………………100

Figure 5-6 Calorific value of test fuels……..……………………………………….100

Figure 6-1: An Agilent 7890B GC linked to an Agilent 5977B MS and an Agilent Z240 computer……………………………………………………………………105

Figure 6-2: Calibration curve of Benzene………………………………………...106

Figure 6-3: Calibration curve of Toluene……………………………………...….107

Figure 6-4: Calibration curve of p-Xylene………………………………………...107

Figure 6-5: Calibration curve of m-Xylene………………………………………..108

Figure 6-6: Calibration curve of o-Xylene………………………………………..108

Figure 6-7: Calibration curve of nC_8……………………………………………109

Figure 6-8: Calibration curve of nC_{13}…………………………………………...109

Figure 6-9: Representative chromatograms of NRD sample…………….….115

Figure 6-10: Infrared spectra of all test samples………………………………...119

Figure 7-1: Experimental setup…………………………………………….….…..126

Figure 7-2: Brake Thermal Efficiency (BTE)…………………………………..….129

Figure 7-3: Brake Specific Fuel Consumption (BSFC)…………………………131

Figure 7-4: Cylinder Pressure…………………………………………………….132

Figure 7-5: Cylinder Pressure…………………………………………………….133

Figure 7-6: Maximum cylinder pressure…………………………………….……134

Figure 7-7: Exhaust Gas Temperature (EGT)……………………………….....135

Figure 7-8: Oxides of Nitrogen (NO_x)…………………………………….……136

Figure 7-9: Carbon monoxide (CO)……………………………………………....137

Figure 7-10: Carbon dioxide (CO_2) ……………………………………….…...139

Figure C1-1 Petroleum products made from a barrel of crude………………..200

List of acronyms

ASTM	American Society of Testing and Materials
ATR	Attenuate Total Reflection
BPSD	Barrels Per Stream Day
DEE	Diethyl ether
DPR	Directorate of Petroleum Resources
EGT	Exhaust gas temperature
FTIR	Fourier Transform Infrared
GDP	Gross Domestic Product
GHG	Green House Gas
GLSW	Generalised Least Square Weighting
GV	Gaseous Vapour
HPLC	High Performance Liquid Chromatography
HRMS	High-resolution Mass Spectrometric Analysis
ISO	International Organization for Standardization
JTF	Joint Task Force
NAF	Nigerian Air Force
NDR	Niger Delta Region
NEMA	National Emergency Management Agency
NESREA	National Environmental Standards and Regulations Enforcement Agency
NMR	Nuclear Magnetic Resonance
NNPC	Nigerian National Petroleum Corporation
NOSDRA	National Oil Spill Detection and Response Agency

NRD	Non-Standard Refined Diesel
OPEC	Organisation of Petroleum Exporting Countries
OSC	Orthogonal Signal Correction
PAH	Polycyclic Aromatic Hydrocarbon
PLS	Partial Least Square
POS	Point of Sale
SVM	Support Vector Machine
Tcf	Trillion Cubic Feet
TPH	Total Petroleum Hydrocarbon
ZnSE	Zinc Selenide

Chapter 1 Introduction

"The gasoline, kerosene and diesel come out as only one product which is diesel. There is no way we can separate them, so all the products will form into diesel and that is all we are after. After diesel has been extracted, other possible products are discharged through pipes as waste"- (Owolabi, 2018)

1.1 Background of study

Nigeria is the largest crude oil producer in Africa (Olujobi and Ousola-Olujobi, 2020) and has the largest proven reserves of natural gas in Africa (Gungah et al., 2019)., and is a prominent member of the organization of petroleum exporting countries (OPEC) (Itsekor, 2020). Nigeria produces 2.5 million barrels of crude oil per day (Babatunde, 2020). The Nigerian economy depends majorly on foreign exchange derived from the sale of crude oil (Olalekan and Adebiyi, 2020). According to Bodo and Gimah (2020) about 90% of Nigeria's earnings come from the sale of crude oil. The petroleum sector contributes over 11% to the Gross Domestic Product (GDP) of the nation (Onyena and Sam, 2020). Most of this crude oil deposits are found in the Niger Delta Region (NDR) of Nigeria (Babatunde, 2020). This vast crude oil deposit consists of 606 oil fields of which 251 are situated offshore and 355 are onshore with about 7,000km of crude oil pipelines (Onyena and Sam, 2020).

The natural environment of the NDR which the people depend on for their sustenance and livelihood, is being destroyed daily (Babatunde, 2020).The process of the extraction and refining of the large deposits of crude oil located in the NDR, has led to damaging environmental pollution in communities hosting crude oil flow stations and non-standard refineries. "The non-standard refinery employs simple and rudimentary procedure to produce refined products by subjecting large drums of crude oil to heat from open fire" (Onakpohor et al., 2020), see Figure 1-1. The spills from government owned pipelines and non-standard refineries has become a recurrent situation leading to devastating effects on the aquatic ecosystem (Luke and Odokuma, 2021). Surface water bodies are being destroyed by the non-standard refineries springing up in various communities in the NDR (Imoobe and Aganmwonyi, 2021). The air quality around host communities of non-standard refineries has also suffered. Onakpohor et al. (2020) reported that non-standard refineries are a source of air pollution that affects the environment of their host communities. The mangroves of the NDR are also disappearing rapidly as a result of crude oil pollution. According to Onyena and Sam (2020) 60% of fish breed in the mangroves of the NDR. Thus, the sustained impact from pollution on the mangroves from crude oil and its refinery waste products will affect fish distribution, cultural services, aesthetics, and spiritual enrichment (Onyena and Sam, 2020).

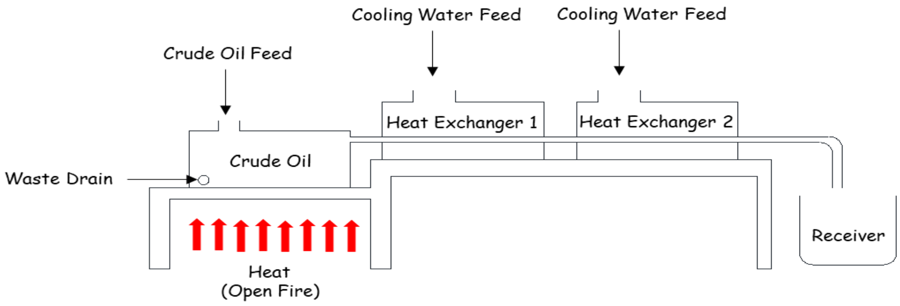


Figure 1-1 Cross section of a non-standard crude oil refinery

As a nation develops so its demand for petroleum products increases (Curl and Donnell, 1977). Countries all over the world, need petroleum products for the smooth running of their industries, power sector and transportation (Akpoghomeh and Badejo, 2006). Although, some nations have started looking beyond fossil fuel because of its level of emission from exhaust and depleting nature and moving into the use of biofuel and biodiesel because it reduces carbon footprint and greenhouse gas emissions (Gowda et al., 2021; Mathew et al., 2021), Nigeria still depend solely on fossil fuel because of the economic benefits accruing to the nation to the detriment of the environment. There is a precipitous rise in the demand for petroleum products in Nigeria, due to her rapid population growth, local technology inventions, and increase in small scale industries (Adewuyi, 2016; Adewuyi, 2020). This demand is high in Nigeria because of her population which is about 200 million people (Adewuyi, 2020). Daily consumption of refined crude oil products in Nigeria as of 2016 was about 428,000 barrels per day (Worldometer, 2017). Nigeria consumes over three billion litres of diesel fuel oil, seventeen billion litres of gasoline, and 400 million litres of aviation fuel annually (Omontuemhen, 2018). According to Ogbuigwe (2018), the combined demand for petroleum products in Nigeria as of 2017 was equal to 750,000 barrels per stream day (bpsd).

The four government owned refineries have an overall installed refining capacity of 445,000 barrels of crude oil per day (Kadafa, 2012; Waheed *et al*., 2014) while the only privately owned refinery in Nigeria has a refining capacity of 1,000 barrels of crude oil per day (DPR, 2021). The government owned refineries have had a poor operational record over the past 15-20 years with an average capacity utilization of around 15% per annum (Ogbuigwe, 2018). The privately owned refinery refines diesel fuel oil for its internal use with excess sold in its immediate locality (DPR, 2021).

Although, the government owned refineries' designed refining capacity is 445,000 barrels per day (bpd), low refining yield has been recorded leading to scarcity of various refined products (Mamudu et al. 2019). Obasi et al. (2017) and Itsekor (2020) reported that with the installed capacities of all the refineries, this is still less than 40% of the daily national consumption requirement. Furthermore, the relatively low production capacity is hampered by operational shortcomings and lack of adequate maintenance (see Table 1-1) (Obasi et al., 2017). Olujobi (2021) reported that poor maintenance of the refineries frequently leads to their breakdown and therefore to supply shortages causing fuel scarcity. This deficit in supply relative to demand is bridged by the import of refined petroleum products (Ogbon et al., 2018). More than 90% of petroleum products consumed in Nigeria are imported from other countries because the refineries are not working to full capacity (Obasi et al., 2017).

Table 1-1 Refineries in Nigeria (EIA, 2021)

Refinery Name	Location	Status
Kaduna	Kaduna	Under maintenance
Port Harcourt 1 and 2	Rivers	Under maintenance
Warri	Delta	Under maintenance
Ogbele	Rivers	Active

1.1.1 Scarcity of petroleum products in Nigeria

The scarcity of petroleum products (see Figure 1-2) drives up prices, with government licensed retail outlets selling refined petroleum products like diesel, and gasoline above the designated pump price.

Figure 1-2 Customers queuing to buy petroleum products as a result of product scarcity in the Federal Capital Abuja, Nigeria (BBC News, 2021).

According to Ogunleye (2016) angry motorist queued overnight at fuel retail outlets across Nigeria, with cars and trucks blocking traffic in the commercial city of Lagos. Individuals who need diesel, gasoline, or kerosene to power their generators, stoves, and outboard marine engines, including unlicensed retailers are not left out (Dunmade, 2019) as shown in Figure 1-3. The quality of petroleum products sold by unlicensed operators on the black market are of questionable quality as many peddlers usually adulterate them with other products to make more profit (Dunmade, 2019).

Figure 1-3 Petroleum scarcity; Large queues at retail outlets and black-market trade (Elendu, 2017; Business Day, 2016)

The consistent scarcity of refined petroleum products in Nigeria has led her citizens to look for cheaper products to buy to power their engines (cars, trucks, generators, and boats). The shortfall in supply and steep rise in prices is now met by products from non-standard refineries in the NDR of Nigeria (Onakpohor et al. 2020). The Directorate of Petroleum Resources (DPR) the agency saddled with the responsibility of overseeing petroleum products quality in Nigeria warned the public in 2015 of the presence of adulterated petroleum products used for both domestic and automobile like diesel, kerosene, and gasoline in circulation causes explosion (Glory, 2016).

1.2 Statement of the problem

The Niger Delta Region of Nigeria today, finds itself awash with non-standard refineries, which refine crude oil, for local sale and consumption, using basic technology (Katsouris and Sayne, 2013). According to Balogun (2015) some oil is transported to small scale undeveloped refineries in the mangroves and creeks, where it is boiled to produce low grade diesel fuel. The refined products are sometimes blended with properly refined products such as diesel and gasoline and sold to fuel retail outlets and other suppliers of refined petroleum products in the

NDR (Katsouris and Sayne 2013). Figure 1-4 shows refined petroleum product yields from non-standard refineries. The non-standard refining of crude oil, comes with a damaging effect for the economy, the environment and host communities (Anifowose et al., 2014; Yeeles and Akporiaye (2016). While research has been carried out in the areas of the economic effect of sabotaged to crude oil pipelines in Nigeria's NDR, the effect on the ecosystem (causing spillage, both on land, in rivers and the sea) of the region and national security, there is a dearth of research on the sustained impact of the activities of the refiners on their host communities coupled with the effect of the non-standard refined products, on marine craft, diesel generators, ships and tugs and their resultant emissions on the environment of the Niger Delta Region.

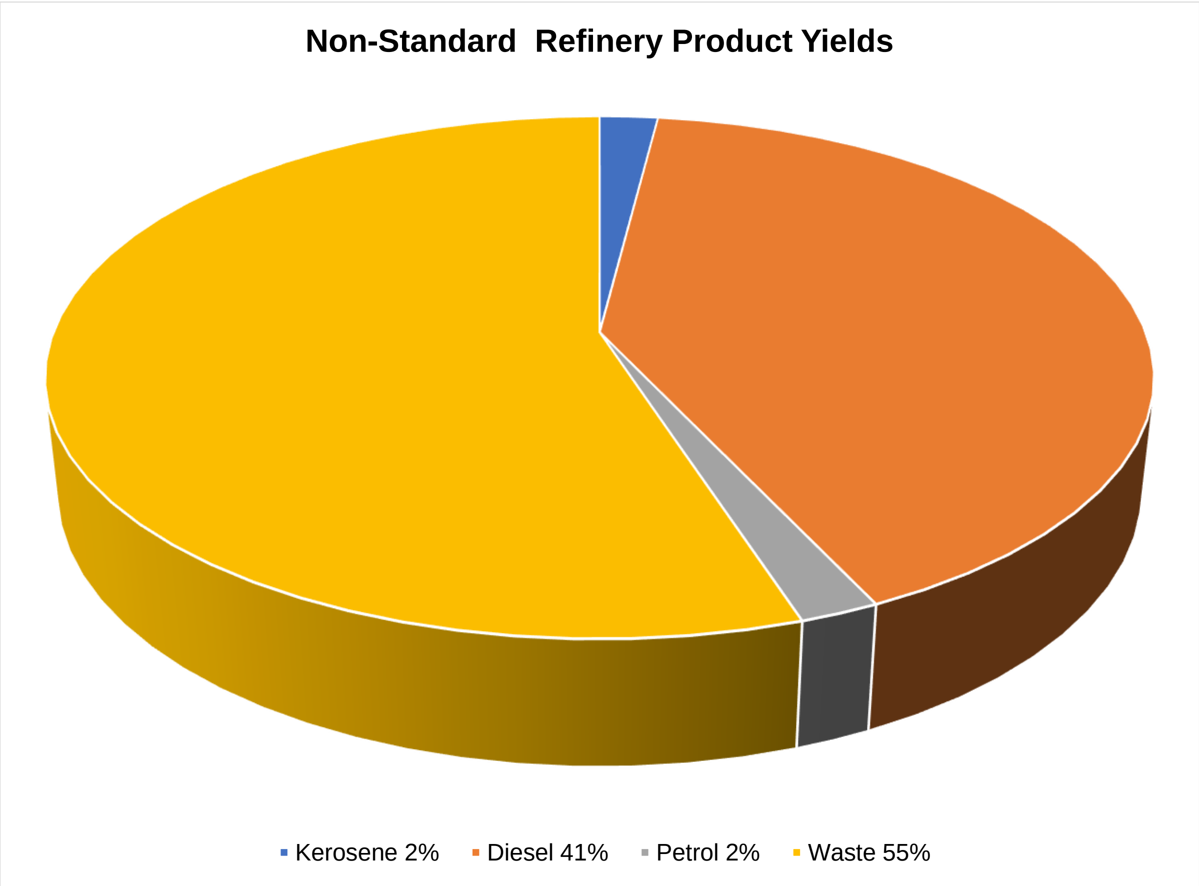


Figure 1-4 Yields from non-standard crude oil refineries (Network, 2013)

1.3 Scope of the problem

The non-standard refining of crude oil in the NDR of Nigeria has brought about several challenges to the government, people and the environment of the region. Onuh et al. (2021) and Okafor et al. (2021) reported that the increase of non-standard refineries in the NDR has resulted in untold adverse effects on the environment with related long-term impacts on the atmosphere, biosphere, hydrosphere and litosphere. This section decribes the environmental, community, health and economic impacts of the activities of the refiners. According to Nwogwugwu et al. (2012) while crude oil is the blood of the Nigerian economy, it has failed to translate into development and regional prosperity in the Niger Delta. Instead, the region has been rewarded with political and economic marginalisation coupled with massive environmental degradation.

According to Agbonifo (2022) the allocation of resources by the Nigerian state is heavily skewed against communities in the region where oil is produced, which led to violence of unimaginable proportions. The non-standard refining of crude oil in the NDR could be traced to the agitation of the people againts the allocation of resources and the degredation of their environment as a result of oil exploration and exploitation (Asimiea and Omokhua, 2013). Onuh et al. (2021) reported that the lack of development in communities hosting crude oil facilities in the region and environmental pollution connected with its production remains the basis for the anti-state mobilisation which manifested in the form of militancy, crude oil theft and non-standard refining. The conflict began as a peaceful protest with the Ogoni people under the aegis of the Movement for the Survival of the Ogoni People (MOSOP), but as the Nigerian government responded with repression, the resistance became radicalised and widespread in other places in the Niger Delta (Naanen, 2019). The agitation came to a climax with open armed confrontation against the Federal Government of Nigeria between 1999 and 2009 (Asimiea and Omokhua, 2013). The resistance from the Niger Delta Youths fractured the steady production of crude oil in Nigeria which also affected the country's external reserves (Ugor, 2013).

However, when repression failed the government introduced reforms that gave birth to the Presidential amnesty programme. The amnesty program ensured that agitators dropped their armed struggle against the Nigerian state. This enabled the government, through the oil multinationals to increase its crude oil production capacity and raise oil profits that were almost grounded by the agitators (Ugor, 2013). Borne out of the agitation for resource control was the rise in theft of crude oil and other petroleum products like condensate from oil well heads and crude oil pipelines (Ogbuigwe, 2018). The illegal activities of the non-standard refiners like sabotage of oil pipelines leading to oil spills and the transportation of the crude oil in open boats to their refining sites have been very harmful to the environment (Gundlach et al., 2021). The process of the non-standard refining incurs careless wastage of crude oil, with refining waste dumped haphazardly on land, and in streams, rivers, and mangroves, leading to severe damage to the environment and public health (Onuh et al., 2021).

The waste management process of the non-standard refiners is also of major concern. Howard et al. (2021) reported that the harmful use of crude oil by sabotaging crude oil facilities for financial gains through their crude refining process and continuous discharge of petroleum products into the environment with absolute disdain for the safety of the environment of the Niger Delta is a major burden. The crude refining process has led to outbreaks of fire, explosion, and emission of dangerous gases; with dozens of lives lost every year at non-standard refinery sites (Onuh et al., 2021). The economic and environmental sustainability of the people of the Niger Delta has been threatened by the activities of the non-standard refiners (Babatunde, 2020). An unsoiled and sustainable environment is vital to the overall wellbeing and development of the Niger Delta people (Nriagu, 2011).

1.3.1 Environmental impact

Oil pollution in the Niger Delta impacts the total environment (i.e., water and land), biodiversity and public health (Sam et al., 2022). The sustainability of the environment is critical to human security of not only the present but also the future generations (Babatunde, 2020). Serious environmental hazards have been credited to crude oil exploration and exploitation, largely arising from the discharge of wastes, atmospheric emissions, oil spills, gas flares, and deck drainage (Adeola et al., 2022). In addition, damage is caused as a result of the close proximity of the non-standard refineries to water bodies particularly wetlands, mangroves, and estuaries (Chikere et al., 2020). A major impact of the non-standard refining of crude oil in the NDR is in its environment. Crude oil refining contributes liquid, solid and gaseous waste to the environment (Obenade and Amangabara, 2014). Over 1300 distinct chemicals could be emitted into the environment as a result of crude oil exploration and exploitation (Orisakwe, 2021). These chemicals which are of public health and ecological concerns includes biocides, oxygen scavengers, Polycyclic Aromatic Hydrocarbons (PAHs), Volatile Organic Compounds (VOCs), particulate matters, and heavy metals (Orisakwe, 2021). Hydrocarbon contamination is commonplace as a result of more than five decades of exploitation, poor oil spill response regime, and acute incidents (Sam et al., 2022; Iturbe-Espinoza et al., 2022).

With huge smoke plumes above non-standard refineries all day, those involved in the refining process and the surrounding communities are at high risk of exposure to extreme hydrocarbon levels which could have prolonged and acute effects on human and animal health (Onuh et al., 2021). The method of waste disposal at the non-standard refineries directly affects the surface and ground water, aquatic life, and farmlands.

1.3.2 Health impact

In many developing economies of the world, crude oil could be described as the bitter-sweet crude for its double-edged impact on the wellness and welfare of the people (Orisakwe, 2021). Ukhurebor et al. (2021) reported that spills from crude oil have been identified as a major factor responsible for most of the environmental imbalance and health conditions in some of the Niger Delta communities as a result of pollutants released into the environment. Ana et al. (2009) reported that human exposure to dangerous air pollutants emitted during the incomplete combustion of stoked flames from non-standard refineries and gas flares from crude oil flow stations are known to impact human health, with effects which include cancer, neurological, reproductive, and developmental effects. Respiratory ailments, skin lesions, cancer, food poisoning, loss of arable land, and other livelihood structures of riverine and coastal communities have all been attributed to oil spills, illegal bunkering, theft, and crude oil exploration (Onyena et al., 2021). Crude oil hydrocarbon contamination of water and soil resources is of serious environmental concern posing health risks for humans because of their mutagenic and carcinogenic properties (Lubi and Akinluyi, 2022). Hydrocarbons from fossil fuel contains the most ubiquitous pollutants such as polycyclic aromatic hydrocarbons (PAHs), volatile organic compounds (VOCs): benzene, toluene, ethylbenzene, and xylenes (BTEX) (Lubi and Akinluyi, 2022). Benzene is a carcinogen, a known cause of leukaemia and other blood related disorders (Ana et al., 2009). Also, BTEX such as toluene are repeatedly connected with the problems of the central nervous system, leading to symptoms such as fatigue, headaches, and dizziness (Ite et al., 2018). High levels of exposure to PAHs cause symptoms such as vomiting, nausea, and skin irritation, with exposure during pregnancy associated with impaired child development and reduced birth weight (Ite et al., 2018).

The quality of drinking water is very important for the health and wellbeing of the Niger Delta people, but pollution from crude oil is a major hinderance. According to Ite et al. (2018) the low molecular weight PAH, naphthalene detected in water samples from Ogale community in Rivers State, Nigeria could adversely affect the hematopoietic system, damaging and killing red blood cells, and causing symptoms such as fatigue and shortness of breath.

1.3.3 Economic and Community impact

The Niger Delta Region is a highly sensitive ecological zone (Asimiea and Omokhua, 2013), situated in parts of the tropical rain forest, and the saltwater and freshwater mangrove swamps in Nigeria. The traditional lifestyle of the people makes them vulnerable to crude oil pollution (Nriagu, 2011). The local population get many goods from the mangroves and tropical rain forest such as wood for construction, firewood, yam staking scaffolds, honey, fish, boat building materials, farm produce etc. (Zabbey et a., 2019). According to Babatunde (2020) the region is rich in cash crops, such as cocoa, rubber, coconuts, oil palm, and food crops such as yam, cassava, and plantain. However, in their comparative study on childhood malnutrition and household food security in the rural and urban areas of the Niger Delta, Ordinioha and Brisibe (2013) reported that there is a major statistical difference in the level of food security between households in rural and urban communities. The latter is statistically more food secure, with reduced childhood malnutrition. Babatunde (2020) argued that a 60% decline in household food security and a 24% increase in the prevalence of childhood hunger and malnutrition could be attributed to pollution from crude oil. This was alluded to by Adow (2012) writing for Aljazeera News where the reporter "found out that fishing and farming, the two main economic activities in the oil-rich Niger Delta, are now all but abandoned. Frequent oil spills have depleted fish species in rivers and streams while millions of hectares of farmlands lie wasted by oil pollution and contamination".

An important need for the sustenance of life and good health is water (Owamah et al., 2020). The people of the region depend mainly on the rivers and swamps for bath water, drinking water and water for other domestic purposes. However, the major source of drinking water and water needed for irrigation is continually polluted (Nriagu, 2011) by run-off water from non-standard refinery sites. Fisheries in the Niger Delta contribute immensely to food security by acting directly as a source of important nutrients or as a source of revenue for riverine, and coastal communities that depend mainly on the resource for subsistence (Okafor-Yarwood, 2018). However, oil pollution kills fish, fish larvae, food sources, and destroys the capability of fish to reproduce, causing both immediate, and long-term damage to fish stocks (Nriagu, 2011).

Crude oil spills from pipeline interdiction affects farmlands, the environment of the Niger Delta, and the economy of the nation. According to Umar et al. (2021) pipeline interdiction is the "hostile situation whereby a certain commodity or goods is prevented from movement from one place to another by certain aggrieved individuals". The researchers identified the key actors as vandals, amateur bunkers, and sophisticated bunkers. They argued that, while the vandals carry out their acts of sabotage of oil facilities as a means to punishing the oil multinationals and government for years of neglect of their communities, both the amateur, and sophisticated bunkers do it for the purposes of economic gain. Pipeline interdiction takes place because, locals look for ways to bribe the authorities charged with responsibilities to monitor the crude oil transportation pipelines of the nation (Ikezam et al., 2021).

The money generated from non-standard refineries is believed to aid the development of host communities and directly sustain families (Ikezam et al. 2021). The refined products of diesel, kerosene, and gasoline are sold to the public as quality products. The products are not only sold to individuals, but they are also sold to fuel retail outlets. According to Yafugborhi (2019) independent petroleum marketers in Rivers State, Nigeria for two years depended on diesel fuel oil refined at non-standard refineries to run their product delivery trucks which had taken a severe toll on their livelihood and business. Also, Emmanuel (2013) reported that if you buy diesel in Lagos (the commercial nerve centre of the economy), or in the Niger Delta region there is a likelihood that you bought a non-standard refined diesel fuel oil.

1.4 Aim of study

The aim of this research is to carry out a detailed investigation into the sustained impact of the activities of non-standard crude oil refiners on their host communities and the effect of the refined diesel fuel oil on diesel engines, and the resultant emissions on the environment of Nigeria's NDR. To meet the study aim, the thesis will address the objectives listed in subsection 1.3.1 and the research questions listed in subsection 1.3.2.

1.4.1 Objectives of the study are:

1. Presentation of a thorough literature and critical review; methodology setup; case studies and presentation of associated results
2. To carry out a sustained impact assessment of the activities of the non-standard refineries on their host communities
3. To determine the physiochemical properties of the NRD (non-standard refined diesel) fuel oils
4. To determine the volatile organic compounds (VOCs), present in the NRD fuel oils.
5. To determine the performance and combustion characteristics of the NRD fuel oils on diesel engines.

1.4.2 Research question

What are the implications of the activities of the non-standard refiners in the NDR for their host communities and the environment and what is the difference in terms of standard parameters between the Nigerian refined diesel from the NRD fuel oil and the effect of those differences on engine performance and emissions?

1.5 Justification of the study

The damage done to government infrastructure, the people and the environement of the NDR are enormous. Detailed information on the scale of the damage to the environment, coupled with the loss of revenue from farmers, fishermen/fisherwomen, and the people who make use of the non-standard refined products for their engines, will help the government to develop policies and also help stakeholders to guard against the losses resulting from reduced farm/fishing yields. Several researchers have studied the economic effects, the security challenges, the remediation of damaged soils, the pollution of water bodies, and emissions from non-standard refineries (Onakpohor et al., 2020; Ogbon et al., 2018; Luke and Odokuma, 2021; Babatunde, 2020; Ogele and Egobueze, 2020; Nwozor et al., 2020; Onyena and Sam, 2020; Ugboma et al., 2020; Igben, 2021). while this research will take a holistic approach in addressing the issue of the sustained impact of the non-standard refining of crude oil on the host communities, the effect of the refining process on the environment, the quality of the refined diesel fuel oil, the consistency in the refining process and the effect of the refined diesel fuel oil on the performance of internal combustion engines.

1.6 Achieved thesis objectives

The thesis objectives, as detailed in subsection 1.4.1, were all successfully met. The first objective as detailed in Chapter 2 was to present a thorough literature and critical review of the current state of the art on methods, tools, and associated results. The second objective which was to carry out a sustained impact assessment of the activities of the non-standard refiners on their host communities, is detailed in Chapter 4 of the thesis. Questionnaires were administered to stakeholders (youths, chiefs, traders, farmers, fishermen/fisherwomen, and residents of host communities). Quantitative data was collected from three communities in the Niger Delta region of Nigeria with non-standard crude oil refineries and the data was analysed using descriptive and inferential statistical methods (Chi Square, Correlation, and Factor Analysis). The third objective, which was to determine the physiochemical properties of the 9 non-standard refined diesel (NRD) fuel oil and the control sample, was also achieved as detailed in Chapter 5. The physiochemical properties were determined according to the American Society of Testing and Materials (ASTM) designated standard D975 which includes seven categories of diesel fuel fitting for several types of diesel engine (ASTM D975-21). The density, kinematic viscosity, flash point, calorific value, water content, pour point, cetane index and distillation ranges were determined. The fourth objective was to determine the Volatile Organic Compounds present in the 9 NRD fuel oil and the control sample. The volatile compounds present in each sample were determined with Gas Chromatography and Mass Spectrometer (GC-MS). GC-MS is employed in the determination of the compositional variations of fuels (Leghrib et al. 2020; Câmara et al. 2017). The fifth objective as detailed in Chapter 7 was to determine the performance and combustion characteristics of the 9 NRD fuel oil and the control sample in diesel engines. The combustion and emission analysis were determined using a variable speed single-cylinder Cussons Engine Test Bed P8252, coupled with a piezoelectric transducer and a Testo 350 exhaust gas analyser. The brake thermal efficiency (BTE), brake specific fuel consumption (BSFC), cylinder pressure, exhaust gas temperature, oxides of nitrogen (NO_x), carbon monoxide (CO), and carbon dioxide (CO_2) emissions was determined.

1.7 Thesis structure

The thesis is made up of eight chapters. Chapter 1 dealt with the introduction to the research, the statement of the problem, research aim and objectives, justification of the research and thesis structure. Following the introductory chapter, Chapter 2 of the thesis reviews extant literatures on crude oil refining in Nigeria, non-standard refining of crude oil, diesel fuel adulteration and its effect on engine performance, terminologies associated with internal combuston engines and physiochemical property analysis of liquid fuels. Chapter 3 summarises the research design and methods adopted in acquiring data for the research. Chapter 4 of the study investigates the sustained impact of the activities of the non-standard crude oil refiners on their host communities. This chapter addresses objective 1 of the thesis. The physiochemical properties of the non-standard refined diesel fuel oils are determined in Chapter 5. Chapter 5 of the thesis addresses objective 2 of the thesis. In Chapter 6, Gas Chromatography and Mass Spectrometer (GC-MS) and Fourier Transform Infrared (FTIR) analysis is presented to determine the volatile organic compounds in the test fuel samples. Chapter 6 addresses objective 3 of the thesis. The performance and combustion characteristics of the non-standard refined diesel fuel oil on engines is presented in Chapter 7. This chapter addresses objective 4 of the thesis. Chapter 8 the concluding chapter, summarises the findings of the study, recommendations, and future study.

Chapter 2 Literature and Critical Review

2.1 Introduction

This study aims to investigate the impact of the activities of the non-standard crude oil refiners on their host communities. The physiochemical properties of the non-standard refined diesel fuel oil, its effects on engine performance and emission. Hence this chapter reviews the extant literatures on the production of crude oil in Nigeria. It, thereafter, looks at the activities of the non-standard refining of crude oil and the effect of the products on the environment and on engines in terms of performance and emission arising from the usage of the fuels. Some sections of this chapter has been published in journal papers by the researcher (Bebeteidoh et al., 2020; Bebeteidoh et al., 2020).

2.2 Crude Oil

Crude oil is a complex and composite mixture of diverse hydrocarbon chains (Nandy et al. 2020; Fingas, 2011) often mixed with mineral suspension and emulsified water (Fetter et al., 2019). It is a yellow-black liquid usually found in underground reservoirs (Eneh, 2011). Crude oil is one of the most important energy resources available to humans (Luo et al., 2020). Yasin et al., (2013), Groysman (2017), and Chinenyeze and Ekene (2017) all stated that crude oil consists predominantly of hydrocarbons, metals, nitrogen, and sulphur in their natural state. However, Groysman (2017) posited that in addition to the hydrocarbons which are present in it, crude oil also contains contaminants that are present as dissolved gases, solids, and liquids. Metals are uncovered in trace concentrations in crude oil as inorganic salts (Fetter et al., 2019).

In its raw form, crude oil is a fossilized mass found below the earth's surface as a geological formation (Vempatapu and Kanaujia, 2017). Crude oil contains all normal Alkanes from C_1 to C_{120} (Yasin et al., 2013). Also, it contains hydrocarbon deposits and organic materials including aromatic hydrocarbons, alkanes, and cycloalkanes with toxic, hazardous, and carcinogenic potentials (Maamar et al., 2020). Also, Chinenyeze and Ekene (2017) asserted that crude oils are hydrocarbon compounds going from pentane to pentadecane (C_5 – C_{15}). Table 2-1 shows crude oil fractions and their various applications. Crude oil has an elemental composition distributed between carbon (85%-90%), hydrogen (10%-14%), sulphur (0.2-3%), nitrogen (<0.1-2%), oxygen (1-1.5%), and organometallic compounds (vanadium, nickel, lead, arsenic, and other trace metals) (Vempatapu and Kanaujia, 2017).

Crude oils are complex but mainly paraffinic, naphthenic, and aromatic, (Yasin et al. 2013, Chinenyeze and Ekene 2017) and play a key role in today's world economy because they are the main source of energy (Mabood et al., 2017). According to Ali and Kumar (2017) crude oil is one of the largest sources of energy in the world, but its extraction and subsequent refining come with an environmental impact on water, air, and land. As stated in section 1.1 several countries have started using biofuel as a fuel for engines, but because of the economic benefit and government policy, Nigeria has not made any concrete effort to diversify from the use of fossil fuels, and her citizens are left with just one option, the use of products refined from fossil fuel. Adewuyi (2020) identified weak government policies, high production cost, land tenure system, and competition between biofuel feedstock and food as the challenges hampering the development of biofuel in Nigeria.

Table 2-1 Crude oil fractions (Eneh 2011)

Boiling Range (°C)	Composition (No. of carbon atoms per molecule)	Name	Main Issues
<20	C_1 to C_4	Natural Gas (gaseous compounds)	Fuel, chemical synthesis (i.e. raw material for chemical industry)
0 - 30	-	Natural gas (Zymogene and Rhigolene)	Liquid Zymogene is used in the manufacture of ice. Rhigolene is used in medicine as a local anaesthesia
20 - 90	C_5 to C_7	Light petroleum (Petroleum ester)	Solvent
30 - 150	C_5 to C_{14}	Crude naphtha	Solvent
70 - 90	C_6 to C_{18}	Gasoline of petrol	Motor fuel, solvent in dry cleaning
70 - 200	C_6 to C_{10}	Petrol (gasoline)	Motor fuel
90 - 120	C_7 to C_8	Ligroin (high b.p petroleum either or light petroleum fuel)	Solvent in dry cleaning
100 - 200	C_5 to C_{10}	Fuel	Automobiles
120 - 160	C_5 to C_{10}	Benzene	Solvent (in dry cleaning and in oil and plant industry)
150 - 300	C_{10} to C_{38}	Kerosene	Fuel, illuminant, making oil gas
175 - 300	C_{10} to C_{18}	Kerosene (Paraffin)	Fuel for jet engines or central heating systems
200 - 300	C_{12} to C_{18}	Kerosene (Paraffin)	Fuel (lamps and stoves)
>275	C_{12} to C_{20}	Gas oil	Fuel for diesel engines
>300	C_{18} to C_{38}	Gas oil or heavy oil	
300 - 400	C_{15} to C_{25}	Diesel oil	Fuel (locomotive)
	C_{20} to C_{24}	Lubricating oil	Lubricant (making candle, shoe polish, etc.)
>400	C_{21} to C_{30}	Paraffin wax	Various
Non-volatile oil	$>C_{20}$	Lubricating oils, waxes, etc.	Lubricant, candles
Solid residue	$>C_{40}$	Asphalt, bitumen	Road surfaces, roofing
		Vaseline	Lubricant
		Pitch	In toilet goods and ointment
		Petroleum coke (on re-distillation of tar)	In paints and varnish. As fuel

2.2.1 Crude Oil in Nigeria

Oil was first discovered in Nigeria in 1956 by Shell D'Arcy (later Shell-BP) in a town called Oloibiri, in the heart of the Niger Delta, with production and exploration commencing in 1958 (Madu 2015). This set the stage for multinational oil producing companies to find their way into Nigeria, notably Gulf oil (later Chevron and now Chevron/Texaco), Mobil (Exxon Mobil), Agip, Texaco, and Elf (now Totalfina/Elf) (Obi 2010). Nigeria's export blends are sweet crude and light crude, and both have low sulphur contents of 0.05% - 0.2% (Badmus et al., 2012).

The bulk of Nigeria's crude oil production takes place in the Niger Delta Region (Onyena and Sam, 2020), where most of the crude oil deposits are found (Audu et al., 2016). Presently Nigeria has159 oil fields in operation and 1,481 oil wells in the Niger Delta region (Babatunde et al. 2019). However, the exploration and production of crude oil has had a damaging effect on the ecosystem, surface and groundwater, and soil (Kharaka and Hanor, 2003). Also, Ana et al. (2009) added that oil exploration causes a range of environmental problems including, the contamination of groundwater by xylene, toluene, benzene, ethylbenzene, and other derivatives of benzene.

Oil spills, no matter the size, affect the natural microbial community, the chemical, and the physical properties of the soil (Ana et al., 2009), and devastate forest and water bodies causing loss of biodiversity (Okonkwo and Etemire 2017). According to Kharaka and Dorsey (2005) these effects arise because of improper disposal of large volumes of saline water produced with oil and gas, abandoned oil wells, land modification for drilling activities, impact, and ground-surface disturbances. Anifowose et al. (2012) in their research reported that while the oil multinationals could be held culpable, some of the crude oil spills are a result of deliberate attacks on oil pipelines, which are often followed by oil theft carried out by well-trained professionals or at a smaller scale by opportunistic local residents. Table 2-2 shows the critical pollutants in the Niger Delta Region.

Table 2-2 Critical air pollutants in the Niger Delta region of Nigeria (Wilson et al. 2018)

Pollutants	Description	Sources	Effects
Particulate Matter	$PM_{2.5}$ and PM_{10}	Residues from burning of hydrocarbons – gas flaring etc.	Increase respiratory symptoms, aggravate asthma, and cause premature death.
Carbon Monoxide (CO)	Poisonous gas	incomplete combustion from vehicles and gas flaring	Affect mental function, alertness, and worsen cardiovascular diseases. Harmful even in low concentrations.
Nitrogen Dioxide (NO_2)	Reactive gas. Part of smog formation	Vehicles and power plants, gas flaring	Respiratory illness (short term). Lowers resistance to respiratory infection (long term).
Ground level Ozone (O_3)	Reactive gas. Main chemical in smog formation	Sunlight reacting with exhaust from motor vehicles and refineries	significantly decrease lung function, increase respiratory symptoms, aggravate asthma
Sulphur Dioxide	Poisonous gas	Exhaust fumes, gas flaring and residues from burning of hydrocarbons	Sore throat, runny nose, cough, and burning eyes. Inhaling high levels can cause swollen lungs and breathing difficulty. Skin contact with sulphur dioxide vapour can cause irritation or burn

Gas flaring is a practice used for the disposal of associated gas by the multinationals in Nigeria during production, which has been linked to global warming (Audu et al. 2016; Aniefiok et al. 2016; Okonkwo and Etemire 2017) and also a high prevalence of cancer, respiratory and skin disorders in host communities (Ana et al. 2009). Gas flaring is a concern to the people of the Niger Delta, this is because it directly influences the quality of human health, which in extreme cases may lead to death (Wilson et al. 2018). It is also important to highlight that flared gas emissions are often corrosive and toxic and can contribute to the formation of acid rain because of their nitrogen dioxide content. Nitrogen dioxide is an acid rain precursor as it reacts with moisture to form corrosive nitric acid (Wilson et al. 2018).

2.2.2 Crude Oil Refining in Nigeria

As discussed in Chapter 1, Nigeria has four crude oil refineries all in a moribund state (Adegbite 2013) with an estimated total refining capacity of 445,000 barrels per day (Kadafa 2012; NNPC 2016; Majekodumi 2013). The Port Harcourt Refining company is made up of two refineries; the first, which was commissioned in 1965, was built with an on-stream capacity of 60,000 barrels of light crude per day, and the second refinery, which was commissioned in 1989, was built with a refining capacity of 150,000 barrels of crude oil per day (Odeyemi and Ogunseitan 1985; NNPC 2016; Kadafa 2012). The Warri refining company and Kaduna refining company have one refinery each with installed capacities of 110,000 barrels, and 125, 000 barrels of crude oil per day (NNPC 2016).

2.2.3 Non-Standard Refining of Crude Oil in Nigeria

The quality of fuel determines whether it can be commercialized because the presence of adulterants could lead to some operational challenges (Torres-Jimenez et al., 2011). The non-standard refining of crude oil, as described by Nwajiaku-Dahou (2012) and Networks (2013), is the rudimentary refining of crude oil into gasoline, kerosene, and diesel in relatively small amounts for use in local markets. The non-standard refineries make use of crude oil as its feedstock and as such refineries are built close to communities that host crude oil flow stations and those with crude oil pipelines running through them in the Niger Delta, while the non-standard refined products such as diesel and kerosene are sold in towns and villages in Nigeria (Ogbuefin 2014). According to Networks (2013) non-standard refining camps along the riverbanks, store crude oil in locally-made drums, or in large holes dug in the ground covered in plastic and other synthetic materials to prevent any leakages. Likewise, EIA (2016) reported that non-standard refineries in the Niger Delta's swampy bushes refine crude oil, and by-products from the refined crude oil such as diesel, kerosene, and petrol are sold domestically and regionally at low cost compared to government recognized retail outlets. A typical non-standard refinery is shown in Figure 2-1.

Figure 2-1 A typical example of a non-standard refinery (Onyekakeyah 2017)

The process of refining begins when the ‘’black is heated in an oven, burning crude oil to start the distillation process, with most of the process kept cool through cold-water pumps and storage tanks’’ (Networks 2013). The product of each refining process depends on the refining method, with variations in the quality of products obtained, and to correct these variations the refiners sometimes mix kerosene with diesel to reach the product standard of large refineries (Networks 2013). “We mix the diesel with kerosene and gasoline; no chemical is used because the quality is standard. Before now we used to buy a chemical from NNPC staff but when we discovered mixing diesel with our refined fuel and kerosene improves the quality, we stopped buying it’’ Networks (2013).

2.2.4 Perspective of the Non-standard Refiners

Several reasons have been adduced for the rise of non-standard refineries in the Niger Delta region. Perpetrators of the illegal acts have attributed this to unemployment, the government, and multinational oil companies near neglect of the Niger Delta region in the allocation of oil resources. Others have attributed it to the devastation of the environment of the region from crude oil exploration and exploitation. Babatunde (2012) argued that the proliferation of non-standard refineries could be attributed to the battle by the local communities towards securing increased local participation in the oil business and suitable access to the oil revenues. Wizor and Wali (2020) reported that the communities of the region are not put into the equation of oil activities by the government and oil multinationals, despite the degradation of their soil, atmospheric pollution, and water poisoning, which are their sources of sustenance. Based on secondary data this section reviews excerpts of published reports of interviews conducted with perpetrators of this illegal act of non-standard crude oil refining by both international and local journalists.

2.2.4.1 Unemployment

Owolabi (2022) reported that high-levels of unemployment have made the non-standard refining of crude oil an attractive business in the Niger Delta. Ngada and Bowers (2018) argued in favour of the view that poor standards of living, high unemployment and poverty are associated with the non-standard refining of crude oil. Over the years, the illicit business of non-standard refining of crude oil, operated by unemployed youths has grown in leaps and bounds with a typical camp engaging between 12 and 20 people with larger camps employing even more (Onuh et al., 2021). Umukoro (2012) asserted that deteriorating and poor economic conditions due to worsening land shortages, few opportunities beyond farm and declining farm yields have accelerated conflict through unemployment and rising poverty. Umukoro (2012) went on to note that with its large population dependent on water, land, and other resources from a deteriorating resource base as a result of crude oil exploitation, the Niger Delta clearly exhibits both demand-and supply-induced environmental scarcity. However, Okpo and Eze (2012) argued that the issue of the non-standard refiners could be attributed to ignorance and greed. Below are excerpts of quotes from interviews conducted by reporters of several news outlets with the non-standard crude oil refiners.

"Forty-year-old Goodluck, who shares his name and tribe with the president, says he would much rather have got a respectable job, except that, despite the billions of petrodollars coursing through the region's creeks over decades, there aren't any". This refinery is the only thing I know that can ensure my survival, at least for now," he told Reuters, sitting under a small makeshift iron roof shelter from the

boiling sun, his hands sticky with crude. Doing this you can make up to $60 in a day," he said, gesturing with a nod towards oil drums full of homemade diesel shaded by smoked-blackened palm trees".- **Akintunde Akinleye., Reuters News, 2013**

"We are bleeding," said one man working at a nearby illegal oil refinery, who gave his first name as Prince. "We need this one to balance out our life. "It is the only job we are doing," said an illegal refiner who gave his name as Ibeci. "There is no other job." – **Jon Gambrell, The Washington Post, 20/07/2013**

"Not only the workers were there; some were there as customers to buy and arrange for finished products to be transferred to various destinations in the morning. The environment is a hustling place," he said. Austin said it would be difficult to stop people from engaging in illegal refining of crude oil. He gave his reasons: "I cannot tell people to stop going there because, we take that place as a ground where we go to hustle instead of going to steal". – **Osa Okhomina, Leadership Nigeria, 23/06/2019**

2.2.4.2 Claim to oil resource

"Environmental Justice" as described by the United States Environmental Protection Agency (EPA) is the meaningful involvement and fair treatment of all people, irrespective of race, national origin, colour, income, or education, with respect to the execution, enforcement and development of environmental laws, regulations, and policies (Ako, 2009). However, this is not the case with the Niger Delta people. The claim that oil resources entrapped in the land belong to the people is not a new discourse depending on who you speak to in the region. To forestall such claims the Federal Government in 1978, under the leadership of General Olusegun Obasanjo as head of state introduced the Land use decree; this is now an Act of the Federal Republic of Nigeria. According to Ebeku (2002) the law confers 'all land' in Nigeria on the State, thus denying the previous owners of their original title. In addition, the Land Use Act has been interpreted to deny the communities, and families of their right to compensation, despite the amount of damage the multinational oil companies cause (Ebeku, 2002). Ako (2009) argued that the Land Use Act is a major cause of high incidence of violent conflicts in the region due to the environmental injustice it promotes.

The Petroleum Act/Decree of 1969 is another law of the Federal Republic of Nigeria that has brought continuous strife between the people on one hand, and the government and oil multinationals on the other. As reported by Obi (2010) in his research titled "*Oil Extraction, Dispossession, Resistance, and Conflict in Nigeria's Oil-Rich Niger Delta",* Section 1 of the law provided that "the entire ownership and control of all petroleum in, under or upon any lands to which this section shall be vested in the state." This is contrary to the claims made by some people in the Niger Delta, that the crude oil belongs to them. Below are excerpts of quotes from interviews conducted by reporters of several news outlets and researchers, with the non-standard crude oil refiners.

"It's mainly because of anger we are doing this job, because the government and oil companies don't recognise us," he told Al Jazeera. "We want to tell the politicians that Nigeria's oil is for all of us. They eat the oil revenue in Abuja, and we take the crude down here. That's how it's going to be." **Mohammed Adow, Aljazeera News, 3/08/2012.**

"Here is our business place," a man, who did not want to give his real name but asked to be called Edward, told me as we walked around a remote, heavily polluted palm-tree fringed creek in Ogoniland in the Niger Delta. We use these to go and collect our natural resources - our crude oil," he said, pointing to a locally carved boat lying on its side" - **Will Ross, BBC News, 26/07/2012**

"The government and oil companies are collecting our oil and we don't have jobs, no money, so we have to collect the oil and refine our own," says one man. "We have no fish in these creeks because of pollution. Even the farmers, their lands have been polluted with oil – so they all joined the practice of illegal oil refining." – **John Vidal, The Guardian UK, 16/10/2013**

"As an informant told me, 'We know the youths who operate the refineries, for many years, the corporations would come and take our oil without giving back and the state will support them" (Adunbi, 2020).

2.2.4.3 Relationship to community and other stakeholders

The non-standard crude oil refiners are said to be youths and residents of communities in the Niger Delta whose activities have contributed to the devastation of the environment. According to Ogele and Egobueze (2020) some inhabitants of oil-bearing communities are part of the illegal business of the non-standard refining of crude oil due to its inherent boom. According to Onuh et al. (2021) from the organised crime perspective and value chain, a complex network of layers of interest and community actors are involved in the political economy of the non-standard refining of crude oil. Onuh et al. (2021) asserted that, there are three likely layers of interest engaged in the non-standard but illegal refining, with the first layer been youths comprising of welders, carpenters, and electricians involved in the fabrication of makeshift tankers, cooling spots, drums and pipeline drilling for the non-standard refining in the creeks. The second layer is made up of community members who help the refiners to conceal the non-standard refining infrastructure projects by monitoring any interference from the government as resource infrastructures are property of the Federal Government under the Petroleum Act of 1969, the Land Use Act of 1979, and the Hydrocarbon Oil Refiners Act of 1965 (Onuh et al., 2021). The Hydrocarbon Oil Refiners Act of 1965 No. 17 of the Federal Republic of Nigeria states that "no person shall refine any hydrocarbon oil save in a refinery and under a license issued under this Act (hereunder referred to as "a refiners license"). LN. 71 of 1965. "Any person who refines hydrocarbon oils in contravention of the provisions of section 1 of this Act shall be found guilty of an offence and shall be liable- (a) on summary conviction, to a fine of not less than four hundred naira or more than two thousand naira or to imprisonment for a term of two years, or to both; (b) on conviction an indictment, to a fine of an unlimited amount or to imprisonment for a term not exceeding five years, or to both". Onuh et al. (2021) defined the third layer as the 'financers' or 'big boss' of the capital-intensive projects of the non-standard refining of crude oil. They argued that the 'big boss' though invincible are mostly local community members linked to the international oil corporations and/or the corridors of power. This layer owns the numerous non-standard refineries situated in the region. Dominic (2016) compared the non-standard refining and theft of crude oil to the illicit drug business and further described people in the third layer as big men that are well connected in public (government) and private sectors. Human Rights Watch in their 2003 annual report on the Warri Crisis in Nigeria, described those running the racket of the non-standard refineries and their financiers as untouchables.

Another group of collaborators of this illegal act are security forces and government representatives who are supposed to be protecting the pipelines that are the major sources of the crude oil for the refiners. It is uncommon for any bunkering activity to take place in the region without the involvement of the security forces (Onuh et al., 2021). According to Ralby (2017) "the Joint Task Force (JTF) officers, comprising personnel from the Nigerian Army, Air Force, Navy, and the Police, oftentimes provide security cover for the illicit pipeline tapping and refining, as well as escorting vessels conveying illicit crude or refined products. The police also aid in the evasion of some arrested criminals or release them due to political pressure indicating official complicity in the illegal hydrocarbons trade. Several highly placed politicians, oil company staff, the staff of the Nigerian National Petroleum Corporation and military officers are actively involved in both the small- and large-scale illegal oil business in the region". Below are excerpts of quotes from interviews conducted by reporters of several news outlets with the non-standard crude oil refiners.

"Wondering how the illegally acquired products passed through multiple military checkpoints along the creeks was not farfetched to reporters that witnessed the scene because, at the only entry and exit point to the jetty, were stationed several police patrol jeeps with Area Commander's office, B and A Divisions with several police teams led by an Assistant Superintendent of Police. It was apparent that they were already compromised since they were obviously allowing the trailers to load". **Sylvester I., and Emmanuel A., This Day Newspapers, 25/08/2019**

"The following day, there was a repeat of the activities of the previous day. Disguising as an oil dealer, one of THISDAY's journalists approached a 'loader' who promised to assist provided that N200,000 was coughed up. Responding to the worry of the 'oil dealer', the 'loader' said: "Oga, that's no problem. We settle them so we don't have a problem with security. We pay N500 per drum at military checkpoints for easy passage of our products from the creeks. And those you see around the jetty are also here to collect theirs. So, they won't disturb any vehicle

moving the products out on the road." -**Sylvester I., and Emmanuel A., This Day Newspaper, 25/08/2019**

"Also speaking during the programme, Felix Mamode Akugha, broadcaster and executive producer of 'Inside the Niger Delta', accused politicians and security officers of aiding illegal oil refining activities. According to Akugha, illegal refining of crude oil has become "a multi-billion-naira industry" in Rivers and the Niger Delta region, which "employs over 500,000 youths". The broadcaster also cited the comment made by Nyesom Wike, governor of Rivers, who had once accused Major General Jamil Sarham, General Officer Commanding (GOC) 6 division of the Nigerian Army, of running an oil theft ring in the state" -**James O., The Cable, 19/08/2021**

"*Governments at all levels have been incapacitated in trying to stop this business, because quite a lot of big people are involved in it. When I mean big, I mean very influential, very powerful political leaders, military leaders are all involved in this business, and so it is difficult to put a halt to it. They (oil bunkers) get the crude oil from pipelines. In other words, the man who is put to guard something is the one that is taking from it. There is nobody to stop it. The theft of Nigerian crude oil is alarming, but is the government ready to do anything?"-* **James O., The Cable, 19/08/2021**

"*Rivers State Governor, Mr. Nyesom Wike, has urged the State Police Commissioner, Eboka Friday, to redeploy out of the state a particular Divisional Police Officer (DPO) in Emohua Local Government Area of the state who he alleged operates an illegal refinery in the area. The governor frowned at security agencies for the role some of their personnel have played in aiding and providing cover to the operators of the illegal refineries in the state".* **Blessing I., This Day Newspaper, 15/01/2022**

Although, the military has commenced with the destruction of non-standard refineries in the Niger Delta region, they have to do so in environmentally friendly manner and also to ensure that those involved be arrested and prosecuted.

2.2.4.4 Economic model

The youths who carry out the illegal acts of the non-standard refining of crude oil do so for financial gains. Little or no payment for the crude oil, which is the basic raw material needed for the refining process, is seen as a windfall for them. A classical model which is used by most non-standard refining camps is the law of demand and supply. The connection between demand and supply is one of the most important factors that could affect product prices in the market (Torab, 2018), coupled with the supply gap created by the ineffectiveness in the country's downstream sector (Nwozor et al., 2020), see Section 1.1. This was also alluded to by Nigeria's Minister for Petroleum during a shareholder's meeting. He was quoted as saying "The prevalence of illegal refineries in the region is attributed to the non-availability of legitimate alternatives." (Okafor, 2021). The demand for petroleum products like diesel, kerosene and gasoline and the price differential between the government products, which are imported, has also increased the demand of the non-standard refined products. The imported refined products are affected by the rise in crude oil prices in the international market. In which case, as the prices of crude oil go up in the international market, the prices of the refined petroleum products imported by the government also goes up. According to Evbuomwan and Alete (2020) the non-standard refined products are sold at very cheap prices and, coupled with the extreme poverty in the region, the inhabitants would rather use them than the standard refined products.

The unavailability of fuel retail outlets in the creeks of the Niger Delta is another factor that creates high demand for the locally refined products. Though, the non-standard refiners do donate free cooking fuel (kerosene) and diesel to their host communities, the demand for the product is still very high as the scarcity of petroleum products is a nationwide issue. "We give out kerosene and fuel to our people here at home and fuel our community generator with our diesel. We don't sell at home, we dash (gift out)" (Ogala, 2013).

2.2.5 Drivers of Non-Standard Refineries

The increase in the number of non-standard refineries in the NDR could be attributed to several reasons. The scarcity of petroleum products like diesel, kerosene, and gasoline, see (section 1.1.1). Other factors include the absence of fuel retail outlets in and around most riverine (coastal) communities in the NDR. This leaves people in riverine (coastal) communities traveling long distances with difficulties in purchasing petroleum products. According to Ariweriokuma (2008) the riverine (coastal) communities in the NDR are faced with major logistic issues in maritime transportation taking into consideration the fact that they are remotely located and depends on Warri, Eket, Calabar, and Port Harcourt for petroleum products. The federal government of Nigeria in other to reduce this burden, in 2006 commenced the construction of 12 floating Mega station to give riverine (coastal) communities access to quality petroleum products (NNPC Retail, 2021), see (Figure 2-2).

Figure 2-2 NNPC floating Mega station (JBN, 2020)

Most of these 12 floating Mega stations are either not functioning presently or are starved of refined petroleum products, thereby leading to scarcity of the products in riverine communities. According to Today (2020) floating Mega stations constructed on the Niger Delta waterways by the NNPC to improve maritime transport have been abandoned. Also, Ogu (2021) reported that fifteen years after their construction, NNPCs floating Mega station in the Niger Delta waterways have become rotten floating mammoths. The NNPC's inability to manage the stations, which are located in the middle of rivers, has exacerbated the challenges faced by passengers and boat operators (Today, 2020). Due to the dormant conditions of the floating stations, boat drivers are said to be purchasing petroleum products from private merchants, who sourced their products from non-standard refineries (Today, 2020). “It is really concerning that something that will serve our local government and nearby communities is not working. The station has been shut down over four years now and we do not know why. There is nobody we can ask,” (Ogu, 2021).

The non-functioning of the nation’s four public refineries as reported in Chapter 1 (section 1.1), has also affected the national supply and delivery of petroleum products and irregularity in pump price (Alaba and Agbalajobi, 2014). As a result of the downward turn of the nation’s public refineries the Nigerian government between 2015-2018 granted licenses for the establishment of 45 private refineries, of which 17 had expired (KPMG, 2019). Olujobi (2021) reported that the effort of the federal government to encourage private partnership in the establishment of refineries has not yielded any fruit. Of the 45 companies awarded licenses to build the private refineries in Nigeria, Waltersmith Modular Refinery has completed its phase one development of 5,000 barrels of crude oil a day refinery in November 2020 and had flagged off its expansion to 50,000 barrels of crude oil (NS Energy, ND). Others are the Dangote Oil Refining Company which is 80.3% completed (This Day, 2021) and the Azikel Modular Refinery that is expected to be completed in 2021 (Brelsford, 2021).

2.2.6 Impact of Non-Standard Refining of Crude Oil in Nigeria

Crude oil storage facilities and refineries emit toxic pollutants dangerous to humans (Sopian et al., 2016). The Niger Delta region of Nigeria is rated among the ten most important wetlands and marine ecosystems in the world (Kadafa, 2012), but the continuous dependence of the Nigerian economy on fossil fuel exploration and extraction has contributed greatly to the degradation of the region and its environment (Zabbey et al., 2017). According to Adaramola et al. (2014), the continuous exploitation of these petroleum resources has significantly impacted the cost of living, and also the deterioration of the environment as a result of the emission of regulated and unregulated emissions resulting from gas flaring and the activities of non-standard crude oil refiners. Similarly, Tukur and Hajj (2017) highlighted that petroleum from crude oil exploration is a key challenge facing the people of the Niger Delta region as oil spillages and theft are major sources of environmental pollution.

Importantly crude oil spillage occurs through operational errors, natural hazards, and mechanical failure, corrosion of pipelines, theft, and sabotage (Aroh et al. 2010). Akpomera (2015) describes environmental degradation in the Niger Delta as resulting from excessive oil spillage of petroleum resources and sabotage. The aquatic and terrestrial environment acts as receptors to the oil spills, which majorly affects the livelihood and assets of the host communities (Iloeje 2015). A typical example of a labourer feeding a fire with crude oil in an illegal refinery is illustrated in Figure 2-3

Figure 2-3 A labourer feeds a fire with crude oil at an illegal refinery (The Guardian UK, 2013)

According to Ogbuefin (2014), the activities of non-standard crude oil refiners include the destruction of farmlands, aquatic life, and the shortfalls in resources experienced by the Nigerian government. Similarly, Adegbite (2013) added that as a result of the activities of nonstandard crude oil refiners agricultural lands are polluted, there is a build-up of harmful substances in food webs and diminishing biodiversity. Non-standard refining of crude oil also carries significant health risks (Obenade and Amangabara 2014).

Worse, the non-standard crude oil refineries that are present in the oil-rich Niger Delta see oil spilled everywhere, in the process of either getting the feedstock or during the refining process, soaking the ground with a mix of crude and mud that swallows the legs of the operators of non-standard crude oil refineries up to the knees (Boris 2015). A great number of Niger Delta indigenes have complained that water from freshly sunk boreholes shows evidence of oil contamination which makes the water undrinkable even after treatment (Boris 2015). Likewise in their research, Asimiea and Omokhua (2013) and Ghazvinian (2007) established that the activities of non-standard crude oil refiners severely impacted the aesthetic scenery of the forest and biodiversity causing destruction of wildlife habitat and loss of medicinal plant species and limiting the regeneration of plant species.

The heating and handling of crude oil in the non-standard refining camps pollute the air (Obenade and Amangabara 2014). The camps have a toxic feel, the health impacts on those working there are unknown but surrounding communities are constantly exposed to the inhalation of poisonous gases, causing coughing, and breathing problems (Obenade and Amangabara 2014). The activities of the non-standard crude oil refiners have not gone unnoticed by the Nigerian government due to the huge economic losses they have brought to the nation (Allen, 2012; Dominic, 2016). However, the government's response in dealing with the activities of the non-standard crude oil refiners has exacerbated the damage to the environment rather than eliminating it (Channels, 2015). Pointer (2018) reported that in September 2017, the Nigerian Navy destroyed over 1,000 non-standard refineries in the Niger Delta region. In November 2018, several non-standard crude oil refineries in and around the Okarki community in the Ahoda West Local Government Area of Rivers State were destroyed using a swamp buggy (Osahon, 2018). Also, as discussed by Rageh (2014), while the government is making efforts to curb the activities of the non-standard crude oil refiners, the process of throwing the refined products into rivers and swamps and setting the camps ablaze contributes to the destruction of the environment of the Niger Delta. The federal government through the head of the National Oil Spill Detection and Response Agency (NOSDRA), blamed the activities of non-standard crude oil refiners for the high level of soot experienced in parts of the Niger Delta Region (Vanguard, 2018).

2.2.7 Crude oil Pollution

The exploration of fossil fuels and its by-products is one of the most frequent sources of environmental pollution (Riccardi et al., 2008). It is classed as one of the most common pollutants in soil globally (Lopez-Echartea et. al., 2020). Within the NDR, the many oil fields, flow stations, tank farms, refineries, and pipelines continuously offer possible sources of oil pollution (Chikere et al., 2009). The region is regarded as one of the most severely crude oil impacted ecosystems in the world (Adesipo et al., 2020). Crude oil contains a range of hazardous chemicals, which pose a serious threat to agriculture, human health, and marine life (Keshavarz et al., 2020). Pollution of the environment from crude oil and its by-products can cause long-term and severe damage (Wang et al. 2020). Crude oil spills in the environment exposes humans and presumably other mammals and marine species to numerous toxic hydrocarbons (Afshar-Mohajer et al. 2020). A product of crude oil pollution is its damaging effect on the physical properties of the soil such as pore spaces which might be clogged and lead to a reduction in soil aeration, infiltration of water into the soil, and increased bulk density of the soil which may affect plant growth, yield, and leaf chlorophyll (Abosede, (2013); Odiyi et al., 2020). The spread of the oil affects soil characteristics and general soil health, vegetation, microbial communities, and wildlife (Lopez-Echartea et. al., 2020). This source of pollution prevents plant photosynthesis and upsets the food chain (Olajuyigbe et al., 2020). Another source of soil contamination is leaking petroleum storage tanks (Xiang et al., 1995). The addition of total petroleum hydrocarbon (TPH) into the soil could alter the natural environment of the soil and cause macro and micro-scale biotic community changes (Khan et al., 2018).

Udo and Fayemi (1975) in their research into the effect of oil pollution of soil, germination, growth, and nutrient uptake of corn, discovered that the poor growth of maize was attributed to suffocation of the plants as a result of the exclusion of air by oil. In a similar study on pollution and organic amendment of soil physicochemical properties Nwachukwu et al. (2020) reported that the oil reduced germination percentage, depressing growth, and resulted in a reduction in leaf number. The spilled crude oil also contributed to the extremely acidic nature of the soil. Also, Ojimba and Iyagba (2012) in a study into the effects of crude oil pollution on horticultural crops such as fruits, pepper, okra, melon, and leafy vegetables revealed that output of crops in crude oil polluted lands were lower than non-polluted farms. Furthermore, Odjuvwuederhie et al. (2006) reported that spillages from crude oil reduced land productivity, crop yield and significantly reduced farm income as a 10% increase in oil spill reduced crop yield by 1.3% while farm income dropped by 5%.

Fish and other aquatic organisms in Nigeria face extinction or total collapse because of damage to their natural habitats by pollution of water bodies (Adeyemo, 2003). Crude oil spillage into water bodies such as rivers, streams, lakes, and oceans is a serious concern for environmentalists internationally due to its devastating impact (Olajuyigbe et al., 2020). The spill forms different layers of thickness on the water surface (Tang et al., 2019). The oil spreads over the water surface in a thin layer and prevents oxygen from reaching aquatic plants and animals (Olajuyigbe et al., 2020). According to Ogbeibu et al. (2020) the discharge of drilling mud, hydrocarbons, drill cuttings, and produced water into the environment during the production of crude oil impacts aquatic flora, fauna, and water quality. The short-term effect of oil spills on marine ecosystems could primarily depend on the composition and quantity of the oil, while the long-term effect could be linked to the biodegradation of microorganisms (Tang et al., 2019). Crude oil spills severely impact coastal resources and shallow waters, salt marshes, mangroves, fishery resources, the tourist industry, and the ecosystem (Gundlach and Hayes, 1978). Oil spills have an obvious influence on heterotrophic plankton (Tang et al. 2019). The brain, kidneys, liver, and cardiac performance of fish and other marine mammals are affected by toxicity when high concentrations of oil are spilled (Milinkovitch et al., 2013; Peterson et al., 2003). Of great concern are the rise in mortality rate and deformity of fish, decreases in the survival rate of eggs and larva of plankton (Tang et al. 2019).

In a 96-hour laboratory bioassay on *Palaemonetes africanus* (brackish water shrimps), Amaeze et al. (2015) found an increase in the effluent over the study period which is damaging to aquatic life. Shellfish like periwinkles and oysters readily succumb to oil pollution (Nriagu, 2019). Oyibo et al. (2018) reported that there is a significant health risk associated with the consumption of fish and other sea animals caught around the Forcados river as a result of the presence of high levels of polycyclic aromatic hydrocarbon (PAHs), total petroleum hydrocarbon (TPHs), and heavy metals in them.

Water is a very important resource to humans and other living organisms (Akpan-Idio et al. 2012; Rim-Rukeh et al. 2007). The people of the Niger Delta region of Nigeria depend on freshwater from rivers, ponds, and streams for their basic household water supply (Rim-Rukeh et al. 2007). The freshwater from the rivers and streams are also used for irrigation in farms (Akpan-Idio et al., 2012). Achudume (2009) in a study to determine the effect of petrochemical effluent on the water quality of Ubeji creek in the Niger Delta region of Nigeria, reported that water quality parameters were very poor, with high toxicity, coupled with the absence of fish and other aquatic lives as a result of high levels of heavy metals. Another study to determine the levels of petroleum hydrocarbons in surface water in the vicinity of a fuel oil spillage by Nganje et al. (2012) found very high concentrations of anthropogenic polycyclic aromatic hydrocarbon (PAH) in polluted surface water compared to unpolluted surface water. In a similar study into oil contamination in the Ogoni Land, of the Niger Delta, by Lindén and Pålsson (2013) the results show widespread oil contamination of creeks, rivers, and groundwater. Levels found in the more contaminated sites are high enough to cause a severe impact on human health and the ecosystem (Lindén and Pålsson, 2013).

Oil pollution, mostly from drilling, refining, and bunkering processes, creates problems that affect the lives of persons living very close to oil camps, pumping stations, tank farms, and pipelines (Briggs and Briggs, 2018). Liquid fuels like diesel, gasoline, and jet fuel emit volatile organic compounds (VOC) when burnt (Briggs and Briggs, 2018). Volatile organic compounds (VOC) are key contributors to environmental pollution (Li et al., 2020; Zhang et al., 2020). Also, human exposure to toluene, formaldehyde, and xylene are linked with negative health impacts (Zhang et al., 2020). Human exposure to BTEX (benzene, toluene, and xylene) either through ingestion or inhalation, could have serious health implications such as cancers, neurological diseases, and teratogenic effects (Moolla et al., 2015).

Table 2-3 Contaminants associated with crude oil production and their potential health effects (Nriagu, 2019).

Contaminants	*Sources*	*Potential health effects*
Polycyclic aromatic hydrocarbons (*PAH*)	Diesel exhaust Gas flaring Storage ponds and pits Conflagration of oil spills and waste	Possible or probable carcinogens
Metals (*arsenic, barium, cadmium, chromium, lead, mercury, selenium, and zinc*)	Storage ponds and pits Produced water Diesel exhaust Drilling mud	Skin problems High blood pressure Kidney damage Increased cancer Neurological damage Hair loss
Volatile organic compounds (*VOC*) (*benzene, toluene, ethylbenzene, xylenes, and formaldehyde*)	Venting and flaring of gas Storage ponds and pits Oily waste Diesel engine exhaust Compressors Conflagration of oil spills and waste	Cancer Respiratory problems
BTEX (*benzene, toluene, and xylene*)	Produced water Storage ponds and pit	Benzene is a known carcinogen Toluene may affect the central nervous and reproductive system Ethylbenzene and xylenes may have neurological and respiratory effects
Diesel fuel	Stimulation fluids Engines and heavy equipment Diesel exhaust	Both fuel and exhaust contain carcinogenic substances like benzene and Polycyclic aromatic hydrocarbons (*PAH*)
Aerosols	Diesel exhaust Pits Venting and flaring Conflagration of oil spills and waste	Can be inhaled and cause health effects like respiratory ailments, aggravation of asthma and allergies, painful breathing, shortness of breath, chronic bronchitis, and premature death
Nitrogen oxides	Diesel and natural gas exhaust Conflagration of oil spills and waste	React with VOCs to form ground-level ozone and smog, which can cause respiratory problems. React with other chemicals to form particulate pollution, which can damage lungs and cause respiratory illness, heart conditions, and premature death. React with common organic chemicals to form toxics that may cause biological mutations
Carbon monoxide	Engine exhaust Power generating plants Flaring Anaerobic pits and ponds Heavy equipment	Can cause brain damage
Carbon dioxide	Engine exhaust Flaring Power generating plants	Greenhouse gas

2.2.8 Regulation and Policy

The management of hydrocarbon spills and their waste is guided by legislation from the Nigerian government. The government of Nigeria has several laws and regulatory agencies with the responsibility of bringing to book those involved in crude oil pollution (Agbonifo, 2016). Government agencies like the Directorate of Petroleum Resources (DPR), the National Emergency Management Agency (NEMA), and the National Oil Spill Detection and Response Agency (NOSDRA) are all responsible for the management of oil field pollution response in Nigeria (Ite et al., 2013; Olaniyan, 2015; Yakubu, 2017). The policy on pollution provides operational elements that promote responsible environmental behaviour by all stakeholders (Yakubu, 2017). The NOSDRA establishment Act of 2006 empowers the agency to co-ordinate the implementation of a National Oil Spill Contingency Plan (NOSCP) in accord with the International Convention on Oil Pollution Preparedness, Response and Cooperation (OPRC 90) to which the Nigerian government is a signatory (NOSDRA, 2020).

However, even with these agencies and laws, the government is still not able to carry out proper enforcement. According to Agbonifo (2016) weak enforcement and poor implementation of the existing regulations provides fertile ground for environmental degradation. Similarly, Ejiba et al. (2016) reported that response to incidents of crude oil pollution in the Niger Delta has been weak from regulatory agencies. Also, with enabling laws that provide for a multi-agency response model to incidents of oil spills in Nigeria efficient operationalisation of this multi-agency response is absent (Olaniyan, 2015).

Although Nigeria has numerous environmental regulations that guide the safe exploration and production operations in the oil industry, implementation and enforcement of these laws are poorly executed (Elenwo and Urho, 2017; Ibaba, 2010; Ite et al., 2013). This is further compounded by a lack of commitment from environmental protection agencies to effect sustainable changes (Elenwo and Urho, 2017). According to Ibaba (2010) poor funding from the government, lack of operational facilities, corruption, and low-level involvement of professionals are the reasons that environmental protection agencies cannot properly enforce the laws. In their review of the environmental laws in Nigeria, Orubu et al., (2004) identified a probable flaw in that no clear provision is made to incorporate the host communities in the process of implementing environmental protection and management schemes. Indeed, Ayeni (2019) recorded that community participation in environmental policy and decision making is a proven approach, which addresses issues of environmental degradation in their domain. This is because, over the years, indigenous communities have developed a close affinity with their environment – rivers, lakes, streams, and land around them – for their livelihoods (Campese et al., 2009).

In the NDR, stakeholders have been left out in the decision-making process resulting from crude oil pollution, land and river contamination, the eradication of non-standard refineries, and mangrove conservation processes. Sam et al. (2016) describe stakeholder engagement as the process of informing, consulting, involving, collaborating with, and empowering affected people involved in a policy forming or decision-making process. Zabbey et al. (2021) reported the existence of evidence to show that during land contamination management decision making processes, in the NDR of Nigeria community representatives (stakeholders) are excluded. This omission excludes communities from opportunities for robust contribution (Zabbey et al., 2021). Sam et al. (2017) reported that Nigeria lacks a published stakeholder engagement framework for the development of policy. Also, Zabbey et al. (2017) reported that communities groups in the NDR perceive the government as being weak in the implementation of available policies. In their research to review the threat of oil exploitation to mangrove ecosystem Onyena and Sam (2020) reported that mangrove protection and conservation policies exclude community participation.

2.3 Fuel Adulteration

The adulteration of fuel occurs by the addition of cheaper products of good miscibility with the fuel (Cunha et al., 2016). The adulteration of fuel involves the introduction of foreign substances into the fuel with results showing nonconformity with standard parameters (Babu et al., 2017). It makes tailpipe emissions more toxic, aggravating the pollution crisis leading to a high rate of respiratory ailments (Taksande and Hariharan, 2006).

The adulteration of diesel and gasoline with other petrochemical products has become a regular phenomenon in developing countries (Kulathunga and Mahanama 2013). The detection of petroleum fuel adulteration is challenging because the adulterants commonly consist of those compounds which are already present in the fuel (Vempatapu and Kanaujia, 2017). According to Ubeidalah (2015) premium, motor spirit (gasoline) is often adulterated with cheaper products like domestic kerosene in parts of Africa. Also, Mabood et al (2017) reported that excessive adulteration of diesel and gasoline fuels for financial gains has resulted in serious health and environmental problems.

In the adulteration of diesel fuel, the most common adulterant is Kerosene (Yadav 2005; Muralikrishna et al. 2006). Kerosene is mostly used because of the overlapping hydrocarbons, C_{10}-C_{19} in diesel, and C_6-C_{16} in kerosene (Vempatapu et al., 2019). Test carried out by Igbani and Lucky (2015) in their research revealed the presence of impurities due to adulteration and poor refining processes in gasoline samples obtained from retail outlets in Bayelsa State, Nigeria. The adulteration of fuel comes with implications, both to the environment and end-users. In its bulletin, Nigeria's National Petroleum Corporation (NNPC) alerted states in the Niger Delta region of the presence of adulterated kerosene in the market.

'*'We wish to alert members of the public of the presence of adulterated kerosene in the market, especially in the Warri-Benin axis, as a result of the nefarious activities of pipeline vandals who attacked our Warri - Benin products pipeline and made away with kerosene mixed with AGO and PMS. The vandals may bring the stolen product to the market for sale to unsuspecting members of the public. Such adulterated kerosene could cause explosions and fire accidents. The consequences of past kerosene explosions are still very fresh in our mind, we cannot afford to have a repeat of such tragic incidents. We are therefore appealing to members of the public to be vigilant and desist from procuring kerosene from unauthorized dealers and outlets to avoid getting the adulterated products into their homes," Ajuonuma (2011).*

The addition of solvents is a common practice in the adulteration of fuel due to the huge difference in taxation between solvents and gasoline (Mendes and Barbeira 2013; Monteiro et al., 2008). Also, Monteiro et al. (2008) and Wiedemann et al (2005) reported that adulteration in Brazil involves the addition of aromatic hydrocarbons, heavy aliphatic (C_{13} –C_{15}) and light aliphatic (C_4 –C_8), like hexane, xylenes, diesel, rubber solvent, benzene, thinners, kerosene, and mineral spirits.

These adulterants are chosen based on ease of blending, economic benefits, physicochemical similarities to the fuel, and availability (Mabood et al. 2017). In their paper, Vempatapu and Kanaujia (2017) added that the adulterants are selected based on several criteria while keeping in mind the specification of the final product. Sharma and Gupta (2007) reported that the expected adulteration range is from 10% to 30% by volume, if less than 10% or higher than 30%, adulteration is financially unattractive. This is because when adulteration is higher than 30% it could easily be detected by the end-user as a result of degradation in engine performance (Sharma and Gupta, 2007).

Ale (2003) attributed the main reasons for adulteration to financial incentives arising from differential taxes that are imposed by the governments. However, Wiedemann et al (2005) added that the addition of solvents in fuels could lead to rubber corrosion, environmental hazards, and engine malfunction. Takeshita et al. (2008) reported that the addition of solvents into fuels changes their original composition thereby affecting their physicochemical properties in different ways.

Ale (2003) and Babu et al. (2017) grouped fuel adulteration into four classes.

- the blending of kerosene into petrol
- the blending of kerosene into diesel
- the blending of used lubricants into diesel
- the blending of lubricants into kerosene as a substitute for diesel

2.3.1 Diesel Fuel Adulteration and Recent Detection Methods

A fuel's quality determines whether it can be commercialized (Torres-Jimenez et al. 2011). The determination of adulterants present in diesel fuel oil is very challenging and requires the use of different analytical techniques (Vempatapu et al., 2019). According to Leghrib et al. (2020) and Verma et al. (2018), the difficult process of adulteration detection in diesel fuel has led researchers to develop thorough analytical techniques and clear data interpretation tools. According to Vempatapu and Kanaujia (2017), the monitoring and detection of adulterants in diesel fuel oil could be classed into two groups, namely offsite (laboratory) and onsite (filling station). The offsite is further classed into two groups of physicochemical methods or chromatography/spectroscopy methods, while the onsite has density as its only test method (Vempatapu and Kanaujia, 2017). Countries mostly impacted by diesel fuel adulteration are developing countries like India, Brazil, Nigeria, Morocco, and Kenya (Chowdhury et al., 2021) to name a few.

The discovery and identification of distinct problematic organic compounds within diesel fuel oil remain a major test; they could be separated chromatographically, allowing for detection and classification (Loegel et al., 2019). According to Sparkman et al. (2011), gas chromatography, mass spectrometry (GC-MS) is a synergistic combination of two prevailing microanalytical techniques. However, GC-MS is restricted to analytes that are not only thermally labile and volatile but could also withstand the harsh conditions of the chromatograph (Sparkman et al., 2011). Diesel fuel adulteration could also be detected using sensor-based techniques. Several methods have been applied for the detection of adulteration of diesel fuel oil by kerosene, gasoline, and other solvents.

2.3.1.1 Physicochemical properties

Yadav et al. (2005) explored the use of density and kinematic viscosity to determine the extent of kerosene adulteration in diesel. Results obtained indicated a considerable level of diesel fuel adulteration, requiring strict compliance and dispensation of fuels of prescribed quality. Though, test results for density for clean diesel and that which was adulterated with kerosene was within acceptable limits, the result for kinematic viscosity and percentage opacity was a better indicator for assessment of the adulteration level. In another study to determine diesel oil discrimination by origin using physicochemical properties and multivariate analysis, Aleme et al., (2010) reported that the use of physicochemical properties, distillation curves and chemometric tools was adequate to classify and prove their origin. Furthermore Aleme et al. (2010) posited that to certify that the quality of a diesel fuel sold to the public is genuine, some physical and chemical properties should be monitored using standard procedures (from the American Society for Testing and Materials- ASTM), and the approved limits must be met for the diesel fuel oil to be considered to conform or be suitable for sale to the public otherwise the diesel fuel sample is classified as non-conforming. Diesel fuels classed as non-conforming could be as a result of contamination, adulteration, or natural processes (Aleme et al., 2010).

In another study, the influence of diethyl ether (DEE) addition on selected physicochemical properties of diesel oil and ignition delay period was evaluated (Górski and Przedlacki, 2014). The kinematic viscosity, lower heating value (LHV), lubricity, density, cetane number and cold filter plugging point (CFPP) were determined experimentally. Though, the added DEE met the European standard PN-EN 590, in volumetric proportions of 5, 10, 15, and 20 vol%, the kinematic viscosity, density and lower heating values were lower than values obtained for the tested diesel fuel oil. Results further revealed that the DEE had major influence on diesel fuel oil kinematic viscosity. While the DEE addition did not have any influence on shortening the ignition delay period, 5% DEE and to diesel fuel oil decreased its viscosity by 26%. Similarly, Kalligeros et al., (2003) in determining the presence of adulterants in automotive diesel fuel oil sold in Greece, used some key properties such as density, cetane index, distillation properties, and sulphur content. Results for the automotive diesel fuel oil revealed 28% of the test samples were found to be adulterated with marine fuel oil or heating fuel based on their sulphur concentration. Also, there was a huge variation of the diesel fuel properties among the oil suppliers. Some 28% of the diesel samples suffered from some degree of adulteration, primarily with cheaper heating fuel. Dobrzyńska et al. (2021) in determining the physicochemical properties of the tested fuel samples in their study to investigate the effect of nano-additives on diesel engine exhaust emissions determined their cetane number, and cetane index, sulphur, fractional composition, impurity content, water, density, and viscosity in accordance with International Organization for Standardization (ISO). Results revealed that the addition of nanoparticles of both ferrocene and cerium dioxide had little effect on the fractional composition of the mixtures. However, the auto-ignition capability of the fuel decreased while the viscosity and combustion quality increased. The addition of solvents to diesel fuel oil changes its original composition, affecting its physicochemical properties in several ways (Takeshita et al., 2008). The investigation of physicochemical property analysis to determine diesel fuel adulteration is time consuming, requires sophisticated equipment and qualified personnel (Barra et al., 2019).

2.3.1.2 Chromatographic analysis

Chromatography and spectroscopic analysis is also widely used in the detection of adulterants in middle distillate fuels like diesel. For the analysis of middle distillate fuels like diesel and kerosene, the standard test methods are ASTM 2425, ASTM 2786, and ASTM 3239. According to Vempatapu and Kanaujia (2017), these methods have wide acceptability for quality control as well as measuring any variations due to adulteration. According to Chowdhury et al. (2021), owing to the numerous hydrocarbons present in gasoline and diesel fuel, separation methods such as gas chromatography (GC) provide both quantitative and qualitative analytical information of the samples. This has made GC the gold standard method for quality control (Chowdhury et al., 2021). In addition, de Aguiar et al. (2022) reported that chromatographic and spectroscopic methods, coupled with chemometric methods, have demonstrated outstanding potential for use in the analysis of diesel fuel adulteration. However, a major drawback to GC analysis is that it is time intensive, with run times of at least 30 minutes or more (Ramos et al., 2022), while Soares and Rocha (2020) reported that they consume solvents like, hexane, heptane, and dichloromethane.

Several studies have been carried out to determine diesel fuel adulteration using gas chromatography. One such study was the use of ultrafast gas chromatography to analyse biodiesel-diesel blends, carried out by Ramos et al. (2022). The researchers compared a moderately polar column to a traditional gas chromatographic column for the evaluation of biodiesel-diesel blended fuels. Principal component analysis was performed to identify clustering based on concentration and feedstock. The ultrafast gas chromatography proved to be a fast and effective technique, compared to traditional GC. In a similar study biodiesel and used cooking oil in automotive diesel and green diesel fuels were determined through high-performance liquid chromatography by Vempatapu et al. (2020). The researchers employed silica stationary phase, n-hexane mobile phase and isopropanol modifier to achieve optimal separation between diesel and biodiesel, and between vegetable oils and used cooking oil. The applied method was authenticated with samples simulating real-world scenarios. The method proposed by Vempatapu et al. (2020), had the advantage of determining three analytes without co-elution within a short life span. In a different research study, Vempatapu et al. (2019) determined kerosene as an adulterant in diesel through use of chromatography and high mass spectrometry. The study investigated the widespread use of low-value subsidised kerosene as an adulterant of Euro IV diesel fuel oil. The aniline point, density, atmospheric distillation, viscosity, cetane index and total sulphur were determined to generate an initial assessment. The researchers reported that as a result of inadequacies of the physicochemical property method, gas chromatography (GC), high performance liquid chromatography (HPLC) and high-resolution mass spectrometric analysis (HRMS) were carried out to detect the adulterants. The GC, HPLC and HMRS methods revealed a significant level of adulterants, in the Euro IV diesel.

Two-dimensional gas chromatography has also been used in the separation of compounds in fossil and biofuels. Murtada et al., (2022) described two-dimensional gas chromatography as a robust separation method that is based on the use of two columns containing different stationary phases based on an orthogonal separation mechanism. Hua et al. (2003) further described two-dimensional gas chromatography (GCxGC) as a hyphenated method in which two distinct chromatographic separation mechanisms act in series with better result for component identification and separation. Ferreira et al. (2021) used colour based chromatographic images obtained from comprehensive two-dimensional gas chromatography in authentication analyses to determine adulterants in diesel fuel oil. A GCxGC-MS comprising of a Trace 1300 GC coupled with an ISQ single quadrupole mass spectrometer was used to determine the Volatile organic compounds in the samples. Results from the chromatographic images allowed the determination of all brands and just about every tested adulterant. Rocha and Sheen (2019) determined the physicochemical properties of petroleum derivatives and biodiesel using GC-MS and chemometric methods with uncertainty estimation. The researchers used chemometric modelling to determine the physicochemical properties of the biodiesel samples in place of ASTM standards because they are expensive and time consuming. GC-MS profiles were obtained, and physicochemical properties was measured using ASTM standard methods. Results revealed that SVM was found to be better for predicting physicochemical properties, while the PLS could be used to generate predictive models of physicochemical properties based on the GC-MS data.

Hua et al. (2003) proposed the use of two-dimensional gas chromatography with a sulphur chemiluminescence detector to determine the sulphur containing compounds in diesel fuel oil. Hua et al. (2003) used an HP 6890 GC fitted with a jet-cooled thermal modulator assembly. Data collected was detected, analysed, integrated and quantitated by the GCxGC special software.

2.3.1.3 Infrared spectroscopy analysis

Fourier Transform Infrared Spectroscopy and Mid Infrared Spectroscopy have also been used to determine adulteration in diesel fuel oils. Barra et al. (2020) described FTIR as a strong and non-destructive analytical method that could afford a rapid and effective analysis of fuel samples regardless of their physical state (solid or liquid). Nespeca et al. (2018) reported the use of a rapid and simultaneous prediction of eight diesel fuel quality parameters using ATR-FTIR analysis. The diesel quality parameters determined were density, flash point, distillation points, total sulphur content, and cetane index. The attenuate total reflection (ATR) makes it possible for a small quantity of sample to be used for an analysis; a simple drop maybe adequate to register a spectrum (Barra et al., 2020). The researchers determined the quality parameters of 409 samples using standard methods and FTIR spectra acquired in ranges of 4000-650 cm^{-1}. To improve the signal to noise ratio of the models, generalised least square weighting (GLSW), partial least square (PLS) and orthogonal signal correction (OSC) were evaluated. The FTIR/PLS models presented accuracy comparable to other reference methods. Barra et al. (2020) used FTIR spectroscopy and Partial Least Square (PLS) to predict the cetane number in diesel fuels. Fifty diesel samples conditioned in opaque glass vials and stored at 4-9°C to avoid component degradation were used for the analysis. The FTIR spectra were recorded using a Perkins Elmer Spectrum One FTIR Spectrometer, with a crystal attenuate total reflection (ATR) of Zinc Selenide (ZnSE). Results showed that the combination of FTIR spectroscopy and

Partial Least Square (PLS) regression offered an efficient technique for predicting cetane number in diesel fuel oil in the range of 49-59.

Barra et al. (2019) used FTIR fingerprints associated with a partial least squares discriminate analysis (PLS-DA) model for the rapid detection of smuggled non-compliant diesel sold in Morocco. The researchers reported that in order to certify the quality of a diesel fuel sample, as set in the quality criteria circular of the Morocco Ministry of Energy, their physicochemical properties (viscosity, cetane number, distillation points, and sulphur content) must be determined. However, the physicochemical properties test require qualified personnel, sophisticated equipment, and time. Thus, the researchers used an FTIR; a rapid, cheap, and non-destructive technique. A GC-MS was used to determine the chemical composition of the 19 authentic and 11 smuggled diesel samples used in the analysis. The infrared fingerprint of all the samples was recorded and each spectrum processed by PCA. The PCA result was able to show dissimilarities between both classes of diesels. In a different study to determine biodiesel adulteration with vegetable oil Paiva et al. (2015) used a portable near-infrared spectrometer. The transmittance and absorbance spectra of the 118 samples in the range of 950-1650 nm was acquired using an ultra-compact spectrophotometer (MicroNIR) and a Fourier transform benchtop instrument (FT-NIR) from 800-2500 nm. Result revealed comparable performances between the portable and the benchtop instruments demonstrating the feasibility of monitoring in situ the quality of diesel/biodiesel blends.

Skrobot et al. (2019) reported the use of infrared spectroscopy and parallel factor analysis to determine the stability of diesel fuel oil. Eighteen diesel fuel oil samples containing 8% v/v biodiesel were used in the four standard stability test analyses and analysed with mid-infrared spectroscopy. Stability studies were conducted using ASTM standard procedures D7545, D4625, and D6468 and the European standard EN15751 with the generated data analysed with the chemometric tool parallel factor analysis. The above study showed that the developed parallel factor analysis model with the FTIR spectra data supported the detection of specific modifications caused by the stability test. In addition, Shimamoto and Tubino (2016) reported the use of ultraviolet-visible spectroscopy as an alternative method to quantify biodiesel in standard diesel-biodiesel blends and samples adulterated with vegetable oil. Vegetable oil produced from soya beans oil was used as the adulterant, while methanol was used as the alcohol and sodium methoxide as the catalyst. The ultraviolet spectra were recorded in an Agilent Cary 5000 spectrophotometer with a spectral range of 190-700 nm and a spectral resolution of 1 nm. Results revealed the satisfactory performance of the ultraviolet method for the quantification of biodiesel in diesel-biodiesel blends

2.3.1.4 Sensor based techniques

Sensor based techniques have similarly been used for the determination of adulterants in diesel fuel oil. In their research, Tamer et al. (2020) used a mathematically based sensor integrating transmission line for the detection of adulteration in unbranded and branded diesel fuel oil. The investigation was done both numerically and mathematically. The electrical properties of the test samples were evaluated, and simulation was carried out using Finite Integration Technique (FIT) based electromagnetic simulation software. Simulated results showed that the mathematically based sensor integrating transmission line could be used as a liquid sensor especially to identify different types of adulterants in diesel fuel oil. The transmission line-based sensor could be used for the detailed sensing of different liquids. In a study by Kanyathare et al. (2018), the researchers used a prototype optical sensor for the identification of diesel fuel oil adulterated by cheap kerosene. The prototype sensor utilized the reflection from a fuel film over a roughened glass plate. Results revealed a high sensitivity of the developed sensor in determining the adulteration of diesel with kerosene composed of as low as between 5 and 15%.

A portable, inexpensive but robust light weight optical fibre sensor was designed by Dilip and Sivasubramonia (2020) to estimate fuel adulteration in automobiles. The researchers used vthe light intensity difference that occurs due to the difference in the refractive index of the adulterated diesel fuel oil. Of note is the use of physicochemical properties by the researchers to determine the compositional variations of the fuel samples and statistical designs in discriminating the adulterated samples. In this method, each fuel sample was poured into the sensor, the transmission loss was then calculated which helped to identify the percentage of adulteration with the help of the output voltage. Diesel samples adulterated with kerosene and petrol were used in the experiment. In similar research study into the use of fibre optic sensors, Datta and Saha (2021) investigated the use of ultra-sensitive fibre optic sensors for use in the detection of kerosene as an adulterant in gasoline by propagating a higher-order Bessel-auss beam. Result revealed as low as 0.02% kerosene adulteration. Also, Yadav et al. (2019) in their research to detect the adulteration of automobile fuel (gasoline and diesel) with kerosene introduced a novel clad planar waveguide technique. A novel metal clad planar waveguide, having a hollow prism, was filled with adulterated diesel and gasoline. The proposed sensor has a two-step fabrication process: firstly, the deposition of metal film and secondly the deposition of polymer film on the hollow rectangular prism. The researcher's reported that this proposed method of automotive fuel adulteration detection has several benefits which include its small size, safety with flammable liquids, ease of fabrication and the possibility of making it portable and compact for in-situ measurements.

2.3.1.5 Nuclear magnetic resonance spectroscopy

Nuclear magnetic resonance (NMR) is a flexible spectroscopic technique that has become one of the most powerful methods for the interpretation of the structure of chemical compounds, while the hydrogen nuclear magnetic resonance (^{1}H NMR) is a faster automated measurement method that allows for larger number of samples to be measured in a short period of time (Monteiro et al., 2009). Monteiro et al. (2009) used the ^{1}H NMR and chemometric method for the evaluation of biodiesel-diesel blend quality. Results revealed that the chemometric models were suitable for the prediction of biodiesel and oil concentration in fossil diesel. The researchers concluded that the ^{1}H NMR and chemometric methods were useful for the quality control of biodiesel-diesel blends. In a similar study, Cunha et al. (2019) used the time-domain NMR as a methodology to quantify the percentage adulteration of diesel fuel with soybean oil and frying oil. The researchers first determined the kinematic viscosity of the commercial diesel and adulterant samples at 25°C. Low field NMR experiments were then performed to detect and quantify the level of adulteration. To validate the NMR as a technique to detect and quantify the percentage of adulteration of diesel, the researchers used the middle infrared (MIR) experimental method. Results further revealed that the NMR data showed a strong linear correlation to kinematic viscosity and MIR measurement. Similarly, de Aguiar et al. (2022) used data fusion of middle-resolution NMR spectroscopy and low-field relaxometry coupled with common dimension analysis to monitor diesel fuel adulteration. According to de Aguiar et al. (2022) Middle-resolution NMR and time-domain NMR relaxometry using low-field and benchtop NMR instruments are effective tools to deal with diesel fuel adulteration. Results revealed that the common dimensional exploratory analysis showed that middle resolution nuclear magnetic resonance (MR-NMR) and time domain NMR are complimentary techniques for assessing diesel fuel quality. The method also provided excellent accuracy in quantification and classification.

2.3.1.6 Other Related Adulteration Detection Methods

Diesel fuel adulteration techniques are not limited to FTIR, GC-MS, NMR, and sensor-based methods. Several researchers have developed other methods of diesel fuel adulteration detection. Mahmodi et al. (2019) reported the detection and classification of diesel-biodiesel blends by quadratic discriminant analysis (QDA), linear discriminant analysis (LDA) and support vector machines (SVM) using an electronic nose. LDA is a statistical method used in pattern detection and machine learning to determine the linear combination of features capable of discriminating two or more objects from each other (Mahmodi et al., 2019). SVM is a supervised training technique used for regression and classification while QDA is a simplified form of linear discriminant analysis (Khasnobish et al., 2011). Results revealed the superior efficacy and precision of the support vector machine technique in the discrimination and classification of biodiesel and diesel fuel oil. In a different study to detect diesel fuel adulteration with kerosene, Bell et al. (2018) reported the use of fluorescent paper strips with smartphone read-out. The researchers investigated 4-dimethylamino-4-nitrostilbene fluorescent molecular rotors for their likely use as viscosity probes. Results revealed a good linear correlation between the decrease in fluorescence and an increase in the less viscous kerosene in diesel blend. Also, immobilisation of the hydroxyl derivative 4-dimethylamino-4-nitrostilbene in cellulose paper yielded test strips that could preserve the behaviour of the fluorescence indicator. The method could dependably reveal the presence of kerosene in diesel from 7-100%.

Ejofodomi et al. (2021) reported the use of the gaseous vapour (GVE) technique as an innovative method for automobile fuel adulteration detection at point of sale (POS) terminals. A PePVEAT device was used to test 1 litre samples of Kerosene, gasoline and diesel fuel obtained from Nigerian Petroleum Corporation (NNPC). The PePVEAT is a portable device for adulteration detection at the POS, unlike other methods that require specialised equipment, are time consuming, need experienced technicians to operate them and cannot be used at the point of sale (Ejofodomi et al., 2021). Results obtained from the GV analysis of the fuel samples revealed that the three petroleum products displayed differing chemical characteristics. Diesel gave its peak emission between 10-20 seconds, kerosene between 10-30 seconds and gasoline emission between 50-70 seconds. The variations observed in the concentration and timing of emissions showed that GV could be utilized to detect adulteration of diesel with kerosene. Leghrib et al. (2020) reported the use of an ultrasound technique for the monitoring of automobile fuel adulteration. The adulteration experiment was performed using three separate automotive fuel samples, namely diesel, gasoline, and kerosene. The measurement analysis was performed using the ultrasound technique in backscattering pulse echo mode. To determine the behaviour of the three different samples under ultrasound, parameters such as acoustic impedance and propagation speed were calculated on the basis to two main recorded echoes. To successfully discriminate between adulterated fuel samples and unadulterated fuel samples the collected ultrasound data was subjected to principal component analysis.

Soares and Rocha (2020) reported the use of a green volumetric technique for the determination of biodiesel content in diesel blends or mixtures with vegetable oils while exploiting the solubility differences in an ethanol-water medium. The proposed technique was based on the differences observed in the solubility of diesel and biodiesel or vegetable oils in an aqueous-ethanol medium. A linear response was obtained for biodiesel-diesel samples from 7.0 to 25% v/v, while for biodiesel-vegetable two linear ranges were obtained at 20 to 50% v/v, and 50 to

80% v/v all dependent on the water content in the titrant. Results obtained for the volumetric technique agreed with those obtained with flow-based spectrophotometric reference methods at 95% confidence level. The proposed technique is practical, fast, environmentally friendly, and cost effective.

2.3.2 Effects of Fuel Adulteration on Engines and the Environment

All engines are designed and manufactured to operate on specified fuel (Ale 2003). The deliberate addition of adulterants to diesel fuel has damaging effects on fuel properties and engine performance, such as fuel consumption, engine heating, and engine start-up control, likewise, adulteration of fuel increases the emission of exhaust gases, hydrocarbons, and particulate material (Corgozinho et al., 2008; Cunha et al., 2019). According to Toche et al. (2015), fuel adulteration results in damage to motor vehicles and emission of harmful gases which affects human health. Fuel adulteration leads to monetary losses for the consumer, greater emissions to the environment, and damage to engine parts (Babu et al., 2017). The adulteration of diesel fuel oil with kerosene known to be high in sulphur in India, could lead to the formation of sulphuric acid, which in turn could lead to starting difficulties, increased emissions, and fuel consumption (Vempatapu et al., 2019). The adulteration of diesel fuel with kerosene reduces the diesel lubrication function, which leads to faster wear of engine parts like valves, pistons, and rings (Taksande and Hariharan, 2006). Similarly, Ehsan et al. (2010) reported that fuel adulteration also leads to crankcase dilution. Crankcase dilution or fuel dilution is a phenomenon in which unburned and excessive engine fuel leaks into the crankcase and mixes with the engine lubricant (Yu et al., 2021). Garg et al. (2015) reported that diesel fuel adulteration could lead to increased engine emissions of NO_x, CO, CO_2, PM, and other toxic substances like PAHs and volatile organic compounds (VOC).

The addition of high boiling compounds to diesel fuel leads to engine wear and increased knock which also leads to starting difficulties, while low boiling compounds cause vapour lock in engines (Wiedemann et al., 2005). Similarly, Skrobot et al. (2007) added that adulteration of fuel with solvents causes poor engine performance, tax revenue losses, and environmental pollution. In contrast Ale (2003) added that not all types of adulteration are harmful to the health of members of the public although some adulterated fuel increases emissions of very harmful pollutants some others may have little or no effect on the air quality. Also, Tharby (2002) stated that the addition of adulterants to diesel fuel is not harmful or damaging provided the end product (fuel) meets the engine manufacturers' specifications, particularly for cetane number and viscosity.

2.4 Summary

This chapter has explored the relationship between the discovery of crude oil in Nigeria, its refining, sales, usage, and the damage to the environment of the Niger Delta Region. The discovery of crude oil in Nigeria in 1956 brought an economic boom to the nation and also brought gloom to the people of the Niger Delta Region. The damage to the ecosystem, soil, surface and groundwater was captured in this chapter. Also, the state of the four refineries, presently moribund, and the non-standard refining of crude oil was presented in this chapter. The perspective of the perpetrators of the non-standard refining of crude oil and a critical review of the current state of the art of adulteration detection methods and tools was presented. However, the main theme that runs across this chapter is the non-standard refining of crude oil to produce diesel fuel oil and the impact of the non-standard refining. Also, the physiochemical properties of diesel fuel oil, diesel fuel adulteration and the effects of diesel fuel adulteration. The effect of the activities of the non-standard crude oil refiners on the environment, government regulations and policy and finally, engine performance analysis.

The chapter shows that the Nigerian government presently relies on importation of refined petroleum products due to the poor state of their refineries. The imported petroleum products do not meet the demand of the public. This had led youths in the Niger Delta to go into the non-standard refining of crude oil. The products from the refined crude oil such as kerosene, diesel and gasoline are sold domestically and regionally to buyers who get it cheap, compared to government recognised retail outlets. Network (2013) reported that variations in the quality of the products refined are corrected by mixing kerosene with diesel. Also, stakeholders in the NDR are excluded in the decision-making process resulting from crude oil pollution, land and river contamination, the eradication of non-standard refineries, and mangrove conservation processes. Several studies have reported on the effect of crude oil exploration to local communities.

A large body of literature exists on the effect of the local refining of crude oil on the economy of Nigeria. Also, there is a good number of publications on the effect of crude oil refining on the environment. However, there is a dearth of literature on the physicochemical properties of the locally refined diesel fuel oil and their effect on diesel engine performance and emissions, and also on the sustained impact of the activities of the local crude oil refiners on their host communities. Thus, this study details:

1. The research design.
2. A study of the sustained impact of the activities of the local crude oil refiners on their host communities
3. An investigation into the physicochemical properties of locally refined diesel fuel oil and its effect on engine performance and emissions.

Chapter 3 Research design

3.1 Introduction

In Chapter 2, a critical literature review was presented. This chapter presents the research design for the investigation into the sustained impact of the activities of the local crude oil refiners on their host communities, the physicochemical properties of locally refined diesel fuel oil, and the effect of the diesel fuel oil on engine performance and emissions. This study used multiple methods to reach its outcomes. Denzin (1978) described this “multiple methods of research” as triangulation and defined it as “the combination of methodologies in the study of the same phenomenon.” In the case of this study, experimental and survey research methods were applied. Also, presented in this chapter is the research gap, a proposed method of stakeholder/community relationship with oil multinationals and the government, data sources, the study area, data collection process, and data analysis tools. Some sections of this chapter have been published in journal papers (Bebeteidoh et al., 2020a; Bebeteidoh et al., 2020b).

3.2 Research gap

It was determined from Chapters 1 and 2 that problems exist that have led youths in the NDR into establishing non-standard crude oil refineries, these being the scarcity of petroleum products like diesel and gasoline from government approved retail outlets, the moribund state of the government refineries and the ready market that has been created as a result of these other factors. The exploration and exploitation of crude oil has been recorded to come with its attendant pollution as reported in sections 2.2.3, 2.2.4, and 2.2.5. The nonadherence of citizens to crude oil extraction and refining laws, and the government’s inability to enforce the regulations, and in cases where they do, their representatives tend to cause more damage to the environment (see section 2.2.4). The inability of the government and oil multinationals to include stakeholders in the NDR in the decision-making process resulting from crude oil pollution as reported in section 2.2.6, has led to sabotage of oil infrastructures, and lack of support for government initiatives on the part of stakeholders. Also, as reported in Chapter 1, the NRD fuel oil is sold to the public daily. While members of the public purchase the products cheaply, and the refiners make huge profit from sales, literature is unavailable on the content of the NRD fuel oil and how harmful it is to engines and its emissions to the environment. This study proposes a method (see Figure 3-1), where the stakeholder/community is consulted in the form of a social study (questionnaire), feeding into a scientific study, and the result from the scientific study and then an engineering study.

The proposed method is applied in this thesis to the specific case of the Niger Delta Region (see Figure 3-2). This approach involves all stakeholders and generates required feedback. Furthermore, the research will ask society about the effect of the activities of the non-standard crude oil refiners on their host communities. This will first be determined by carrying out a pilot study. The essence of the pilot study is to test the study protocols, sample requirement strategies, data collection instruments and research techniques in preparation for a larger study (Hassan et al., 2006). The result obtained from the larger study will determine the scope of the scientific research which further outlines the process of the engineering research to provide evidence-based environmental outcomes. The evidence-based report of this study will detail the sustained impact of the activities of the refiners to host communities, and to members of the public using the NRD fuel oil. Also, the public will be made aware of the contents of the diesel through a physicochemical property analysis, a GC-MS and FTIR analysis and finally with engine performance and emission analysis.

3.2.1 Novelty of the Research Study

A novel approach was developed for this thesis, which could be applied in similar research studies elsewhere. The community's opinions were incorporated in the form of a social study. The opinion of the community then set the direction for the scientific research. The results from this research were fed into the engineering research. The results from the scientific and engineering research can then be fed back to the community to raise awareness of the wider impact and provide evidenced based results for policy makers and environmental agencies. The feedback will help keep communities informed of the inherent danger in the activities of the non-standard crude oil refiners and that of the refined products.

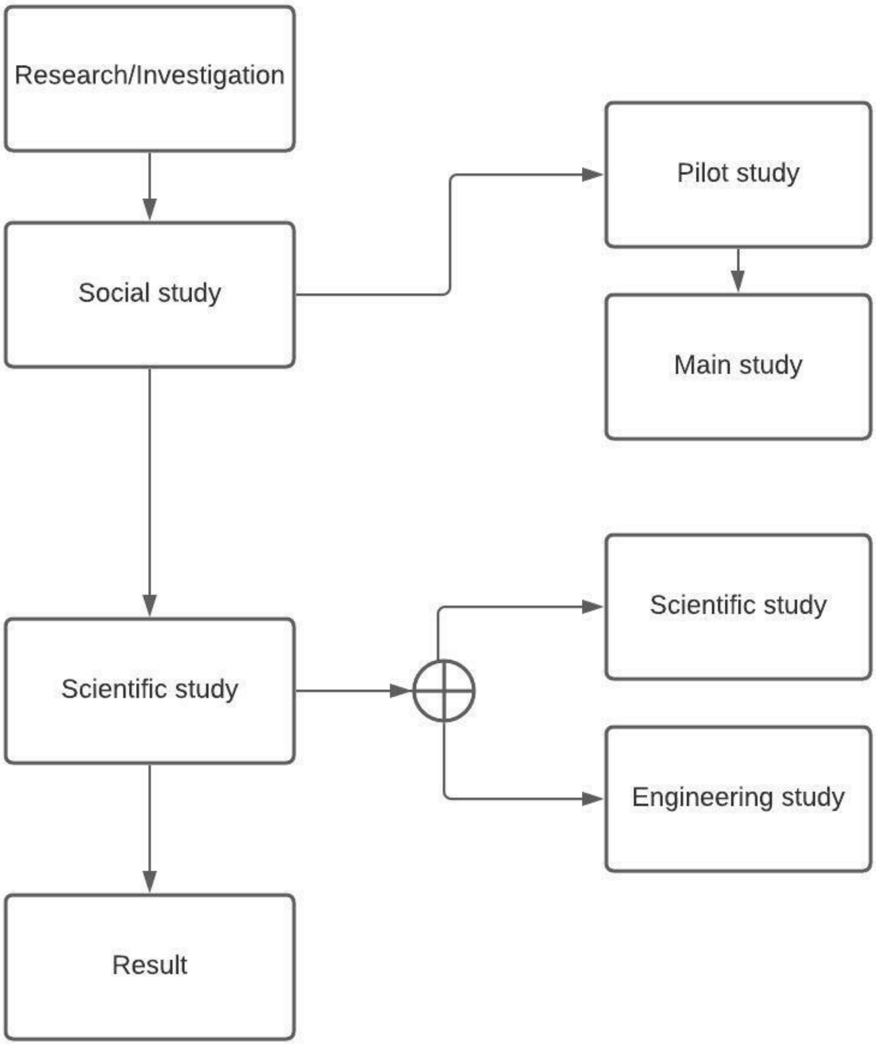


Figure 3-1 Proposed method

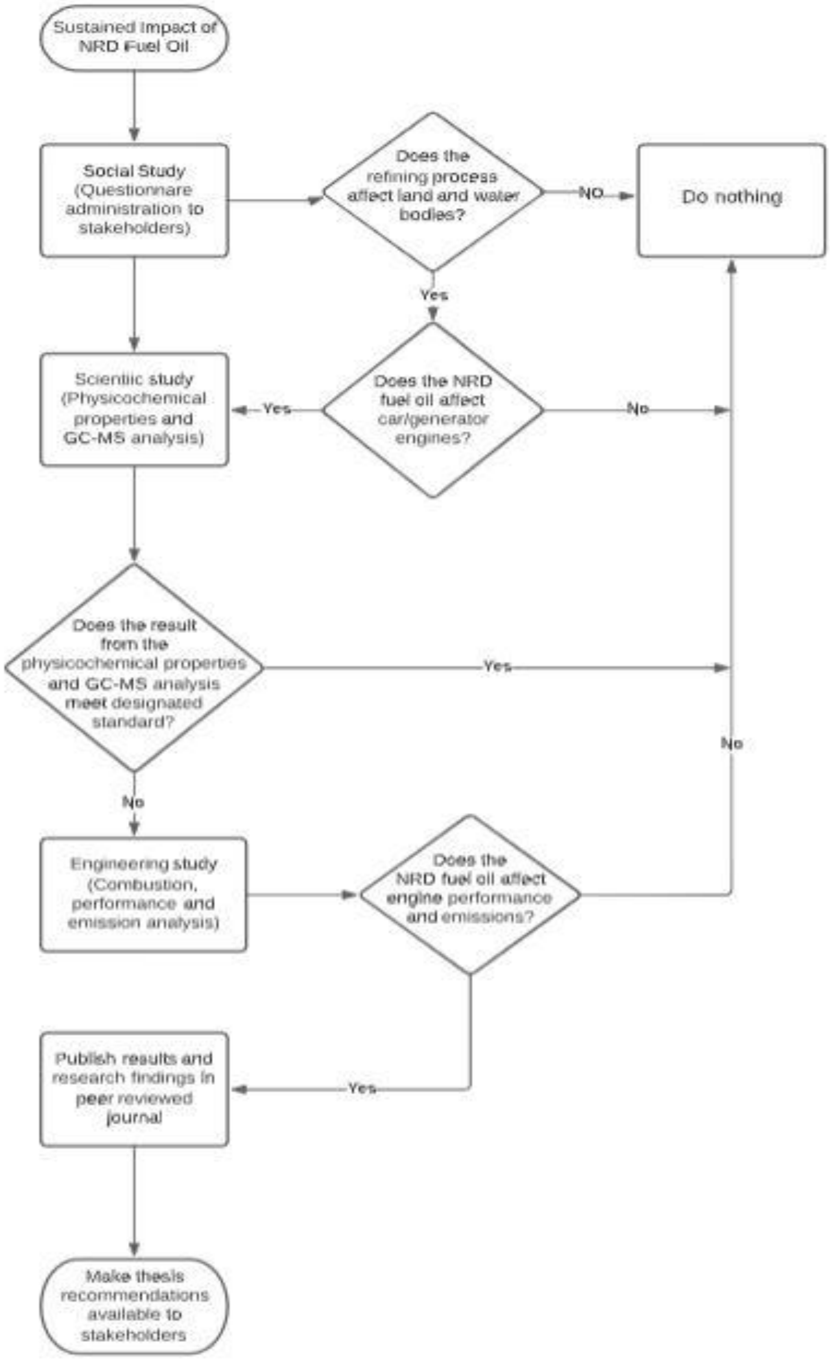


Figure 3-2 Research study approach

3.2.2 Contribution to knowledge

3.2.3 Data sources

The research used both primary and secondary data sources. The primary data were collected to answer the research questions detailed in section 1.3.2. This included the determination of the sustained impact of the activities of the non-standard crude oil refiners on their host communities (reported in Chapters 4), the physicochemical properties of the non-standard refined diesel fuel oils (reported in Chapters 5 and 6), and their effect on engine performance and emissions (reported in Chapter 7). The secondary data sources were mostly used in Chapter 2 (literature review), but also in other chapters of the thesis. The next section describes the data collection process, the questionnaire development process, and the data analysis.

3.3 Study area

The Niger Delta region of Nigeria is located in the southern part of Nigeria and stretches over an area of about 75, 000 sq. km, between longitude 5° E to 8° E and latitude 4° N and 7° N. The Niger Delta region is an important region because of its vast crude oil and gas reserves (see Figure 3-3) which earns the country over 90% of its foreign exchange (Babatunde et al. 2019). The region is a large arcuate delta (Nwaejije et al. 2017), with the biggest wetland in the African continent, freshwater swamps, lowland forest, mangrove swamps, and coastal barrier islands (Edino et al. 2010). The Niger Delta region is made up of nine administrative states (see Figure 3-4) with diverse ethnic groups (Odalonu, 2016). The socio-economic life of the Niger Delta people is mainly dependent on their geography and environment. The coastal, and riverine dwellers are fishermen/fisherwomen, and traders, those of the hinterland are mostly farmers (Orisakwe, 2021). Approximately 1650km of crude oil pipelines crisscross the Niger Delta (Network, 2013). These pipelines have become the major source of crude oil supply to the non-standard refineries in the Niger Delta.

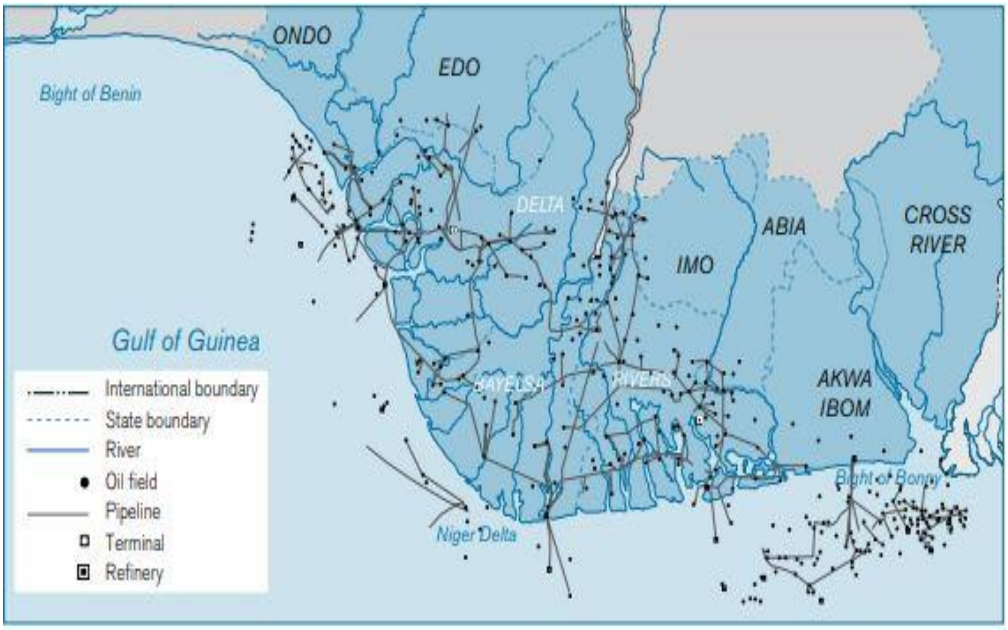


Figure 3-3 Crude oil installations in the Niger Delta (Katsouris and Sayne, 2013).

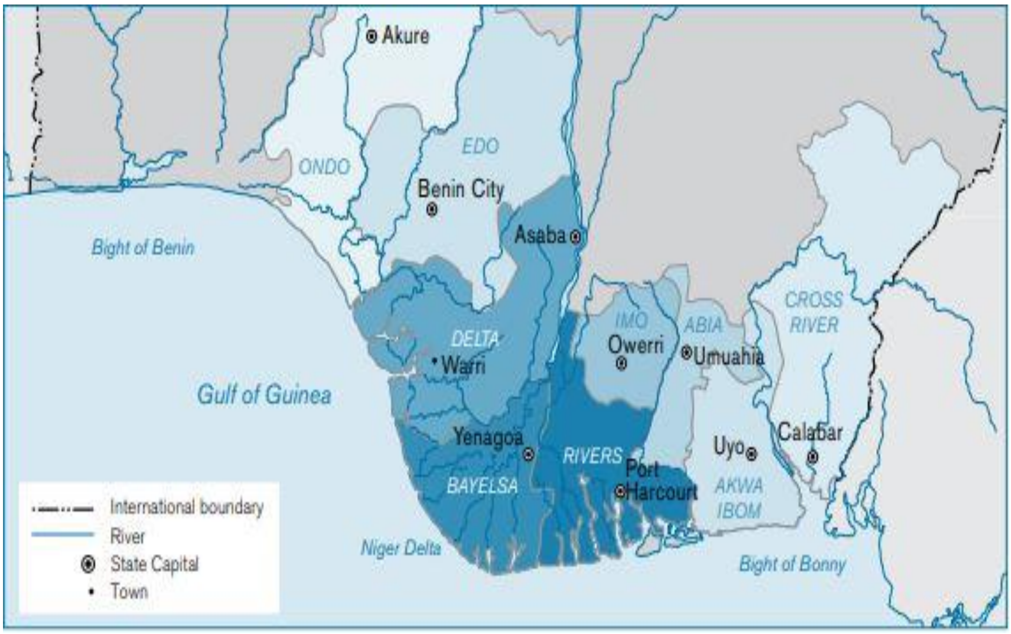


Figure 3-4 States of the Niger Delta (Katsouris and Sayne, 2013).

3.4 Data collection process

The data collection process for this research study was divided into two parts. Firstly, there was the administration of a questionnaire instrument to the communities where the non-standard refineries are located. Results obtained from the questionnaire necessitated the second phase of the study. Secondly, there was the collection of the non-standard refined diesel fuel oil samples from the three different camps (Non-standard refineries) in the Niger Delta region of Nigeria, and the control sample from a government retail outlet in Port Harcourt, Rivers State, Nigeria.

3.4.1 Questionnaire development

The administered questionnaire consisted of three sections. The first section gave the background information about the study, and who could take part in the survey. All participants were expected to read through this section before proceeding to section two. The second section had the contact details of the researcher. The essence of this section was to enable participants who have questions to contact the researcher directly. The third section of the questionnaire which was divided into three parts consisted of the demographic questions (sex, age, marital status, and occupation), the environmental and usage questions.

The questions covering environmental degradation consisted of items around farming, farm yields (harvests), fishing, fishing yields (harvest), refined waste disposal, and water pollution. While the questions covering usage covered the level of usage of the fuel, and challenges faced while using the fuels.

3.4.2. Pilot study

The online questionnaire survey commenced on 29/06/2018, with a pilot survey that ended on 19/07/2018 (see Appendix A). The feedback obtained from respondents enabled the researcher to make corrections to the main study questionnaire survey. The corrections are detailed below. Also see Appendix B for the main study questionnaire.

- Pilot study question 4: What is your occupation? Fisherman, trader, farmer, youth/students, business, and government employee.
- Main study question 4: What is your occupation? Fisherman/fisherwoman, trader, farmer, youth/students, business, and government employee.

- Pilot study question 5: Are you aware of the presence of a non-standard (local) refinery in/around your community?
- Main study question 5: Are you aware of the presence of a non-standard refinery in/around your community?
- Pilot study question 14: Do you buy the refined products from the non-standard (local) refineries?
- Main study question 14: Do you buy the refined products from the non-standard refineries?
- Pilot study question 15: How much quantity of fuel do you buy every month from the non-standard refined products?
- Main study question 15: How much quantity of fuel do you buy every month of the non-standard refined products?
- Pilot study question 17: The lower cost of non-refined fuel is worth the risk of engine damage?
- Main study question 17: The lower cost of non-standard refined diesel fuel is worth the risk of damage to my engine (car/generator)?
- Pilot study question 18: I spend so much to maintain my engine as a result of my using non-standard diesel fuel?
- Main study question 18: I spend so much to maintain my engine (car/generator) as a result of my using non-standard diesel fuel?
- Pilot study question 19: I experience engine stoppages any time, I use non-standard diesel fuel oil?
- Main study question 19: I spend so much to maintain my engine (car/generator) as a result of my using non-standard diesel fuel?

3.4.3 Administration of questionnaire instrument

The main questionnaire survey ran from 26/07/2018 through 31/01/2019. The survey questionnaire was administered to inhabitants of the Ologbobiri community in Southern Ijaw Local Government Area of Bayelsa state (see Figure 3-5), Akinima, and Okarki communities both in Ahoda West Local Government Area of Rivers State, Nigeria (see Figure 3-6). Before the administration of the questionnaires, meetings were held between the researcher and stakeholders, community heads in one instance, and a second meeting between the researcher, community heads, and community members. The meetings were held in order to properly brief the inhabitants of all three communities on the research study and to determine those interested in taking part. All participants who volunteered to take part in the study were informed of the anonymity of their details and thereafter were sent a link to the JISC online survey containing the questionnaire. A hardcopy questionnaire was also provided to members of the three different communities who could not read and write. The administration of the hardcopy questionnaire was to enable the researcher to obtain the opinions of the whole community irrespective of age, gender, level of education and position in the community enabling research outcome to represent all, but not a specific group.

Convenience sampling was used in this study because the respondents are residing close to the non-standard refineries and were willing to take part in the study. The questionnaire was administered to fishermen/fisherwomen, traders, youths, farmers, commuters, and chiefs in the various communities. A total of 487 respondents completed the questionnaire. This was after the initial pilot survey was administered to 30 respondents.

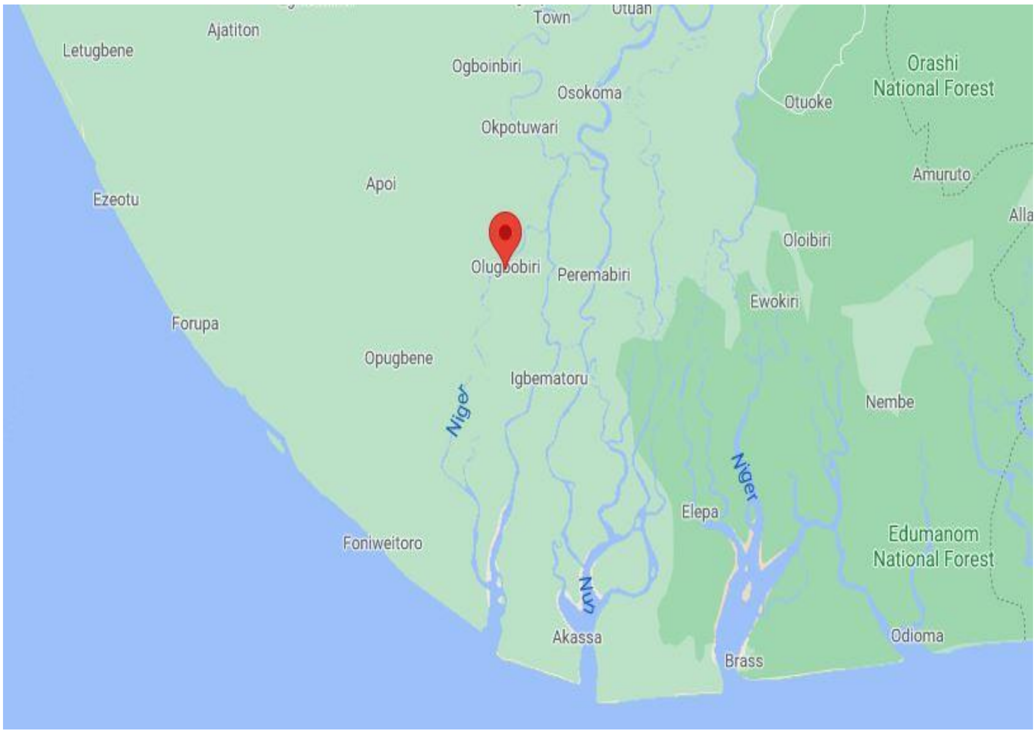


Figure 3-5 Ologbobiri community in Southern Ijaw Local Government Area of Bayelsa State, Nigeria (Google Map)

Figure 3-6 Akinima and Okarki communities in Ahoda-West Local Government Area of Rivers State, Nigeria (Google Map)

3.4.4 Diesel fuel oil samples

The test samples were collected from three different non-standard crude oil refineries. These refineries were selected because they were accessible to both nearby communities and traders who buy the refined products. The non-standard refineries are located in both Rivers and Bayelsa states. Both states are part of the nine oil-producing states in the Niger Delta region of Nigeria as presented in section 3.3. All three communities are riverine and depend on fishing, farming, and trading. Fishing and trading happen all year round while the farming season runs from November through August.

Three different two litre samples, refined at different times, were obtained from each camp. This was done in order to determine their physicochemical properties, the consistency in the refining process from each camp, and the engine performance and emission analysis. The samples were handled, stored, and transported to the United Kingdom for laboratory analysis according to ASTM fixed designation D4057-19.

3.5 Data analysis

3.5.1 Demographics

In the analysis of the questionnaire data, the demographics of the respondents were first considered. A summary of the demographics is presented in Chapter 4. The characteristics of the research participants ranged from their sex, age, marital status, and occupation.

3.5.2 Summary statistics

The data set from the JISC online survey and the hardcopy questionnaire was inputted into a Microsoft Excel spreadsheet and exported into IBM SPSS 26 statistical analysis software. A summary statistics of the six environmental and four usage statements is presented in Chapter 4. The mean, median, mode, and standard deviations were determined. Also, factor analysis was carried out on the data. DeCoster (1998) described factor analysis "as a collection of methods used to examine how an underlying construct influences the responses on a number of measured variables”. Factor analysis is applied as an exploratory tool to decrease the dimensionality of multivariate data (Bartholomew, 1980). Two main factor analysis techniques exist, Confirmatory Factor Analysis (CFA) and Exploratory Factor Analysis (EFA) (Yong and Pearce, 2013). In this study, EFA was applied as the outcome of EFA will discover the number of factors influencing variables and to analyse which variables go together” (Yong and Pearce, 2013).

The Kaiser-Meyer-Olkin (KMO) Measure of Sampling Adequacy (MSA) and Bartlett’s test of sphericity were also determined. The KMO is used to ascertain if a set of variables is properly intercorrelated to justify an exploratory factor analysis (Wiesen and Odum, 2019). Bartlett’s test of sphericity tests the “hypothesis that the study’s correlation matrix is an identity matrix, which would indicate that the variables are unrelated and therefore unsuitable for structure detection” (IBM, 2014). Other test carried out in the analysis of the questionnaire data set includes the Chi-Square test, Correlation Spearman rho, and Cramer’s V. Cramer’s V is a measure of the strength of the association that ranges from a minimum value of zero to a maximum value of one (Acock and Stavig, 1979).

3.5.2.1 Statistical Package for Social Sciences (SPSS)

The SPSS statistical software package (Version 24) was used in the analysis of the questionnaire instrument administered in Chapter 4 to investigate the sustained impact of the activities of the non-standard crude oil refiners on their host communities. SPSS “is a package of programs for manipulating, analysing, and presenting data” which is commonly used in diverse disciplines (Šebjan and Tominc, 2015). SPSS can handle large data sets, has a simple user interface and is easy to learn (Sewall, 2019). Though expensive compared to other statistical software packages like R, STATA and Microsoft Excel (Sewall, 2019), in this research study the SPSS software package was used because of the robust statistical support system, which was made available by Newcastle University. The support program provided the researcher with the basic knowledge used in the analysis of the questionnaire data collected and analysed in Chapter 4.

3.5.3 Physicochemical properties analysis

The physicochemical properties of the non-standard refined diesel fuel oil and the control sample were determined as reported in Chapter 5. This was to identify the quality (Aleme et al. 2010; Rahman et al. 2021), and consistency in the refining process of the NRD fuel oil sold to the public in Nigeria. The study of the physicochemical properties of fossil fuels is undertaken to ensure that the fuels conform with international standards like EN 228 for gasoline, EN 590 and ASTM D975 for diesel (Tsanaktsidis et al., 2013). The density, kinematic viscosity, cetane index, calorific value, pour point, water content, and distillation temperatures were determined for all 9 NRD fuel oils and the control sample. Tests were conducted in line with ASTM D975, the designated standard for number two diesel fuel. All data recorded in the research were determined in triplicate (Knothe, 2005).

3.5.3.1 Fourier Transform Infrared Spectroscopy (FTIR)

The FTIR was used to determine the compositional variation (Nespeca et al., 2018) of the 9 NRD fuel oils and the control sample. FTIR is one of the analytical techniques widely used to monitor petro-diesel quality because of its speed, low cost, non-destructive nature and the quality of the screening (Soares et al., 2009; Barra et al., 2019). The FTIR can increase analytical frequency, reduce cost, and use smaller sample volumes for analysis (Nespeca et al., 2018). Due to the small volume of the NRD fuel oils and the control sample, FTIR was first used to determine the compositional variations of the test samples before the GCMS was used for quantification.

3.5.3.2 GC-MS analysis

The GC-MS analysis, as presented in Chapter 6, was used to separate, and quantify the various components in the non-standard refined diesel fuel oil. It was able to identify the volatile organic compounds (VOCs) present in the fuel samples. The target compounds were benzene (Ion 78), toluene (Ion 92), xylenes (Ion 106), and n-alkanes (Ion 57). The VOCs were quantified using a semi-quantitative method (Paterson et al. 2004).

3.6 Summary

This chapter has detailed the research design of this thesis. The research gap, the data collection process, instrument development, and data analysis processes were also discussed. Chapter 4 will present the element of the sustained impact of the activities of the local crude oil refiners on their host communities. The questionnaire development and analysis is reported in detail.

Chapter 4 Sustained Impact Assessment of the Activities of the Non-standard Crude Oil Refiners on their Host Communities

4.1 Introduction

In Chapter 3, the research design was presented. The non-standard refining of crude oil in the Niger Delta has become a source of worry for the inhabitants because of the environmental pollution resulting from the refining process. Adeloye and Ekadi (2021) reported the emission of harmful substances from the site of non-standard refineries. Also, Imoobe and Aganmwonyi (2021) reported the impact of oil leaks from non-standard refineries on water quality of the Ekehuan River, Edo State, Nigeria. This chapter will investigate the sustained impact of the activities of the non-standard crude oil refiners on their host communities through the administration of a questionnaire. Some sections of this chapter has been published in journal papers by the researcher (Bebeteidoh et al., 2020; Bebeteidoh et al., 2020).

4.2 Study methodology

A survey research method was adopted in this study through the administration of questionnaires to local stakeholders (Youths, chiefs, traders, farmers, fishermen/fisherwomen, and residents of host communities). Quantitative data was collected from three communities in the Niger Delta region of Nigeria with non-standard crude oil refineries and the data was analysed using descriptive and inferential statistical methods (Chi Square, Correlation, and Factor Analysis). Details of the study area is presented in section 3.2.1 in Chapter 3.

4.2.1 The questionnaire instrument

The study questionnaire was designed to investigate the apparent impact of the activities of non-standard crude oil refiners on their host community and the environment. It was divided into three sections, namely demographics, environmental, and usage groupings. The demographic section covered questions relating to the age, gender, and occupation of respondents, whilst the questions in the environmental group were related to the effect of the activities of the non-standard crude oil refiners on the environment. The usage grouping had questions relating to the effect of the non-standard refined diesel fuel oil on engines. Sections 2 and 3 were assessed by respondents on a six-point Likert type scale (Allen and Seaman, 2007) ranging from 1 = strongly disagree (SD) to 6 = strongly agree (SA). The respondents were asked to assess six statements relating to environmental impact, and five statements relating to usage. The six-point Likert scale was aggregated into a two-point scale of Disagree or Agree for ease of presentation. Boone and Boone (2012) established that a Likert Scale is composed of four or more Likert-type items that may be combined into a single composite score/variable during the analysis process. Harpe (2015) reported that “when aggregated scales are used in a study , they must be analysed as a group, because by analysing the items one-by-one causes statistical concerns through the inflation of the family-wise error rate.

4.2.3 Environmental impact statements

The environmental impact statement questions in section 2 of the questionnaire are detailed below:

- S1- The activities of the non-standard refiners has affected my community farm lands?
- S2- The activities of the non-standard refiners has affected the level of farm yields?
- S3- The activities of the non-standard refiners has affected my community fishing areas?
- S4- The activities of the non-standard refiners has led to reduction in fishing yields?
- S5- The major source of water supply is usually polluted by crude oil waste from non-standard refineries?

- S6- I am concerned about the method of disposal of refined waste by the non-standard crude oil refiners.

The usage impact statement questions in section 3 of the questionnaire are detailed below:

- S7- The refined products from non-standard refined have damaged my machine/engine in recent times?
- S8- The lower cost of non-refined fuel is worth the risk of damage to my engine (car/generator)?
- S9- I spend so much to maintain my engine (car/generator) as a result of my using non-standard diesel fuel?
- S10- I experience engine (car/generator) stoppages any time, I use non-standard diesel fuel oil?

4.2.4 Implementation and participants in the study

Preparation for the sustained impact study started in June 2018, with a pilot study (see section 3.3.2) which involved the administration of an initial 30 questionnaires. This enabled corrections to be made to the initial questionnaire before it was used for the larger study. The revised study questionnaire was administered using Jisc Online Surveys (formerly Bristol Online Surveys) from 26/07/2018 through 31/01/2019. The respondents were selected because they are indigenous people and are inhabitants of the affected communities. The respondents also had the required experience as a result of their long stay in their communities consequently this constituted convenient sampling (Riaz et al. 2021). The questionnaires were administered to youths, community chiefs, fishermen/fisherwomen, traders, government employees, and residents of the affected communities.

The analysis of the questionnaire was done using descriptive, and inferential (Chi Square and correlation) statistical methodologies in the IBM SPSS statistics software package (Version 24). Cronbach's alpha coefficient was used to compute the reliability of the questionnaire items. Reliability coefficient describes whether a questionnaire designer was right in anticipating a particular group of items to produce explainable statements about individual differences (Cronbach, 1951). DeVellis, (2016) recommended that Cronbach's coefficient of a scale should be above 0.7. The Cronbach coefficient obtained for the questionnaire items in this study was 0.92, and this provides confidence that the scale used for this study was measuring the same construct. In a research study, a construct is the underlying theme, abstract idea, or subject matter that the researcher wishes to measure using survey questions (Lavrakas, 2008). Nominal data also known as categorical data, was used in this research work because it can be used for classifying items or separating them into groups rather than each item having a numeric value (Gilbert and Prion, 2016).

The questionnaires were administered to three communities in the Niger Delta, namely the Ologbobiri community in the Southern Ijaw Local Government Area of Bayelsa State, Akinima and the Okarki communities both in the Ahoda West Local Government Area of Rivers State (see Figures 3-3 and 3-4 in Chapter 3). The communities were selected because they are riverine in nature and are involved in fishing and farming as a way of earning a living. The selected communities host a number of non-standard refineries and crude oil locations upstream that are owned by multinational corporations.

4.3 Results

The result of the questionnaire study is presented in this section. Firstly, the demographics of the respondents of the survey are considered followed by the responses to the environmental, and usage questions.

4.3.1 Demographics of the respondents and survey responses

A summary of the demographics of the questionnaire respondents is presented in Table 4-1. With an 81% response rate, 487 respondents completed the questionnaire. Of the 487 completed questionnaires, 32% of respondents fell into the age range of 42-45 years and only 3.3% of respondents were over 66 years old. Males made up the majority of respondents with 61.6% and females 38.4%. Some 75.4% of the respondents are married, while fishermen/fisherwomen, farmers and government employees made up 68.2% of the respondents. Chiefs were 4.7%, youths and traders were 12.9% and 8.4% of respondents, respectively.

Table 4-1 Demographics of respondents

Variables	Categories	Frequency	Percent
Age Bracket	18-25 years	40	8.2
	26-33 years	58	11.9
	34-41 years	130	26.7
	42-55 years	158	32.4
	56-65 years	85	17.5
	66 years and above	16	3.3
	Total	487	100
Gender	Male	300	61.6
	Female	187	38.4
	Total	487	100
Marital Status	Married	367	75.4
	Single	90	18.5
	Divorced	9	1.8
	Widow/Widower	21	4.3
	Total	487	100
Occupation	Fisherman/Fisherwomen	107	22
	Trader	41	8.4
	Farmer	103	21.1
	Youth/Student	63	12.9
	Business	28	5.7
	Government Employee	122	25.1
	Chief	23	4.7
	Total	487	100

4.3.2 Response to the six environmental questions, S1 to S6

- **‘The activities of the non-standard refiners have affected my community farmlands (S1) and yields (S2)?’**

Some 78% of the respondents agreed that the activities of the non-standard crude oil refiners affect their farmlands while 64% agreed that it affected their farm yields, as presented in Table 4-2, with the summary statistics of S1 and S2 presented in Table 4-3.

- **‘The activities of the non-standard refiners have affected my community fishing areas (S3) and fishing yields (S4)?’**

An overwhelming majority of respondents (96%) agreed that the activities of the non-standard refiners had significantly affected their fishing areas, while 94% agreed that they had also affected their catches, as presented in Table 4-2, with the summary statistics of S3 and S4 presented in Table 4-3.

- **The major source of water supply is usually polluted by crude oil waste from non-standard refineries (S5)?’**

Some 93% of respondents (see Table 4-2) agreed that waste generated and disposed of by non-standard refineries affects the source of water. The summary statistics of S5 are presented in Table 4-3.

- **‘I am concerned about the method of disposal of the refined waste by the non-standard crude oil refiners (S6)?’**

Some 96% of respondents (see Table 4-2) agreed that the non-standard crude oil refiners have a very poor waste disposal regime. The summary statistics of S6 are presented in Table 4-3.

4.3.3 Responses to the six usage questions, S7 to S10

- **'The refined products from the non-standard refineries have damaged my machine/engine in recent times (S7)?'**

Some 56.2% of respondents agreed that the refined products from the non-standard refineries are damaging to engines, as presented in Table 4-4, with the summary statistics of S7 presented in Table 4-5.

- **The lower cost the non-standard refined fuel is worth the risk of damage to my engine (car/generator)(S8)?'**

Some 57.7% of respondents disagreed that the low cost of non-standard refined fuel is worth the risk of damage to their engine as presented in Table 4-4, with the summary statistics of S8 presented in Table 4-5.

- **I spend so much to maintain my engine (car/generator) as a result of my using non-standard refined diesel fuel oil (S9)?'**

Some 53.1% agreed that they spend a lot to maintain their engine as a result of the usage of non-standard refined diesel fuel oil (see Table 4-4). The summary statistics of S9 are presented in Table 4-5.

- **I experience engine (car/generator) stoppages any time, I use non-standard refined diesel fuel oil(S10)?**

22.2% of respondents agreed that they experience engine stoppages while using non-standard refined diesel fuel oil, while 43.5% disagreed (see Table 4-4). The summary statistics of S10 are presented in Table 4-5.

4.3.4 Factor analysis

Factor analysis was carried out on the data set. Factor analysis (FA) is a multivariate statistical method that is applied in the transformation of data sets with high dimensions to lower dimensions and concentrates on the correlations of variables such that the variables in a factor are extremely correlated with each other while the variables in different factors are extremely uncorrelated with each other (Mahmoudi et al., 2021). To determine if factor analysis is suitable for a particular data set, the Kaiser-Meyer-Olkin (KMO) index is applied (Mahmoudi et al., 2021). A KMO >0.8 confirms the correctness of the factor analysis. The Kaiser-Meyer-Olkin (KMO) was 0.832, Bartlett's test was significant (p=0.001), and the determinant was 0.001. The data satisfies all the conditions for Factor analysis. Also, the number of the key factors in a factor analysis is generally considered as the "eigen-values of the correlation matrix with the values lager than one" (Mahmoudi et al., 2021). In this study, two factors were extracted of eigen-values of 4.62 and 2.75 (see Figure 4-1) which accounts for 73.73% of the variability of the six environmental impact, and four usage statements. The minimum, and maximum loading for the environmental impact statements were 0.701, and 0.807, while those of the usage impact statements were 0.661 and 0.781. So, the six statements came from one primary construct namely the effect of non-standard refineries on the environment, while the other four statements also came from one underlying construct namely the effect of non-standard refined diesel fuel on car/generator engines.

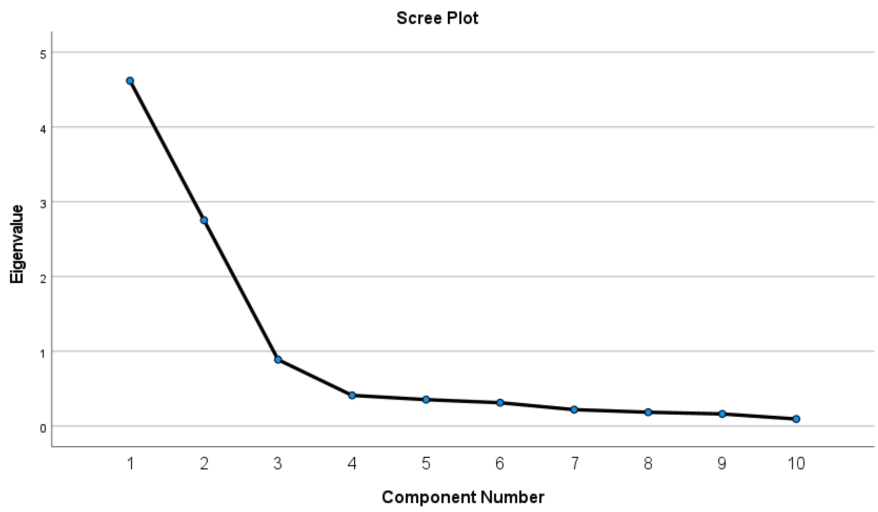


Figure 4-1 Scree plot of eigenvalues against all the factors

Table 4-2 Effect of non-standard crude oil refiners on the environment

Effect of the activities of the local crude oil refiners on the environment?	Count/%	Strongly Disagree	Disagree	Somewhat Disagree	Somewhat Agree	Agree	Strongly Agree	Disagree	Agree
The activities of the non-standard refiners has affected my community farm lands? (S1)	Count	10	39	58	210	85	85	107	380
	Row %	2.1	8.0	11.9	43.1	17.5	17.5	22	78
The activities of the non-standard refiners has affected the level of farm yields (harvest)? (S2)	Count	11	92	70	154	86	74	173	314
	Row %	2.3	18.9	14.4	31.6	17.7	15.2	36	64
The activities of the non-standard refiners has affected my community fishing areas? (S3)	Count	8	8	5	72	202	192	21	466
	Row %	1.6	1.6	1.0	14.8	41.5	39.4	4	96
The activities of the non-standard refiners has led to reduction of fishing yields? (S4)	Count	9	9	9	64	186	210	27	460
	Row %	1.8	1.8	1.8	13.1	38.2	43.1	6	94
The major source of water supply is usually polluted by crude oil waste from non-standard refineries? (S5)	Count	11	10	15	69	201	181	36	451
	Row %	2.3	2.1	3.1	14.2	41.3	37.2	7	93
I am concerned about the method of disposal of refined waste by the non-standard crude oil refiners? (S6)	Count	8	9	3	41	207	219	20	467
	Row %	1.6	1.8	0.6	8.4	42.5	45.0	4	96

Table 4-3 Summary statistics of the six environmental statements

Statements	Summary Statistics			
	Mean (M)	Median	Mode	Std. Deviation (SD)
The activities of the non-standard refiners has affected my community farm lands. (S7)	4.18	4.00	4	1.21
The activities of the non-standard refiners has affected the level of farm yields (harvest) (S8)	3.89	4.00	4	1.37
The activities of the non-standard refiners has affected my community fishing areas. (S9)	5.11	5.00	5	0.99
The activities of the non-standard refiners has led to reduction of fishing yields. (S10)	5.13	5.00	6	1.04
The major source of water supply is usually polluted by crude oil waste from non-standard refineries (S5)	5.02	5.00	5	1.09
I am concerned about the method of disposal of refined waste by the non-standard crude oil refiners (S6)	5.23	5.00	6	0.97

Table 4-4 Effect of non-standard crude oil refined diesel fuel on machine/engines

Effect of the activities of the local crude oil refiners on machine/engines?	Count/%	Strongly Disagree	Disagree	Somewhat Disagree	Somewhat Agree	Agree	Strongly Agree	Disagree	Agree	Not Applicable
The refined products from the non-standard refineries have damaged my/machine in recent times? (S7)	Count	12	25	13	158	78	38	50	274	163
	Row %	2.5	5.1	2.7	32.4	16	7.8	10.3	56.2	33.5
The lower cost of non-standard refined fuel is worth the risk of damage to my engine (car/generator)? (S8)	Count	143	120	18	19	21	20	281	60	146
	Row %	29.4	24.6	3.7	3.9	4.3	4.1	57.7	12.3	30
I spend so much to maintain my engine (car/generator) as a result of my using non-standard refined diesel fuel oil? (S9)	Count	14	16	28	137	79	43	58	259	170
	Row %	2.9	3.3	5.7	28.1	16.2	8.8	11.9	53.1	34.9
I experience engine (car/generator) stoppages any time, I use non-standard refined diesel fuel oil? (S10)	Count	81	81	50	46	37	25	212	108	167
	Row %	16.6	16.6	10.3	9.4	7.6	5.1	43.5	22.2	34.3

Table 4-5 Summary statistics of the four usage statements

Statements	Summary Statistics			
	Mean (M)	Median	Mode	Std. Deviation (SD)
The refined products from the non-standard refineries have damaged my machine/engine in recent times? (S7)	5.12	5.00	7	1.642
The lower cost the non-standard refined fuel is worth the risk of damage to my engine (car/generator)? (S8)	3.61	2.00	7	2.537
I spend so much to maintain my engine (car/generator) as a result of my using non-standard refined diesel fuel oil? (S9)	5.18	5.00	7	1.651
I experience engine (car/generator) stoppages any time, I use non-standard refined diesel fuel oil? (S10)	4.27	4.00	7	2.360

4.3.5 Association between demographic factors and environmental impact statements

A Chi-Square test of association was conducted to determine whether there is any association between the demographic factors and the way the environmental impact statements were answered by the respondents. The results of the analysis are presented in Table 4-6. There are four demographic factors and six environmental impact statements making a total of 24 Chi-Square test. Alpha level was set at 5% (0.05) and p values of 5% (0.05) were significant. On this basis, 10 of the 24 tests were found to be significant. For example, age bracket was significantly associated with the statement that non-standard refineries have affected the level of farm yields (harvests) [χ^2 = 14.99, p = 0.01 (<0.05), Cramer's V = 0.175]; but it was not significantly associated with any of the other statements. Gender was significantly associated with two statements namely those regarding community farmlands [χ^2 = 12.82, P = 0.001 (<0.05), Cramer's V = 0.162], and farm yields (harvest) [χ^2 = 10.41, p = 0.001 (<0.05), Cramer's V = 0.146]. Marital status was only significantly associated with one of the statements, namely non-standard refineries have affected level of farm yields (harvest) [χ^2 = 11.52, p = 0.01 (<0.05), Cramer's V = 0.154]. Occupation was significantly associated with all six of the environmental statements.

4.3.6 Association between demographic factors and usage impact statements

A Chi-Square test of association was conducted to ascertain whether there is any association between the demographic factors and the way that the usage impact statements were answered. The results of the analysis are presented in Table 4-7. There are four demographic factors and four usage impact statements making a total of 16 Chi-Square test. Alpha level was set at 5% (0.05) and p values of 5% (0.05) were significant. In this case, 4 of the 16 test were found to be significant. For example, marital status was significantly associated with the statement that, I experience engine (car/generator) stoppages any time, when I use non-standard diesel fuel oil [χ^2 = 10.96, p = 0.038 (<0.05), Cramer's V = 0.162]; but it was not significantly associated with any of the other statements. Occupation was significantly associated with three of the statements. The first was that the refined products from the non-standard refineries have damaged my machine/engine in recent times [$\chi^2 = 43.06$, $p = 0.00$ (<0.05), Cramer's V = 0.365]. The second was that the lower cost of the non-standard refined fuel is worth the risk of damage to my engine (car/generator) [$\chi^2 = 56.27$, $p = 0.00$ (<0.05), Cramer's V = 0.406]. Finally, occupation was associated with the statement, I experience engine (car/generator) stoppages any time, when I use non-standard diesel fuel oil [$\chi^2 = 114.18$, $p = 0.00$ (<0.05), Cramer's V = 0.597].

Table 4-6 Chi-Square association between demographic factors and environmental impact statements

Demographic	Environmental Impact statement	Chi-Square Test		Strength
		Value	**P value**	**Cramer's V**
Age Bracket	The activities of the non-standard refiners has affected my community farm lands?	7.671	0.175	0.126
Age Bracket	The activities of the non-standard refiners has affected the level of farm yields (harvest)?	14.992	0.010	0.175
Age Bracket	The activities of the non-standard refiners has affected my community fishing areas?	4.756	0.446	0.099
Age Bracket	The activities of the non-standard refiners has led to reduction of fishing yields?	2.294	0.807	0.069
Age Bracket	The major source of water supply is usually polluted by crude oil waste from non-standard refineries?	2.235	0.816	0.068
Age Bracket	I am concerned about the method of disposal of refined waste by the non-standard crude oil refiners?	6.486	0.262	0.115
Gender	The activities of the non-standard refiners has affected my community farm lands?	12.823	0.001	0.162
Gender	The activities of the non-standard refiners has affected the level of farm yields (harvest)?	10.407	0.001	0.146
Gender	The activities of the non-standard refiners has affected my community fishing areas?	0.001	0.977	0.001
Gender	The activities of the non-standard refiners has led to reduction of fishing yields?	0.310	0.578	0.025
Gender	The major source of water supply is usually polluted by crude oil waste from non-standard refineries?	0.176	0.675	0.019
Gender	I am concerned about the method of disposal of refined waste by the non-standard crude oil refiners?	0.102	0.750	0.014
Marital Status	The activities of the non-standard refiners has affected my community farm lands?	2.910	0.406	0.077
Marital Status	The activities of the non-standard refiners has affected the level of farm yields (harvest)?	11.523	0.009	0.154
Marital Status	The activities of the non-standard refiners has affected my community fishing areas?	0.716	0.869	0.038
Marital Status	The activities of the non-standard refiners has led to reduction of fishing yields?	1.759	0.624	0.060
Marital Status	The major source of water supply is usually polluted by crude oil waste from non-standard refineries?	2.669	0.445	0.074
Marital Status	I am concerned about the method of disposal of refined waste by the non-standard crude oil refiners?	4.403	0.221	0.095
Occupation	The activities of the non-standard refiners has affected my community farm lands?	31.384	0.001	0.254
Occupation	The activities of the non-standard refiners has affected the level of farm yields (harvest)?	59.242	0.001	0.349
Occupation	The activities of the non-standard refiners has affected my community fishing areas?	19.452	0.003	0.200
Occupation	The activities of the non-standard refiners has led to reduction of fishing yields?	16.505	0.011	0.184
Occupation	The major source of water supply is usually polluted by crude oil waste from non-standard refineries?	26.092	0.001	0.231
Occupation	I am concerned about the method of disposal of refined waste by the non-standard crude oil refiners?	17.736	0.007	0.191

Table 4-7 Chi-Square association between demographic factors and usage impact statements

Demographic	Environmental Impact statement	Chi-Square Test		Strength
		Value	**P value**	**Cramer's V**
Age Bracket	The refined products from the non-standard refineries have damaged my machine/engine in recent times?	6.788	0.237	0.145
Age Bracket	The lower cost of the non-standard refined fuel is worth the risk of damage to my engine (car/generator)?	9.861	0.079	0.170
Age Bracket	I spend so much to maintain my engine (car/generator) as a result of using non-standard refined diesel fuel oil?	8.329	0.139	0.162
Age Bracket	I experience engine (car/generator) stoppages any time, I use non-standard diesel fuel oil?	10.963	0.052	0.185
Gender	The refined products from the non-standard refineries have damaged my machine/engine in recent times?	0.162	0.687	0.022
Gender	The lower cost of the non-standard refined fuel is worth the risk of damage to my engine (car/generator)?	0.001	0.973	0.002
Gender	I spend so much to maintain my engine (car/generator) as a result of using non-standard refined diesel fuel oil?	0.420	0.517	0.036
Gender	I experience engine (car/generator) stoppages ant time, I use non-standard diesel fuel oil?	0.501	0.479	0.040
Marital Status	The refined products from the non-standard refineries have damaged my machine/engine in recent times?	4.202	0.240	0.114
Marital Status	The lower cost of the non-standard refined fuel is worth the risk of damage to my engine (car/generator)?	5.113	0.164	0.122
Marital Status	I spend so much to maintain my engine (car/generator) as a result of using non-standard refined diesel fuel oil?	1.002	0.801	0.056
Marital Status	I experience engine (car/generator) stoppages ant time, I use non-standard diesel fuel oil?	8.429	0.038	0.162
Occupation	The refined products from the non-standard refineries have damaged my machine/engine in recent times?	43.069	0.000	0.365
Occupation	The lower cost of the non-standard refined fuel is worth the risk of damage to my engine (car/generator)?	56.272	0.000	0.406
Occupation	I spend so much to maintain my engine (car/generator) as a result of using non-standard refined diesel fuel oil?	10.918	0.091	0.186
Occupation	I experience engine (car/generator) stoppages ant time, I use non-standard diesel fuel oil?	114.182	0.000	0.597

4.3.7 Correlation (Spearman rho) amongst environmental impact and usage impact statements

The relationships amongst the responses to the environmental impact statements of the effect of the non-standard refiners are presented in the correlation matrix in Table 4-8. All the bivariate relationships are significant at the 1% level. This shows that there is a complex relationship amongst the statements, and how they affect each other. For instance, the highest correlation is 0.862 between S3 and S4, signifying that “non-standard refiners have affected community fishing areas, which in turn has led to a reduction in fishing yields”. Nevertheless, this is not a cause-and-effect relationship as other factors could also affect fishing yields, such as the effect of farmlands which also has a significant relationship with fishing yields ($r = 0.492$, $p < 0.01$). The next highest correlation is 0.819 between S1 and S2, which indicates that the effects on farmland influence farm yields. In a similar manner, farm yield also has a significant correlation with “pollution of the water supply through the disposal of refined waste by the non-standard crude oil refiners”, with 0.458 and 0.356, respectively. Consequently, there was significant correlation between S3 and S6 ($r = 0.501$, $p < 0.01$), indicating that the “effect of the disposal of refined crude oil waste affects community fishing areas”. However, other factors could also affect the host communities fishing areas and farmlands. Also, there was correlation between S5 and S6 ($r = 0.574$, $p < 0.01$), indicating that the “method of waste disposal affects major sources of water”. All these indicate that the environmental impact of the activities of the non-standard crude oil refiners are complex and interrelated.

The result for the usage impact revealed that all of the bivariate relationships are significant at the 1% level (see Table 4-9). For example, the highest correlation is between S7 and S9 ($r = 0.846$, $p < 0.01$), suggesting that “the refined products from the non-standard refineries have damaged my machine/engine in recent times which in turn has led to spending so much to maintain my engine (car/generator)”. Nevertheless, other factors may lead to damage of car/generator engines. The next highest correlation in this category is 0.782 between S9 and S10, which indicates that “spending so much to maintain car/generator engine is influenced by stoppages from the use of non-standard diesel fuel oil”. In a similar manner, “refined products from non-standard refineries have damaged my machine/engine” (S7) has significant correlation with experience of engine stoppages (S10) with $r = 0.762$ ($p < 0.01$).

Table 4-8 Correlation matrix of environmental impact statements

	Environmental Impact Statements	S1	S2	S3	S4	S5	S6
S1	The activities of the non-standard refiners has affected my community farm lands?	1					
S2	The activities of the non-standard refiners has affected the level of farm yields (harvest)?	0.819**	1				
S3	The activities of the non-standard refiners has affected my community fishing areas?	0.503**	.550**	1			
S4	The activities of the non-standard refiners has led to reduction of fishing yields?	0.492**	.530**	0.862**	1		
S5	The major source of water supply is usually polluted by crude oil waste from non-standard refineries?	0.414**	.458**	0.626**	0.620**	1	
S6	I am concerned about the method of disposal of refined waste by the non-standard crude oil refiners?	0.353**	0.356**	0.501**	0.551**	0.574**	1

**. Correlation is significant at the 0.01 level (2-tailed).

Table 4-9 Correlation matrix of usage impact statements

	Environmental Impact Statements	S7	S8	S9	S10
S7	The refined products from non-standard refineries have damaged my machine/engine in recent times?	1			
S8	The lower cost of non-refined fuel is worth the risk of damage to my engine (car/generator)?	0.607**	1		
S9	I spend so much to maintain my engine (car/generator) as a result of my using non-standard diesel fuel?	0.846**	.637**	1	
S10	I experience engine (car/generator) stoppages any time, I use non-standard diesel fuel oil	0.762**	.663**	0.782**	1

**. Correlation is significant at the 0.01 level (2-tailed).

4.4 Discussion

This chapter aimed to determine the impact of the activities of the non-standard crude oil refiners in the Niger Delta on their host communities and their effect when used in diesel engines. The study showed that the activities of the non-standard crude oil refiners affected the farmlands and product yields of their host communities. This is because a significant number of the respondents agreed that the activities of the non-standard crude oil refiners have affected their community farmlands and harvest. The mode of transportation of crude oil to the non-standard refineries, their storage methods, refining processes, and refined waste disposal methods have resulted in the pollution of the soil and waterways by hydrocarbon components. This has led to the loss of soil quality, leaching and erosion. Hydrocarbon pollution damages farmlands and has a major effect on food security. Farmers in the study area also depend on streams, and rivers for the purposes of irrigation but the runoffs from the non-standard refineries which drains crude oil and refined products into them makes the water, hazardous for irrigation and farming activities. The continuous pollution of the soil has affected product yields of the farmers.

The majority of the respondents agreed that the activities of the non-standard crude oil refiners have considerably affected their fishing areas, and catches, and have become a source of worry for the fishermen, and fisherwomen. The pollution of streams and rivers by hydrocarbons harms the aquatic ecosystem which destroys the habitat of fish. The pollution of streams and rivers by crude oil and other petroleum products from the local refineries will also affect the health of fish which in turn affects the fishermen and fisherwomen. The spilled petroleum hydrocarbons float on the surface of the streams, and rivers thereby suffocating fish, and other aquatic creatures. With streams and rivers acting as the major source of drinking water in the affected communities, the pollution of such streams and rivers with crude oil becomes a major source of concern for the communities. Clean drinking water is needed for the socio-economic growth of any community, but this is not available for these communities. Instead, they are left to drink from streams and rivers in and around their communities. With most riverine communities lacking clean drinking water, the government should provide clean drinking water for the affected communities. This will help reduce sicknesses from water borne diseases. The government provision of clean potable water will help to achieve the United Nations Sustainable Development Goal six (SDG6) (UNDP, 2021).

The method of refinery waste disposal was also a major source of worry for respondents. The majority of respondents agreed that the poor waste disposal methods of the non-standard refiners in and around their production sites is damaging to the environment. Waste generated is disposed into nearby rivers, streams, and surrounding vegetation. This high level of waste is attributed to the crude level of refining. The waste produced not only contaminates the streams and rivers, but it also contaminates the ground water.

Products from the non-standard refineries are being sold to the public at cheaper rates compared to those sold at government approved retail outlets and have become a source of worry for some respondents. 56.2% of respondents agreed that the products from the non-standard refineries were damaging their engines, with some respondents agreeing that they experience engine stoppages while using the non-standard refined diesel fuel oil and others saying that they spend much to maintain their engine as a result of the usage of the non-standard refined diesel fuel oil. Also, from the correlation matrix result it was revealed that there is a bivariate relationship between S7 and S9 which was significant at 0.01 level (2 tailed), which suggests that the continuous usage of non-standard refined products results in engine damage and in turn expense to maintain the engine. Another significant correlation was that of S9 and S10 in which a relationship was found between spending so much money to maintain cars/generator engines which are influenced by stoppages from the usage of the non-standard diesel fuel oil. The result from this study leads the requirement to conduct further research to understand the characteristics of the marketed products from the non-standard crude oil refiners, identifying the probable reasons for engine damage

4.5 Summary

This chapter has investigated the sustained impact of the non-standard crude oil refiners on their host communities and on their fuel being used in diesel engines. The study found evidence that the activities of the non-standard crude oil refiners have led to high levels of environmental pollution in their host communities. This was attributed to by most respondents to their poor refining techniques and waste disposal methods. Respondents in the study agreed with the six environmental impact statements, with over 90% of respondents agreeing with four of the six statements. It was also determined that farming areas and fishing routes were affected by the activities of the non-standard refiners. This has greatly affected the livelihood of the farmers, and fishermen/fisherwomen.

As a result of the damage done to cars/generator engines resulting from the usage of the non-standard refined diesel fuel oils as reported by respondents to the questionnaire a further investigation was carried out to determine the physicochemical properties of the non-standard refined diesel fuel oils.

Chapter 5 Analysis of Physicochemical Properties of Non-standard refined diesel fuel oils

5.1 Introduction

In Chapter 4, the sustained impact of the activities of the non-standard crude oil refiners on their host communities was presented. The study found out that the communities expressed concerns that their activities have led to high levels of environmental pollution, damage to farmlands, reduced farm harvest, and fishing yields. Results also revealed that the continuous usage of the NRD fuel oil was damaging to car/generator engines, that respondents spend more on maintenance when they use the non-standard diesel fuel oil in their vehicles or generators. The study also showed that despite the engine damage and higher maintenance cost as the consequence of using non-standard refined diesel fuel, there is still a demand for it. Therefore, it is necessary to understand the properties of the non-standard refined fuel and their wider impact on the environment to investigate the probable cause and evidence for raising the community awareness. This chapter presents the laboratory analysis of the 9 NRD fuel oil samples and a control sample in order to determine their physicochemical properties, and the consistency in the refining process from each camp (Akpomrere and Uguru, 2020). According to Aleme and Barbeira (2012), diesel fuel oil with one or more physiochemical properties that do not conform to designated standards may increase the consumption of fuel, reduce engine performance, and change the constituents of the emissions. Thus, this chapter compares and discusses the difference between the Nigeria refined diesel (control sample) and the non-standard refined diesel fuel. In addition, the level of consistency in the refining process of the non-standard refined diesel fuel oil from camp to camp and within a camp will be determined. Some sections of this chapter has been published in journal papers (Bebeteidoh et al., 2020; Bebeteidoh et al., 2020).

5.2 Significance of physicochemical properties

Fuels are defined by their physicochemical properties such as density, viscosity, pour point, cetane index, elemental composition, and calorific value, which can vary substantially with their composition (Rocha and Sheen, 2019). Knowledge of the physicochemical properties of the non-standard refined diesel fuel oils is of vital importance to assist in the elaboration of strategies for bunkering, transportation, storage, treatment, and usage in compression-ignition internal combustion engines (Vieira et al., 2019). A number of researchers have written on the importance of physicochemical properties in the determination of quality and usage in diesel engines as detailed in Section 2.2.1 of the literature review.

5.3 Experimental methods

5.3.1. Test fuels

The collection and preparation of samples are very important in every experimental work. A set of 9 NRD fuel oil samples was collected from three different local refineries in the Niger Delta Region (NDR) of Nigeria (see section 3.3.2). For comparison, a commercial diesel fuel sample was obtained from a government retail outlet in Nigeria. The local diesel fuel oil was refined by nonstandard methods while the control sample was refined to industrial standard. All samples were collected, stored, and transported to the laboratory for analysis according to ASTM fixed designation D4057-19 (Gaspar et al., 2019).

5.3.2. Density measurement

The density of a substance is an important physical property that could be used in combination with other fuel properties to characterize light and heavy fractions of petroleum products (ASTM D4052, 2018). The fluid properties depend on essential factors such as temperature and pressure (Safarov et al., 2018). The density measurement was obtained using an oscillating U-tube method following ASTM 4052-18a. The reference temperature for the density measurement was 15˚C. A KEM DA 500 automatic density meter, the specification for which is given in Table 5-1, was used in the determination of the density of the diesel fuel samples.

Table 5-1 Specification of a KEM DA 500 automatic density meter

Type and Model name	KEM DA 500 density meter
Measuring method	Resonant frequency detection
Measuring temperature	4˚C ~90˚C
Accuracy	±0.0001g/cm^3
Reproducibility	SD: 0.00005g/cm^3
Minimum sample required	1.2mL by manual syringe
Measuring time	2~10 minutes by programmed
Measuring range	0~3g/cm^3

5.3.3 Kinematic viscosity measurement

The measurement of kinematic viscosity at 40°C (cSt) was carried out using the Oswald capillary viscometer according to ASTM D445. This method stipulates a technique for the determination of the kinematic viscosity, gauging the point in time for a volume of liquid flowing under gravity through a glass capillary viscometer (D445, 2019).

5.3.4 Flash point measurement

The flash point of the samples was measured according to ASTM D3828 using a Setaflash Series 3 closed cup flash point tester (model 30000-3, Stanhope-Seta) with a temperature ramp mode as presented in Table 5-2.

Table 5-2 Seta flash Series 3 Flash Point Tester

Type and Model name	Setaflash Series 3 (30000-3)
Measuring method	Ramp mode
Measuring range	0˚C ~ 300˚C
Sample size	2mL – 4mL by manual syringe
Test time	1-2 minutes

The ramp mode method was applied because of the unknown nature of the non-standard refined diesel fuel samples. This method allows the tester to determine the flash point with small samples of 2mL – 4mL within 2 minutes. For this test, a volume of 2mL of the sample was injected.

5.3.5 Pour point measurement

The pour point of the tested samples was determined by an automated Mini Cloud/Pour Point Analyser (MPP 5G) according to ASTM D5950-14. A 0.5mL of the test sample was put into a disposable vial and placed into the 10-specimen sample changer. The cooling of the sample is controlled automatically at a cooling rate of 1.5°C per minute. The pour point is then determined by monitoring the temperature at which the pressure differential changes across the cooling cell difference in pressure across the cooling cell.

5.3.6 Water content

Water is a key contaminant of diesel fuel oil (Saleh and Tripp, 2021). The entrained water content in the 9 non-standard refined diesel fuel oil samples and the control sample was determined by coulometric titration using the Karl Fischer Metrohm 756 Coulometer as described by ASTM D6304. The sample is first weighed into a vial and sealed so it is airtight. The sample is then heated in an oven with the entrained water in the sample evaporated and transported by a carrier gas into the titration cell for calculation.

5.3.7 Cetane index

The calculated cetane index (CCI) of the 9 non-standard refined diesel fuel oil samples and the control sample was determined using the Four Variable Equation (ASTM D4737-10, 2016). This method was used because of the small quantity of the samples needed to run an engine for this test. The four-variable equation is presented below in Equation 5-1 (Owusu et al. 2018).

$$CCI = 45.2 + (0.0892)(T_{10N}) + [0.131 + (0.901)(B)][T_{50N}]$$
$$+[0.0523 - (0.420)(B)][T_{90N}] + [0.00049][(T_{10N})^2 - (T_{90N})^2]$$
$$+(107)(B) + (60)(B)^2 \qquad (5\text{-}1)$$

where:

CCI = Calculated Cetane Index by Four Variable Equation

D = Density at 15°C

DN = D – 0.85

$B = \left[e^{(-3.5)(DN)}\right] - 1$

T_{10} = 10% recovery temperature, °C, determined by Test Method D86 and corrected to standard barometric pressure

$T_{10N} = T_{10} - 215$

$T_{50N} = T_{50} - 260$

$T_{90N} = T_{90} - 310$

5.3.8 Distillation curves

The 9 non-standard refined diesel fuel oil samples and the control sample were analysed using Herzog HDA 627 automatic distillation equipment as designated in ASTM D86. For the analysis, a 100mL of the fuel sample was transferred into the distillation flat bottom flask connected with a thermocouple and heated (Aleme et al. 2012). The distillation ratio was between 3.8 mL/min and 5.6 mL/min. The distilled sample was condensed and collected into a measuring cylinder at room temperature. The distillation volumes recovered were the initial boiling point (IBP), final boiling point (FBP) with volume recovered at 5%, 10%, 50%, 90% and 350°C.

5.3.9 Calorific value

The calorific values of the 9 non-standard refined diesel fuel oil samples and the control sample were determined using a Paar 1341 Oxygen Bomb Calorimeter. The ASTM designated standard for this measurement was D4809-18, which is the standard test method for liquid hydrocarbon fuels by bomb calorimeter (Precision Method) (ASTM D4809, 2018). The calorimeter was first calibrated using benzoic acid, C6H5COOH, for which the internal energy associated with combustion was known. The calorific value associated with the 10 fuel samples (9 non-standard diesel fuel oil samples and 1 control sample) was then determined by the combustion of 0.5g ± 0.1g of the samples placed in a crucible inside the bomb cylinder with the aid of a fuse wire (nichrome) and oxygen. The stirrer was turned on and the Pico logger icon pressed to start the logging, then at 5minutes the ignition button was pressed and held for 5-10 seconds. A rapid temperature rise showed that combustion had taken place. The bomb calorimeter was allowed to run for 20 minutes. The stirrer was then turned off. Data obtained was then used to calculate the calorific value of the samples.

5.4 Results

5.4.1 Fuel properties

A summary of the physicochemical properties of the control sample and the 9 NRD fuel oil samples is presented in Table 5-3. The results from the density test show similarities in the density of the control sample and the 9 NRD fuel oil samples at 15˚C as illustrated in Figure 5-1. The density of the ten diesel fuel samples analysed in this study is comparable to those obtained in other studies relating to the physicochemical properties of diesel fuel oils and their blends (Gao et al. 2019; Hoang, 2019; Hoang, 2018; Pasha et al. 2020).

The kinematic viscosities of the control sample and the 9 NRD fuel oil samples tested at 40˚C are also presented in Table 5-3. All ten samples tested fell within designated standards in ASTM D975 as illustrated in Figure 5-2. From the result for kinematic viscosity, issues associated with high viscosities that affect internal combustion engines should not occur using these samples. Nevertheless, it should be noted that other diesel fuel properties also affect the performance of an engine. Thus, a diesel fuel oil with a standard kinematic viscosity is not enough to assume that the fuel is of an acceptable standard.

The pour point of the tested samples presented in Table 5-3 showed a significant difference between the 9 NRD fuel oil samples compared to the control sample.

While the control sample was -17˚C as illustrated in Figure 5-3, values obtained for the NRD fuel samples ranged from 7-10˚C. With the values obtained for the pour point of the non-standard refined diesel fuel oil, bunkering in colder regions would be quite challenging when temperatures fall below zero degrees. However, the NRD fuel oils are used in towns and villages in Southern Nigeria where weather conditions do not affect its, bunkering, transportation, and storage. The results for the cetane index, presented in Figure 5-4, for the control sample and the 9 non-standard refined diesel fuel samples were all within the acceptable international limit of a minimum of 40.

The flash points of the 9 NRD fuel oil samples were all less than 30°C, compared to the control sample which was 65°C; this is significantly different from the acceptable international limit of 55-66°C for diesel fuel oils (Gouveia et al. 2017). With the very low flash points, there is a compelling indication that the 9 NRD fuel oils might contain very volatile materials (Zaharin et al. 2017). Shipping and handling coupled with storage classification will be affected by their low flash points (Phoon et al. 2014).

The test for entrained water in the 9 non-standard refined diesel fuel oil samples and the control sample presented in Figure 5.5 showed some differences in the results. Results from samples A1-A3, B1, B2, C2, and the control sample were all within the acceptable international limit of a maximum of 200 mg/kg water. However, samples B3, C1, and C3 were all above the acceptable international limit. Test results for the distillation range revealed no major differences from the control sample; according to Srivastava and Prasad (2000) the distillation range is vital for performance, fuel safety and also for the estimation of cetane index. The results for the calorific value presented in Figure 5-6, were within acceptable limits of 42-46 MJ kg^{-1} for the control sample and all the 9 non-standard refined diesel fuel oil samples. The calorific value is an important parameter needed for the determination of the brake thermal efficiency of an engine.

Table 5-3 Physiochemical properties of the 9 non-standard refined diesel fuel oil samples and the control sample

Property	Units	Limits (ASTM D975-20c) Min/Max	A1	A2	A3	B1	B2	B3	C1	C2	C3	NGR
Density at 15˚C	kg/m^3	820-860	850.7	836.5	837.8	854.5	841.9	852.3	854.4	854.5	853.0	862.8
Kinematic Viscosity	mm^2/s	1.9-4.1	2.946	2.091	2.108	3.587	2.570	3.453	3.689	3.761	3.723	3.485
Pour Point	˚C		9	8	8	11	7	10	10	10	10	-17
Flash Point	˚C	>52	<30	<30	<30	<30	<30	<30	<30	<30	<30	65.5
Water Content	$mg\ kg^{-1}$	Max 200	77	97	104	87	100	203	214	164	573	78
Cetane Index		Min 40	46.6	48.2	50.3	45.8	46.3	46.2	45.7	45.7	46.3	45.9
Net Calorific Value	$MJ\ kg^{-1}$	42-46	42.36	42.38	42.34	42.28	42.54	42.36	42.50	42.28	42.44	42.50
Gross Calorific Value	$MJ\ kg^{-1}$		45.04	45.08	45.04	44.98	45.24	45.06	45.18	44.96	45.10	45.10
Total Hydrogen	%(m/m)		12.64	12.76	12.68	12.68	12.68	12.74	12.70	12.63	12.62	12.26
IBP	˚C		72.3	65.5	50.3	96.0	104.4	98.3	96.1	96.0	96.9	166.9
5% Recovered	˚C		108.8	100.1	84.6	122.5	142.8	125.2	120.8	121.3	126.4	203.2
10% Recovered	˚C		132.4	119.9	103.1	144.2	142.8	143.4	139.9	142.2	146.2	218.7
50% Recovered	˚C		294.2	269.5	283.9	298.1	267.3	294.6	296.6	297.4	296.2	289.8
90% Recovered	˚C		382.1	371.7	376.2	382.1	365.0	380.6	374.5	380.6	376.3	356.1
Recovered at 350 ˚C	˚C	% v/v	80.5	84.5	82.2	80.0	85.8	80.8	81.2	80.2	80.7	87.4
FBP	˚C		DND	DND	DND	DND	DND	DND	405.1	DND	404.9	376.2

*Did Not Detect

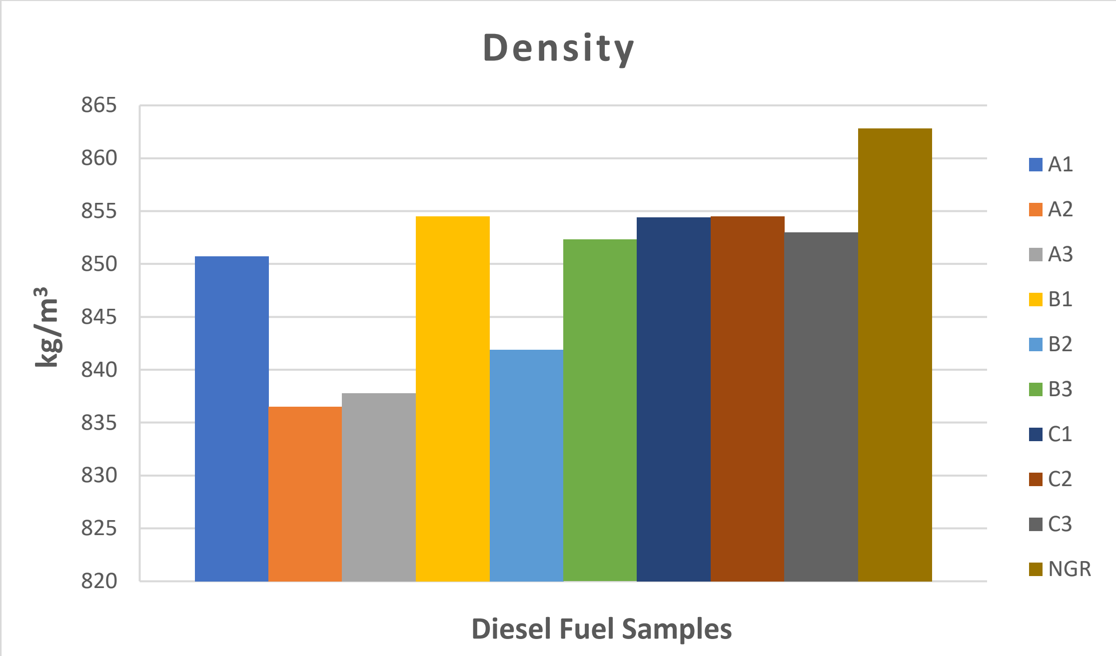


Figure 5-1 Density of the 9 non-standard refined diesel fuel oil samples and the control sample

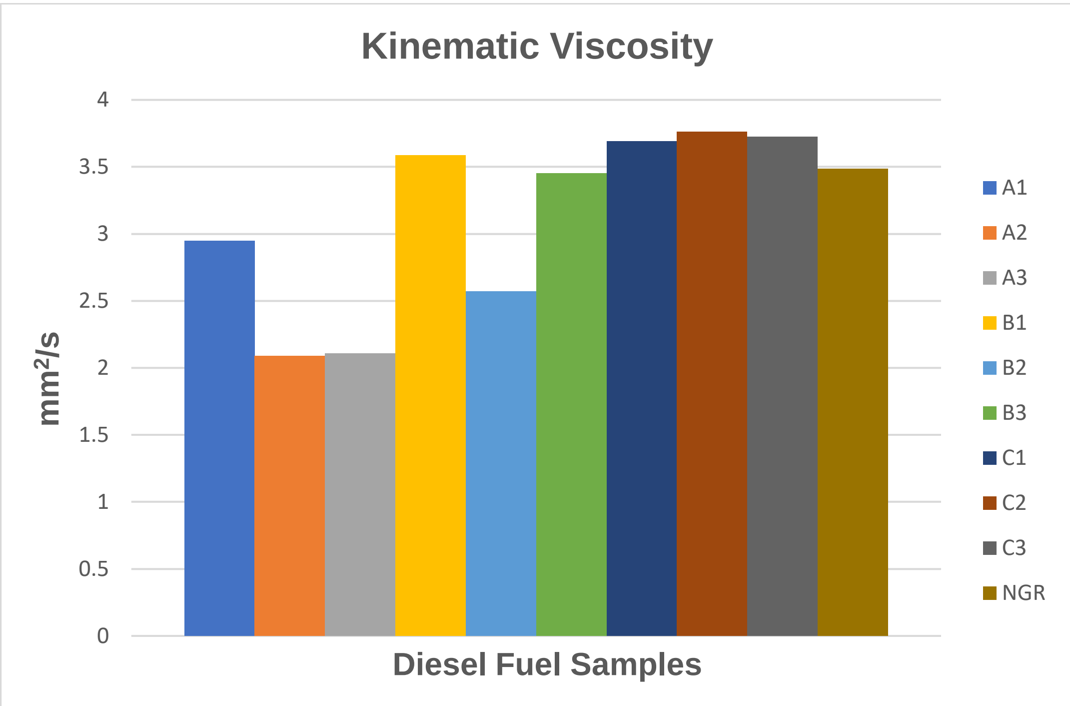


Figure 5-2 Kinematic viscosity of the 9 non-standard refined diesel fuel oil samples and the control sample

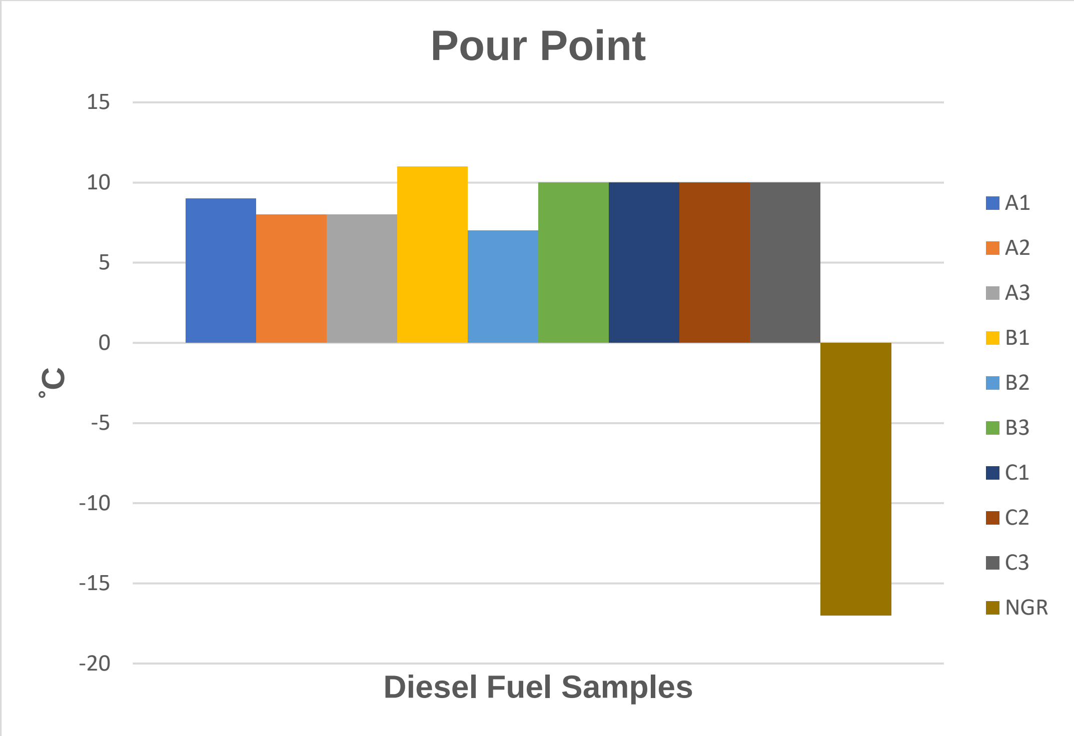


Figure 5-3 Pour point of the 9 non-standard refined diesel fuel oil samples and the control sample

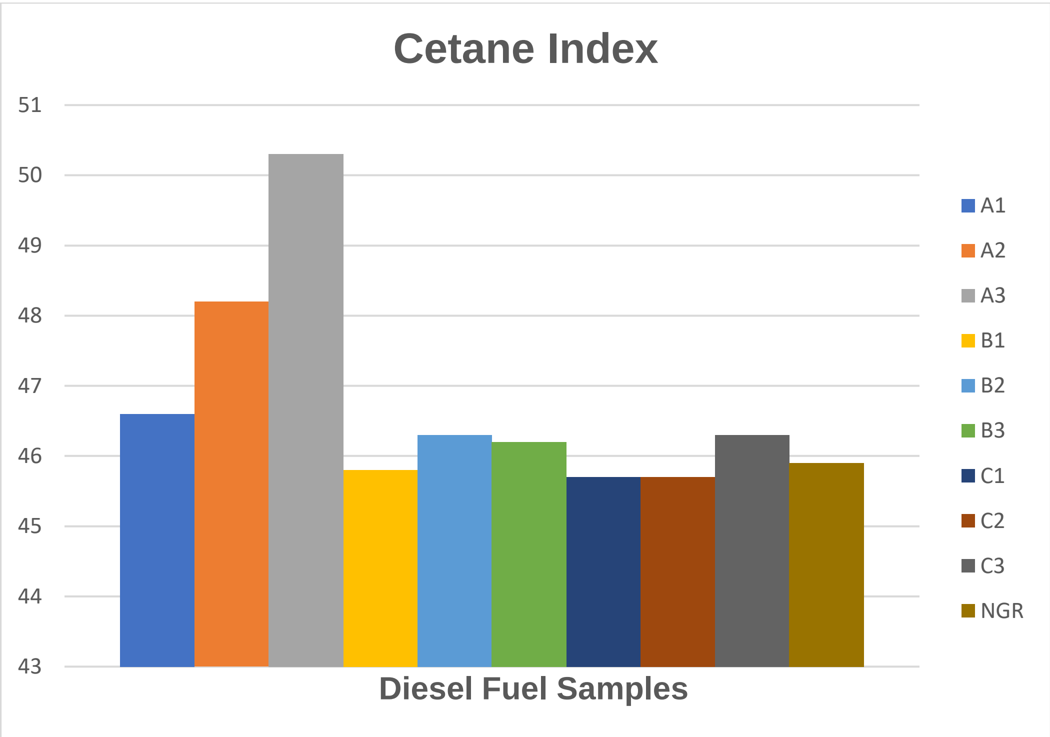


Figure 5-4 Cetane index of the 9 non-standard refined diesel fuel oil samples and the control sample

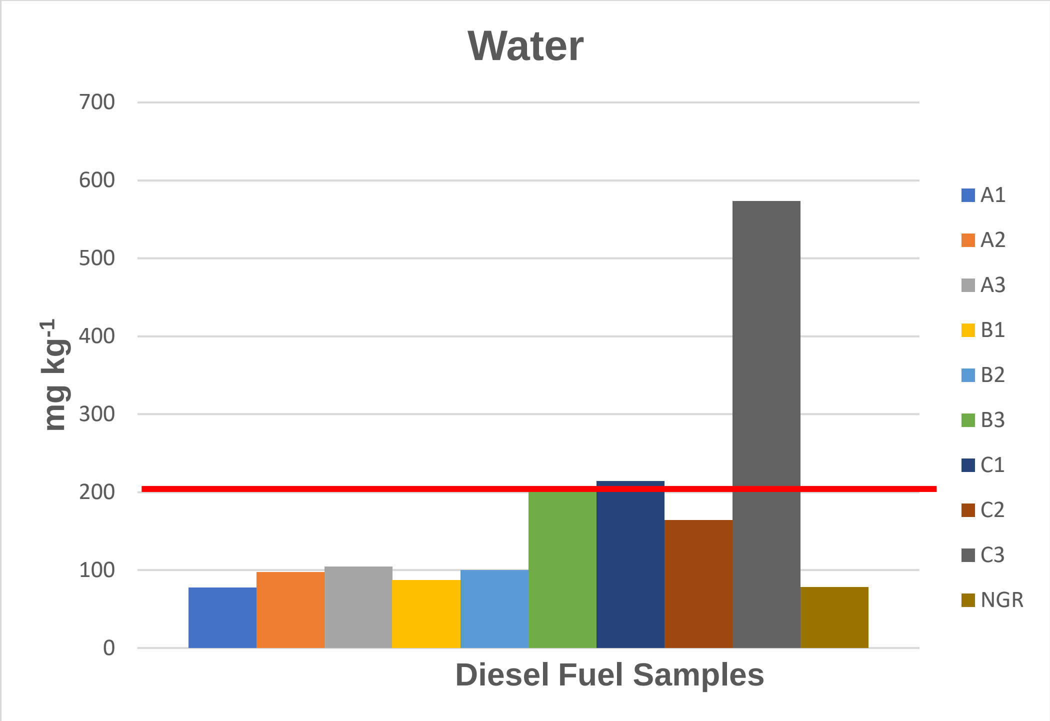


Figure 5-5 Water content of the 9 non-standard refined diesel fuel oil samples and the control sample with the red line representing the ASTM 975 limit of 200 mg kg^{-1}

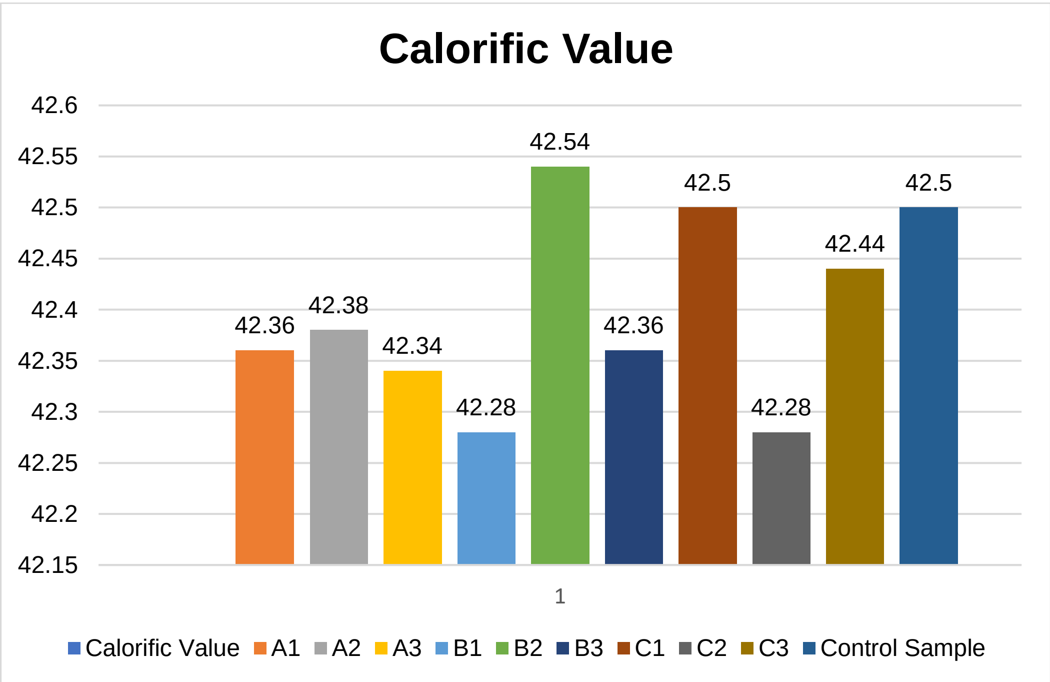


Figure 5-6 Calorific value of the 9 non-standard refined diesel fuel oil samples and the control sample

5.5 Discussion

Results from the experimental analysis of the 9 non-standard refined diesel fuel oil samples and the control sample showed some similarities in parameters like density, kinematic viscosity, cetane index, and calorific value compared to the control sample and internationally acceptable limits. There are a few parameters like the flash point, water content, and pour point for the NRD diesel fuel oil refined in some of the camps that were over the limit. From the test results, it would be expected that the continuous usage of the NRD fuel oil may lead to engine malfunction, fire, and the emission of dangerous tailpipe gases. According to de Oliveira and Lourenço (2021), low-quality automotive diesel fuel oil might lead to the production of pollutants harmful to both human health and the environment.

The flash point results from the samples from the three different camps were all below the designated limit of D975. The usage of the NRD fuel oil could lead to transportation and storage challenges.

Table 5-4 The percentage difference in the water content

Sample	**Sample**	**% Difference Between**
A1	A2	22.98
A1	A3	29.83
A2	A3	6
B1	B2	13.9
B1	B3	80
B2	B3	67.98
C1	C2	26.45
C1	C3	91.23
C2	C3	110.99

Water in diesel fuel oil could be damaging to a diesel engine. It is essential to ascertain the water content of diesel fuel oil because the presence of water can lead to numerous problems (Kizza et al. 2021). Excess entrained water could lead to microbial growth and tank corrosion (Mis et al. 2021). Also, the formation of free particles of iron oxide arising from excess water in the diesel fuel oil could lead to fuel filter blockage (Kizza et al. 2021). Results from camp A showed some inconsistency in the refining process same with camps B and C compared to the control sample. The percentage difference of the water content between the various camps is presented in Table 5-4. The high-water content of 573mg/kg in sample C3 could be damaging if stored for a long time and also damaging to the diesel engine. The percentage difference of the entrained water in the three different camps show inconsistencies in the refining process

The results for the pour point test showed consistency between samples refined in camps A and C but a 44.44% difference between samples B1 and B2 and a significant difference between the control sample and the 9 non-standard refined diesel fuel samples. While results for the cetane index all fell within acceptable international limits in the ASTM D975, there is inconsistency in the refining process between camps A, B, and C.

Inconsistency in the refining process across the three camps is another noticeable feature. The inconsistencies in the products from the refining process would create confusion and the inability to treat the fuel before usage or adjust the engine timing accordingly, as end users are unaware of the quality, they receive anytime they make purchase. This illustrates a lack of quality control in the non-standard refining process. With a lack of quality control in the refining process of the NRD fuel oil, coupled with the recent International Maritime Organization (IMO) regulations on the refining of marine fuels (Chu Van et al. 2019), and the global concerns on environmental pollution arising from diesel fuel emissions (Park et al. 2021) continuous usage of the NRD fuel oil by unsuspecting members of the public will lead to damaged engines and financial burden. The results from the physio-chemical properties of the 9 non-standard refined diesel fuel oil samples and the control sample experiment revealed discrepancies between the 9 NRD fuel oil and control samples, which necessitate further investigation by conducting a Fourier transform infrared spectroscopy (FTIR) and a Gas Chromatography Mass Spectrometry (GCMS) analysis.

5.6 Summary

This chapter has determined the physicochemical properties of the 9 non-standard refined diesel fuel oil samples and the control sample with some differences apparent in standard parameters. While some of the fuel properties were within the internationally acceptable limit in ASTM D975, others like the pour point, flash point, and water content showed some differences. The flash points of the 9 NRD fuel oil samples were all below the limit. This could be attributed to several reasons, one of which maybe because of the refining process, in which the crude oil did not go through the process of pre-treatment which is aimed at the elimination of impurities. Another may be because of volatile substances present in the fuel, which may be a result of additives introduced by the non-standard crude oil refiners. The pour point results showed a huge difference between the control sample and the non-standard refined diesel fuel oils. Although over the limit the non-standard refined diesel fuel oils could be transported and stored without concern of freezing because of the weather conditions in Nigeria.

As a result of the observed inconsistencies in the refining of the 9 non-standard diesel fuel oil samples from each of the camps, and within each camp which revealed very low flash points and high pour points compared to the control sample a further investigation will be carried out to determine the composition of the fuels. In Chapter 6, Fourier transform infrared spectroscopy (FTIR) and Gas Chromatography Mass Spectrometry (GCMS) will be used to determine the functional groups present in the 9 NRD fuel oil samples compared to the control sample.

Chapter 6 Gas Chromatography Mass Spectrometer and Fourier Transform Infrared Spectroscopy

6.1 Introduction

In Chapter 5 the physiochemical properties of the non-standard refined diesel fuel oil and control samples were determined. Results obtained showed very low flash points which were all less than 30˚C for the non-standard refined diesel fuel oils. This is significantly below the acceptable international limit of 55-66˚C. This difference may be related to the Volatile Organic Compounds (VOC) present in the fuel samples (Gouveia et al. 2017). The volatile compounds present in each sample were determined with Gas Chromatography and Mass Spectrometer (GC-MS). GC-MS is employed in the determination of the compositional variations of fuels (Leghrib et al. 2020; Câmara et al. 2017). This is performed to ensure their conformity with regulatory specifications. The GC-MS was used to investigate 5 kinds of VOC (benzene, toluene, and the three isomers of xylene (m-, p-, and o-)) and alkanes (octane ($_nC_8$) and tridecane ($_nC_{13}$)). According to Kaltschmitt and Deutschmann (2012), diesel fuel oil contains more non-volatile components compared to gasoline. The functional groups present in the test samples were also investigated using Fourier Transform Infrared Spectroscopy. Thus, this chapter will characterize the VOCs present in the non-standard refined diesel fuel oil samples as compared to the control sample. Some sections of this chapter has been published in journal papers (Bebeteidoh et al., 2020; Bebeteidoh et al., 2020).

6.2 Experimental methods

6.2.1 Test Fuels

The collection, preparation, and storage of the NRD fuel samples and the control sample are presented in section 3.4.4 in Chapter 3.

6.2.2 Gas chromatography Mass spectrometry (GCMS) analysis

The GC-MS analysis was carried out in an Agilent 7890B Gas Chromatograph (GC) fitted with a split-splitless injector and linked to an Agilent 5977B Mass

Selective Detector (Figure 6-1). For each fuel sample, a 10ul aliquot, was dissolved in 1 ml dichloromethane (DCM) and 1ul was injected onto the GC using an Agilent 7683B autosampler and operated in a full scan mode and ion monitoring (SIM) mode. The sample was injected in pulsed splitless mode, and the split was opened after 1 min. Gas chromatographic separation of compounds was performed on an Agilent HP-5 fused silica capillary column (30 m × 0.25 mm i.d. x 0.25 μm film thickness). The GC oven temperature program was 30 °C (hold time 5 min), then 5 °C min^{-1} to 310 °C (hold time 10 min). Helium was used as the carrier gas at a flow rate of 1 ml min^{-1} and the split flow rate after 1 min was 20 ml min^{-1}. The GC inlet temperature was 280 °C and the GC to GC-MS interface temperature was 310 °C. Samples were analysed initially in full scan mode, scanning the range 45–545 amu sec^{-1} with an electron voltage 70eV, source temperature 230 °C, quad temperature 150 °C, and multiplier voltage 1200 V, and then in selected ion monitoring mode, scanning 20 ions at 3.0 cycles sec^{-1} with a 20 s dwell time. The ions monitored included m/z 57, m/z 78, m/z 92, and m/z 106 (Benzene, toluene, n-alkanes, and xylenes).

Figure 6-1. An Agilent 7890B GC linked to an Agilent 5977B MS and an Agilent Z240 computer

Data were obtained and processed using Agilent Chemstation software installed on an Agilent Z240 computer (Pairohakul et al., 2021). This allows for the study of specific m/z ranges of each ion. Peaks (representing individual compounds) on the resulting mass chromatograms were identified by comparison of their mass spectra with those in the NIST05 library (>90% fit taken as acceptable) and by comparison of relative retention time/elution order with data in the geochemistry literature. Peak areas of selected analytes were obtained by integration and the data were used together with calibration curve data for quantification.

6.2.3 Quantification of Volatile Organic Compounds (VOCs)

Volatile organic compounds in the test fuel samples analysed with the GC-MS were quantified using a semi-quantitative method (Paterson et al., 2004; Monfreda and Gregori, 2011). A standard mixture was prepared comprised of benzene, toluene, o-, m-, and p- xylenes, octane (nC_8), and tridecane (nC_{13}), and analysed at various dilutions under the same condition as the samples. All samples and the diluted calibration standards were analysed in triplicate. The calibration curves for each target analyte, benzene, toluene, xylenes (para, meta, and ortho), nC_8, and nC_{13} as shown in Figures 6-2 - 6-8, were linear with R^2 values of 0.99. The limit of detection (LOD) was 0.037 µg/g and the limit of quantification (LOQ) was 0.0147 µg/g.

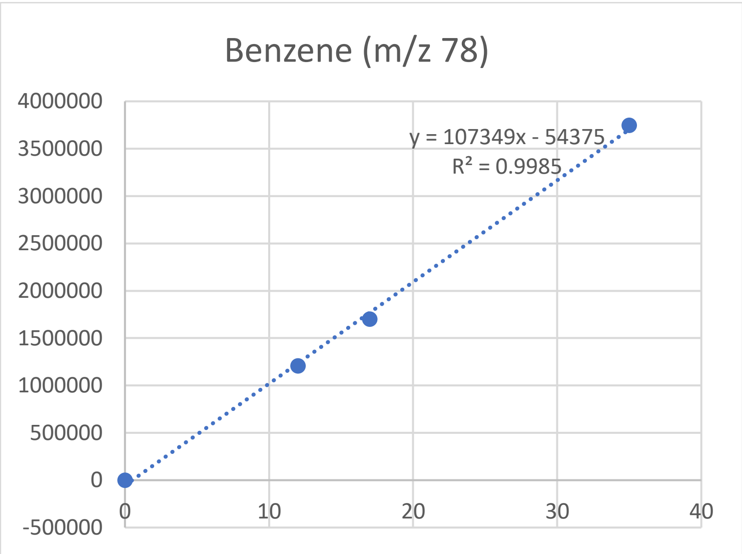


Figure 6-2. Calibration curve of Benzene (m/z 78), R^2= 0.9985

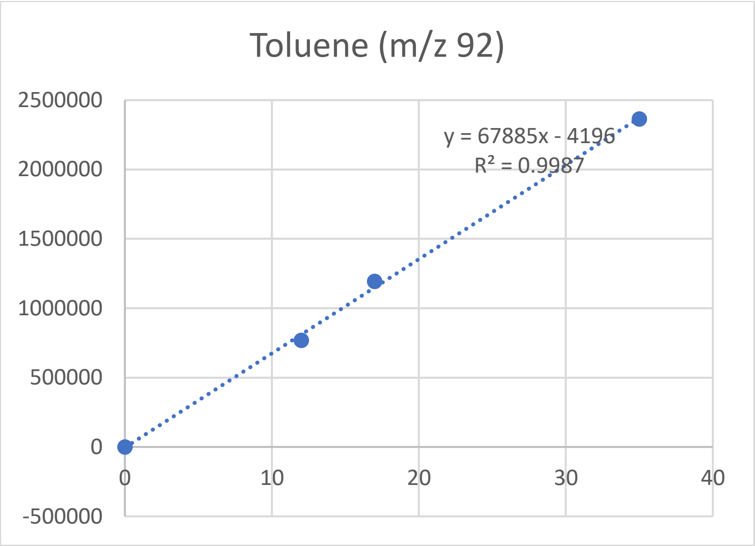


Figure 6-3. Calibration curve of Toluene (m/z 92), R^2= 0.9987

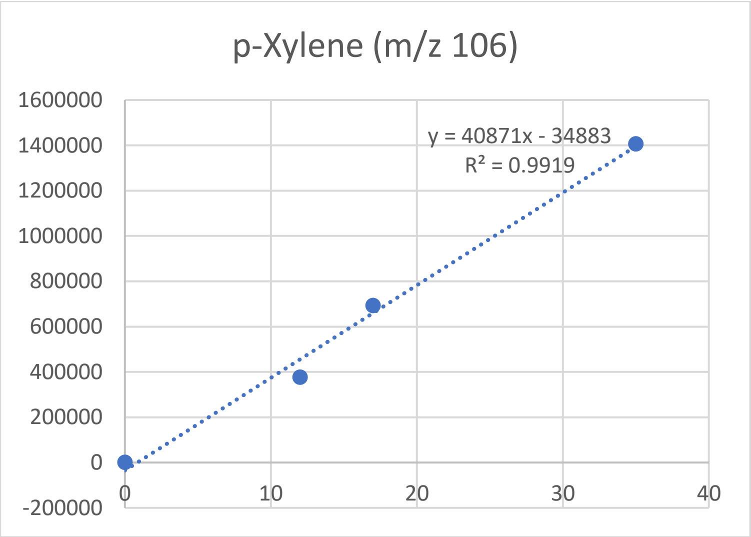


Figure 6-4. Calibration curve of p-Xylene (m/z 106), R^2= 0.9919

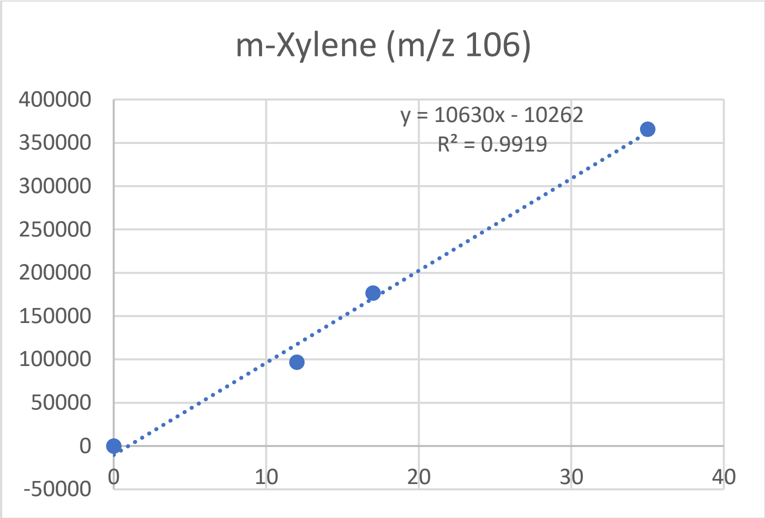


Figure 6-5. Calibration curve of m-Xylene (m/z 106), R^2= 0.9919

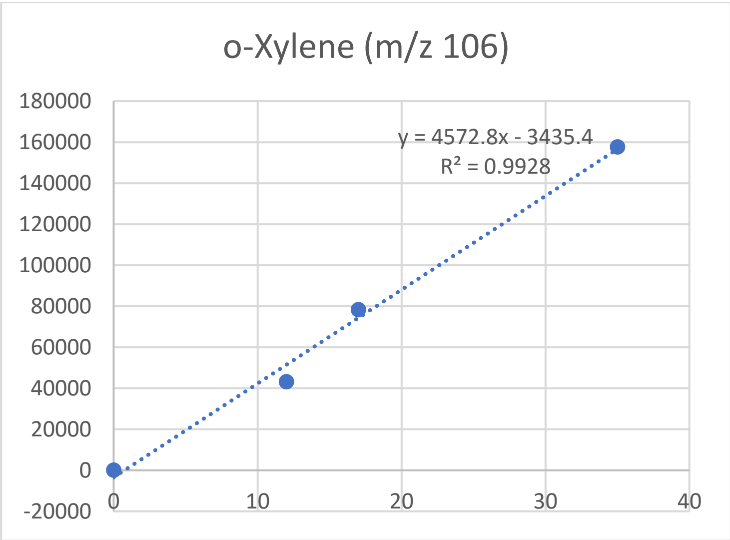


Figure 6-6. Calibration curve of o-Xylene (m/z 106), R^2= 0.9928

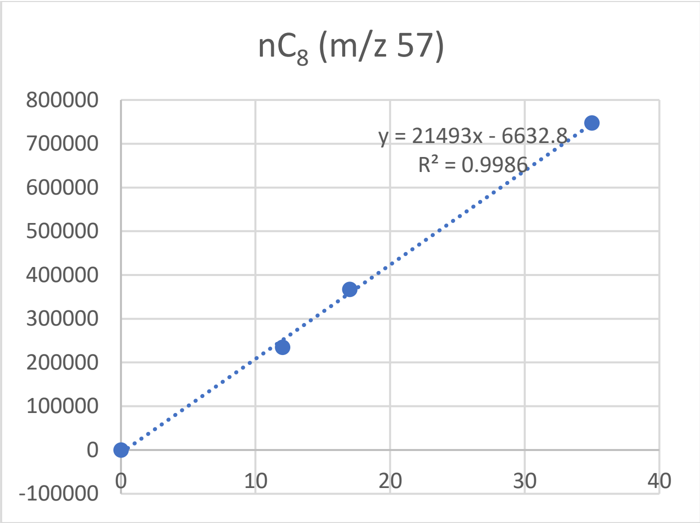


Figure 6-7. Calibration curve of nC_8 (m/z 57), R^2= 0.9986

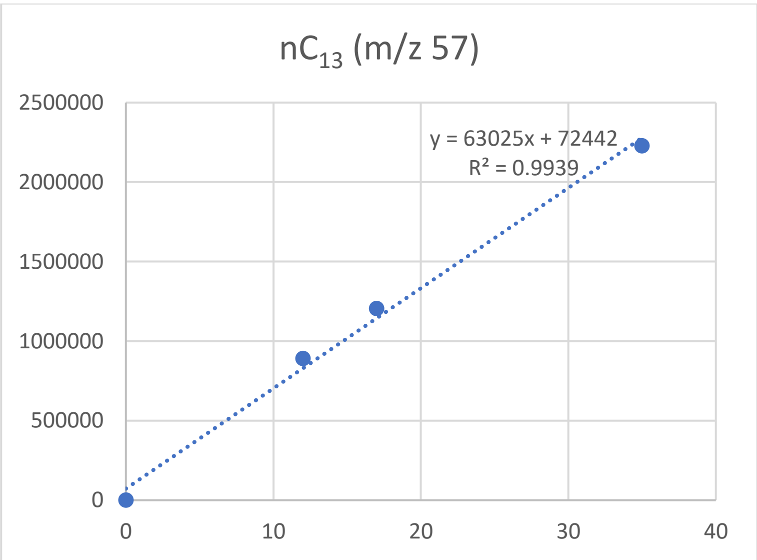


Figure 6-8. Calibration curve of nC_{13} (m/z 57), R^2= 0.9939

6.2.4 Fourier transform infrared analysis

The FTIR analysis was carried out to determine the functional groups present in the test fuels according to ASTM E1252 (2013). An Agilent Cary 630 FTIR spectrometer with an absorbance range of 4000 cm^{-1} to 650 cm-1 was used to measure the absorbance of the samples. Before measuring the spectral intensity, the sample holder was cleaned with acetone, and the CARY 630 FTIR instrument was connected to a computer with the Micro Lab FTIR software installed for data processing. Using a pipette, a 0.5 mL sample was added to the diamond crystal and the spectra were captured. The infrared vibrational groups of standard diesel fuel are shown in Table 6.1.

Table 6.1. Infrared vibrational groups of diesel fuel (Nespeca et al. 2018).

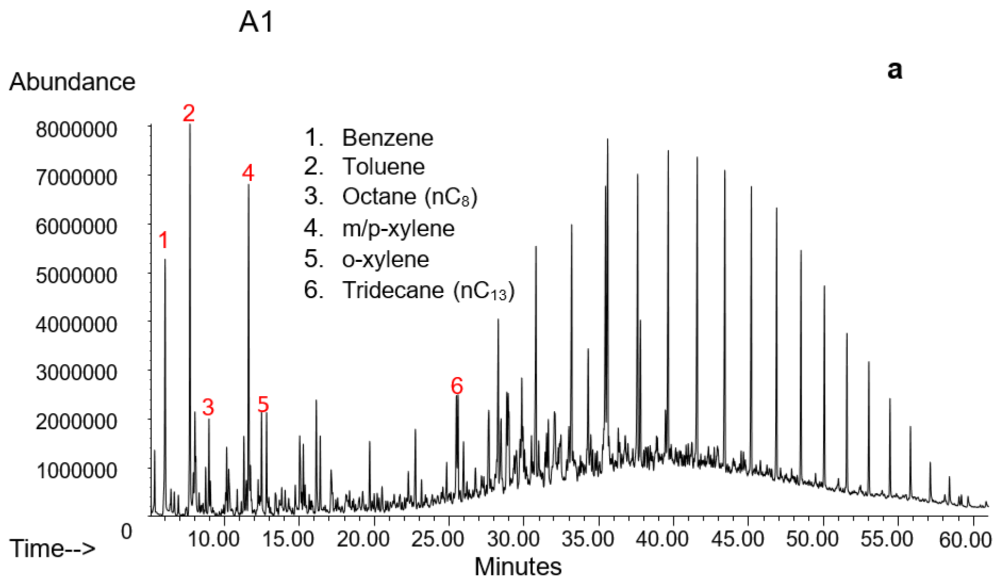
Attribution	**Wavenumber (cm^{-1})**
CH_3 asymmetrical stretch	2953
CH_3 symmetric stretch	2870
CH_3 angular deformation	1379
CH_2 asymmetrical stretch	2922
CH_2 symmetrical stretch	2853
CH_2 angular deformation	1464
C=O carbonyl stretch	1750-1735
C-O stretch (aliphatic ester)	1300-1000
C=O stretch (aromatics)	1600 and 1475

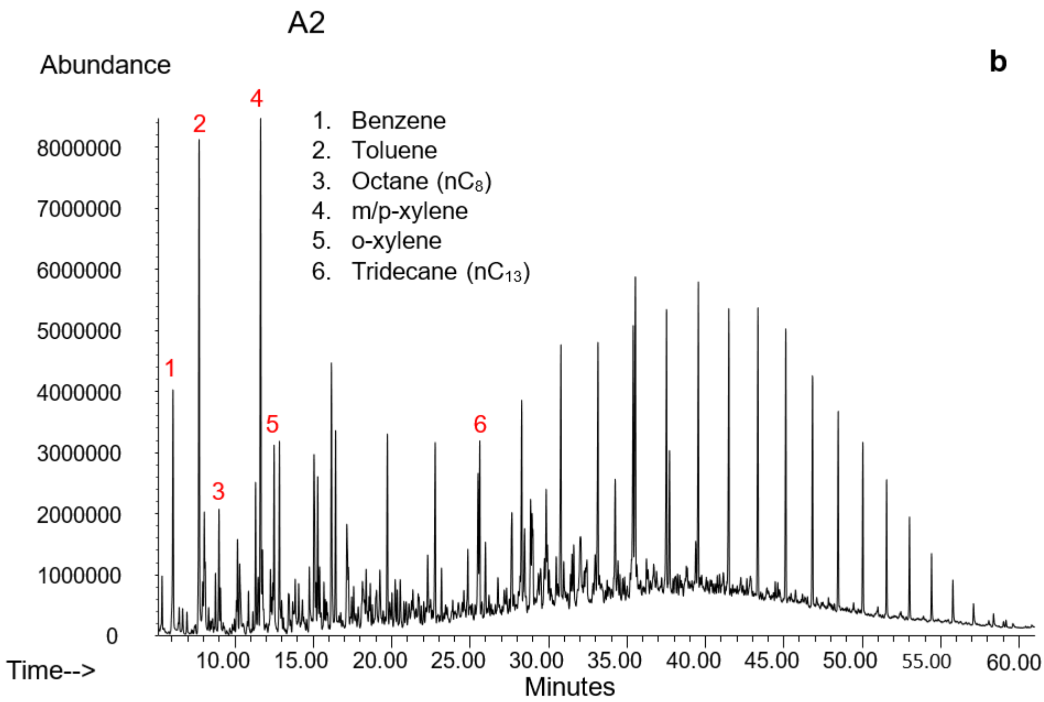
6.3 Results

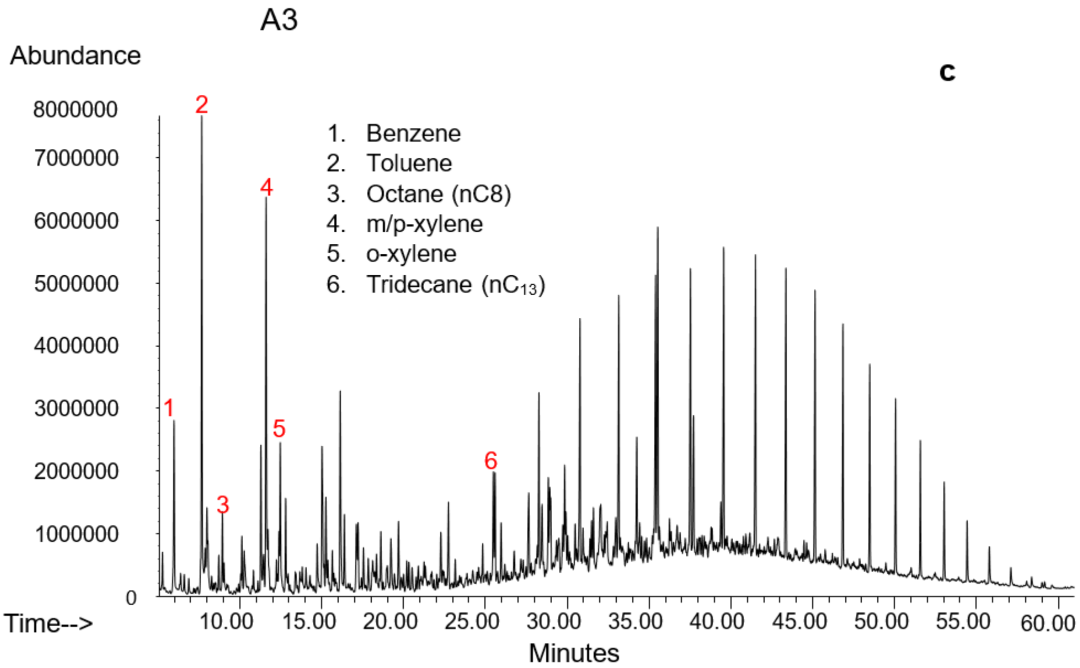
The results for the GCMS and FTIR analysis are presented in this section.

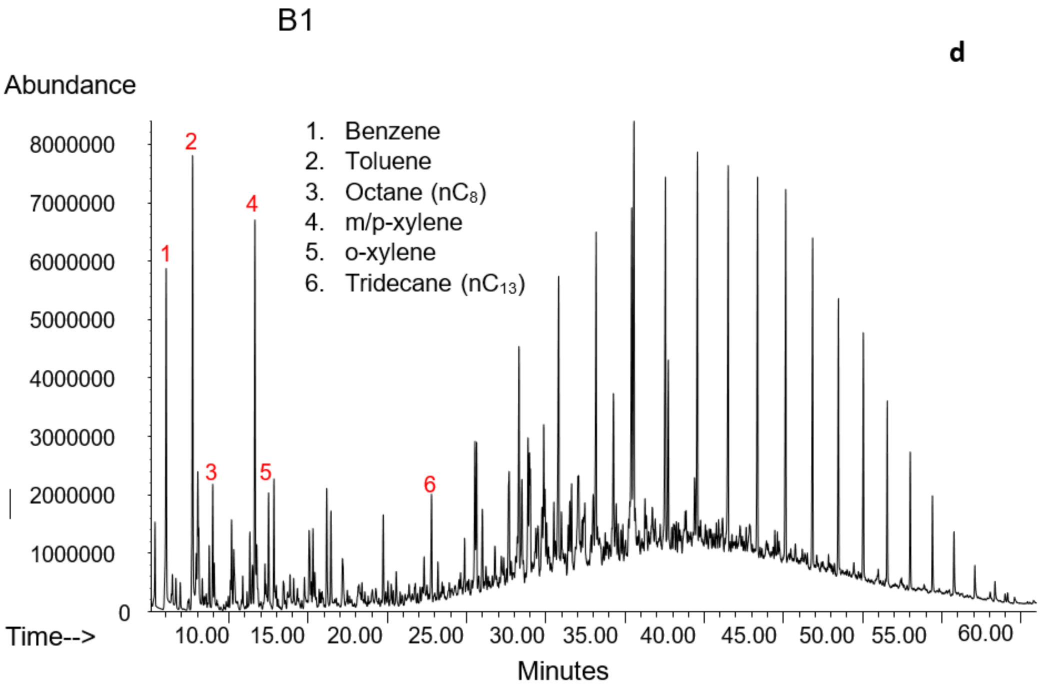
6.3.1. GC-MS Analysis

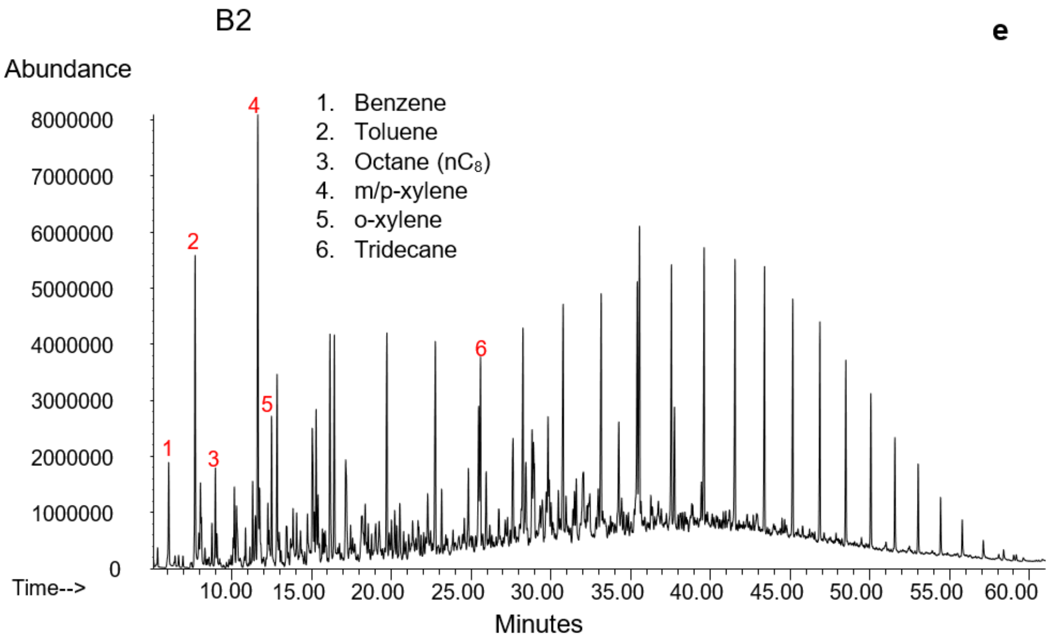
Chromatograms of the NRD fuel oil samples and the control sample are illustrated in Figure 6.9. The information obtained from the full scan analysis was used to identify the individual compounds present in each sample (Suppajariyawat et al. 2019).



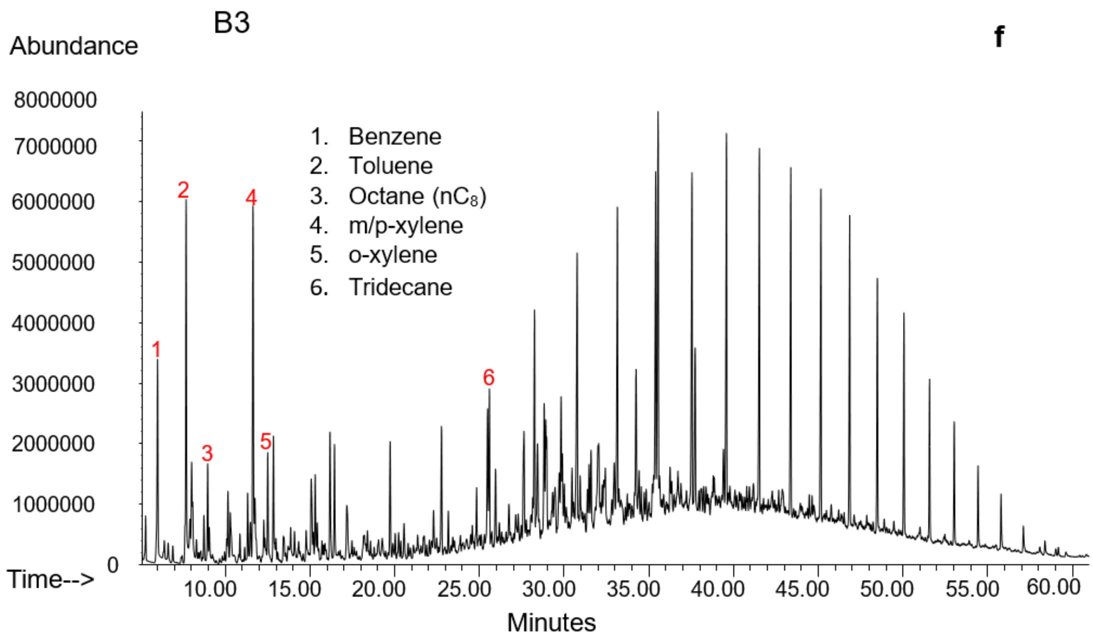



A3
Abundance
c
8000000
7000000
6000000
5000000
4000000
3000000
2000000
1000000
0
Time-->
10.00
15.00
20.00
25.00
30.00
35.00
40.00
45.00
50.00
55.00
60.00
Minutes
1. Benzene
2. Toluene
3. Octane (nC8)
4. m/p-xylene
5. o-xylene
6. Tridecane (nC13)

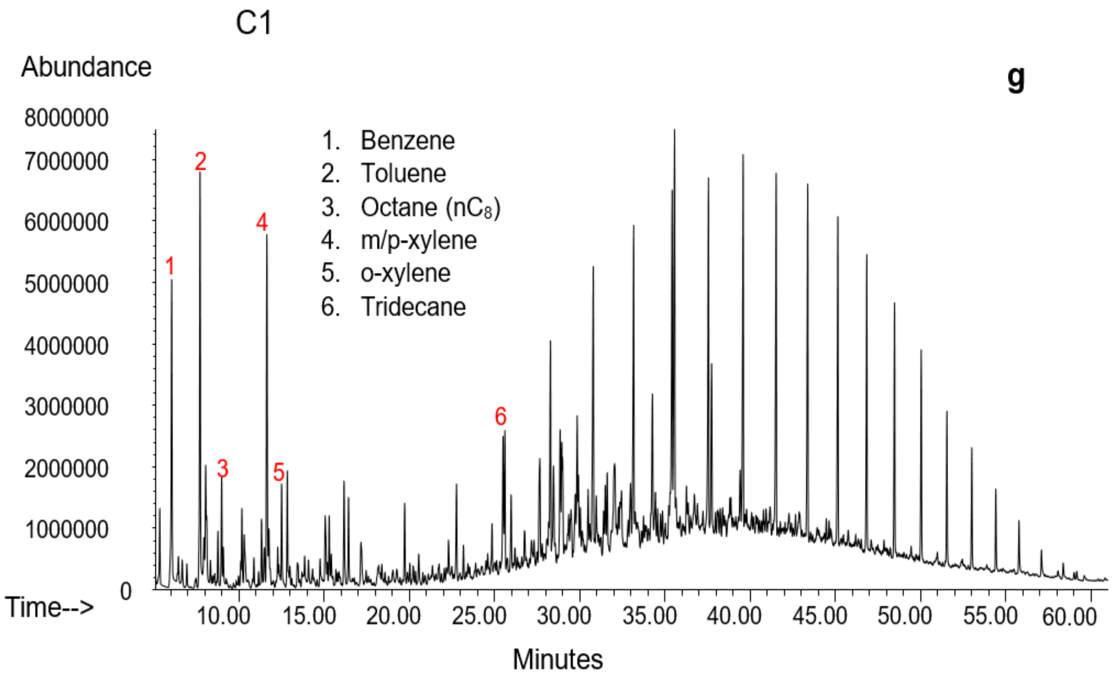

B1
Abundance
d
8000000
7000000
6000000
5000000
4000000
3000000
2000000
1000000
0
Time-->
10.00
15.00
20.00
25.00
30.00
35.00
40.00
45.00
50.00
55.00
60.00
Minutes
1. Benzene
2. Toluene
3. Octane (nC8)
4. m/p-xylene
5. o-xylene
6. Tridecane (nC13)

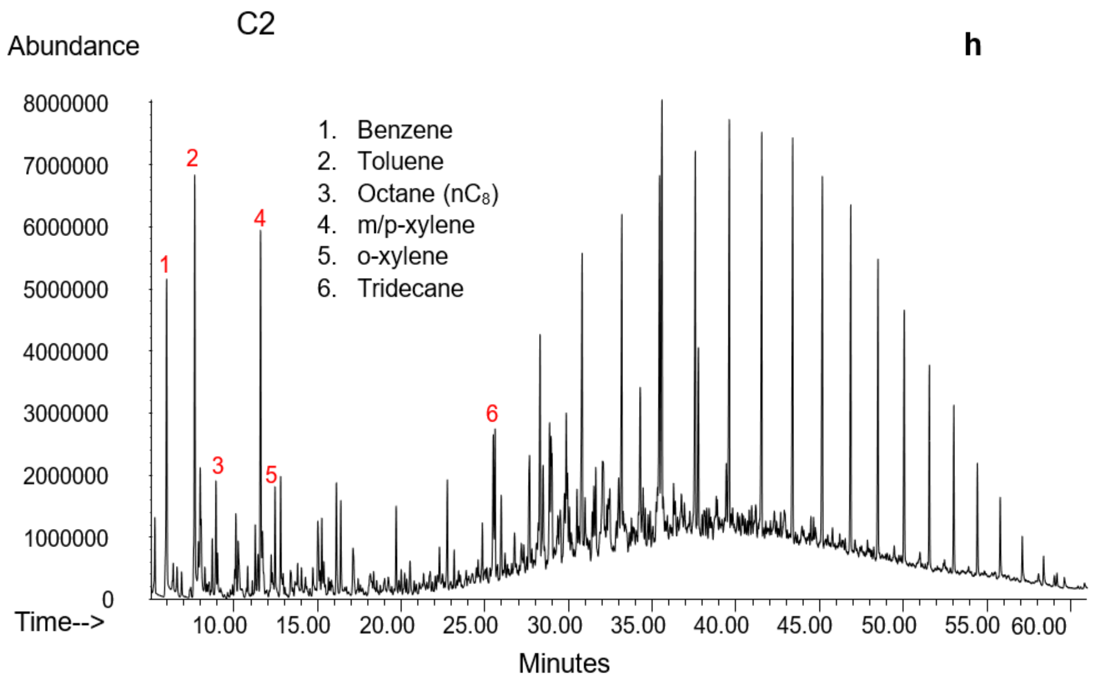


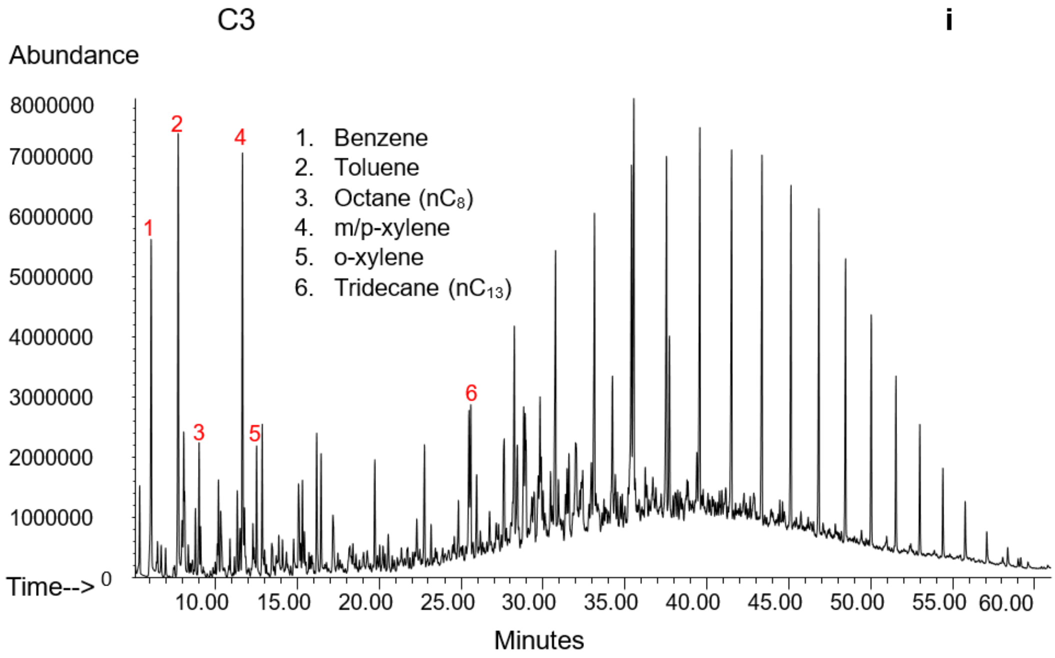
B2
e
Abundance
8000000
7000000
6000000
5000000
4000000
3000000
2000000
1000000
0
Time-->
10.00 15.00 20.00 25.00 30.00 35.00 40.00 45.00 50.00 55.00 60.00
Minutes
1. Benzene
2. Toluene
3. Octane (nC8)
4. m/p-xylene
5. o-xylene
6. Tridecane

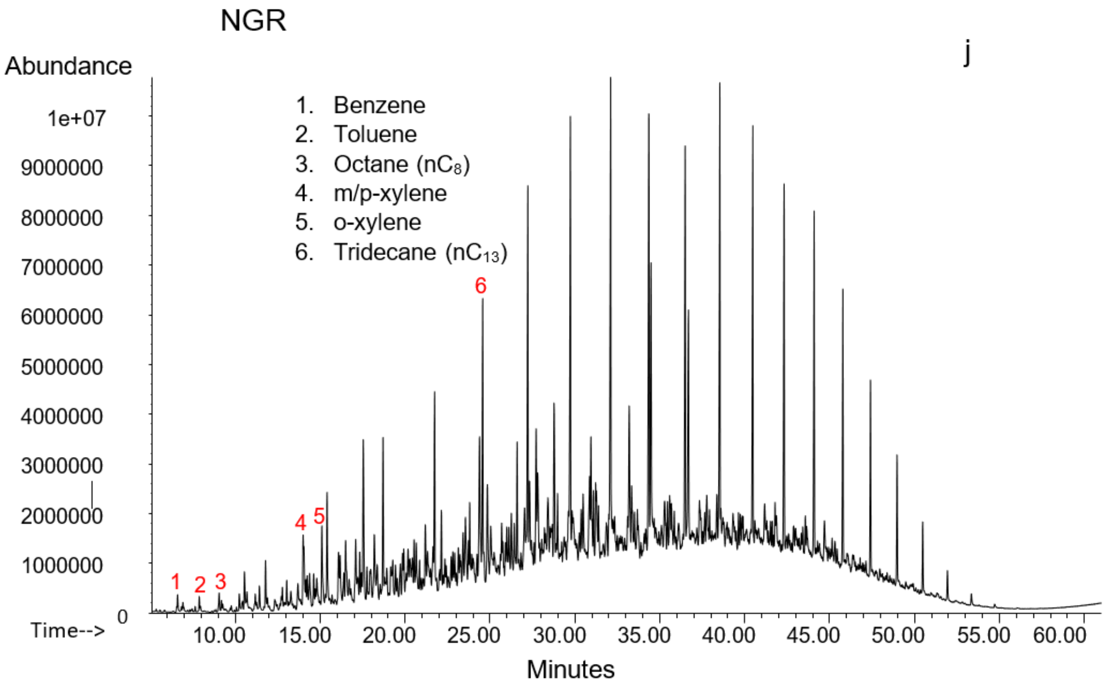


B3
f
Abundance
8000000
7000000
6000000
5000000
4000000
3000000
2000000
1000000
0
Time-->
10.00 15.00 20.00 25.00 30.00 35.00 40.00 45.00 50.00 55.00 60.00
Minutes
1. Benzene
2. Toluene
3. Octane (nC8)
4. m/p-xylene
5. o-xylene
6. Tridecane


C1
Abundance
g
8000000
7000000
6000000
5000000
4000000
3000000
2000000
1000000
0
Time-->
1. Benzene
2. Toluene
3. Octane (nC8)
4. m/p-xylene
5. o-xylene
6. Tridecane
1
2
3
4
5
6
10.00
15.00
20.00
25.00
30.00
35.00
40.00
45.00
50.00
55.00
60.00
Minutes


C2
Abundance
h
8000000
7000000
6000000
5000000
4000000
3000000
2000000
1000000
0
Time-->
1. Benzene
2. Toluene
3. Octane (nC8)
4. m/p-xylene
5. o-xylene
6. Tridecane
1
2
3
4
5
6
10.00
15.00
20.00
25.00
30.00
35.00
40.00
45.00
50.00
55.00
60.00
Minutes





LOD= Limit of detection

Figure 6.9. Representative chromatograms of NRD samples (a) A1, (b) A2, (c) A3, (d) B1, (e) B2, (f) B3, (g) C1 (h) C2, (i) C3, (j) Nigeria standard refined diesel (NGR)

The GCMS analysis revealed a higher abundance of low molecular weight compounds (C_4-C_9) in the non-standard refined diesel fuel oils compared to the control sample as shown in Table 6.2. The spread of the major peaks illustrated in the control sample (Figure 6.9j) is dominated by a homologous series of n-alkanes occurring in a unimodal spread in the carbon range C_8-C_{30}. These unimodal peaks of n-alkanes are also present in the NRD fuel oil samples (Figure 6.9a-6.9i) however in the case of the NRD fuels, there is an additional and significant contribution of components below nC_8 (Octane). The lower molecular weight compounds in the NRD fuel oil samples consist of much higher concentrations of benzene, toluene, and m-, p-, and o-xylenes which are volatile and highly flammable. The most noticeable pattern is the Gaussian distribution (a bell-shaped curve) of spiking normal alkanes associated with diesel fuel oils as illustrated in Figure 6-9j. Also, there is some difference in abundance among the nine NRD fuel oils presented in Figure 6-9a-6-9i. All VOCs (benzene, toluene, xylenes, and nC_8) occurred in higher abundance. However, tridecane (nC_{13}) was found in slightly higher abundance in the control sample compared to the NRD fuel oil.

From Table 6-2 it can be observed that benzene is absent from the control sample (Limit of Detection), while it is of significantly higher proportion in the NRD fuel oils. Also, toluene is ten times or more higher in the nonstandard refined diesel fuel oil compared to the control sample. The crude process of refining could be a factor in the occurrence of a high concentration of low molecular weight aromatics such as benzene, toluene, and xylenes. The refining process of petroleum is divided into four phases namely separation, cracking, alkylation, or polymerization and blending (Gaylarde et al. 1999). While the control sample (NGR) is believed to have passed through the four processes above, the same cannot be said of the NRD fuel oil samples from the three camps (A1, A2, A3, B1, B2, B3, C1, C2, C3). The high level of concentration of BTX in the non-standard refined diesel fuel oil samples could also be attributed to organic solvents used in the adulteration of the final product.

6.3.2 FTIR analysis

Figure 6-10 illustrates the FTIR spectra for the NRD fuel oils and the control sample. The spectrum peak around 2952 cm^{-1} appears in all samples and indicates the presence of asymmetric stretch CH3 of a methyl group which can be found in diesel fuel oil. A similar peak was reported by Nespeca et al. (2018), and Barra et al. (2019). Also, CH2 is the most available functional group in standard diesel fuel oil, therefore the most pronounced in the FTIR. The spectrum peaks around wave numbers 2920 cm^{-1} and 2850 cm^{-1} are the asymmetric and symmetric stretch for CH2 with a strong peak of its angular deformation appearing around 1457 cm^{-1}. The nine NRD fuel oils and the control sample all showed the presence of these spectrum peaks which are all found in standard refined diesel fuel oil. A trace of the spectra peak was identified around 1600 cm^{-1} which indicates aromatic stretch. This peak can be seen in all non-standard refined diesel fuel oil samples but not the control sample. This means the NRD fuel oils have traces of aromatic compounds such as benzene, toluene, and xylenes.

Table 6-2. List of BTX (Benzene, toluene, and xylenes), n-Alkanes, and their concentration in µg g^{-1} of the non-refined diesel fuel oil samples and the control sample. Quantification was based on the GC-MS analysis

Samples	Benzene (µg/g)	Toluene (µg/g)	m/p-Xylene	o-Xylene (µg/g)	nC_8 (µg/g)	nC_{13} (µg/g)
A1	0.86 ± 12.53	3.34 ± 9.81	3.91 ± 8.43	0.84 ± 7.47	2.54 ± 9.65	2.26 ± 7.71
A2	1.22 ± 8.26	3.25 ± 6.40	5.16 ± 6.10	1.24 ± 4.18	2.83 ± 5.88	3.29 ± 3.17
A3	1.90 ± 9.09	3.92 ± 7.15	4.97 ± 6.70	1.21 ± 6.83	2.44 ± 7.62	2.20 ± 5.41
B1	0.42 ± 8.21	2.87 ± 6.69	3.45 ± 6.18	0.71 ± 5.36	2.41 ± 6.43	2.30 ± 6.19
B2	0.34 ± 8.34	2.93 ± 5.86	5.58 ± 6.07	1.26 ± 5.11	3.56 ± 6.00	4.34 ± 4.73
B3	0.42 ± 2.71	3.39 ± 2.06	4.48 ± 1.82	0.94 ± 0.81	2.97 ± 1.28	3.05 ± 0.72
C1	0.39 ± 2.52	2.72 ± 2.04	3.16 ± 2.94	0.65 ± 4.59	2.25 ± 1.48	2.07 ± 3.32
C2	1.07 ± 4.70	3.11 ± 10.69	3.55 ± 10.14	0.70 ± 0.46	2.53 ± 10.30	2.35 ± 8.86
C3	0.44 ± 5.50	3.41 ± 5.73	4.11 ± 4.85	0.85 ± 5.08	2.81 ± 5.05	2.69 ± 3.03
NGR	LOD	0.19 ± 2.97	0.75 ± 4.46	0.22 ± 4.84	0.15 ± 7.39	3.54 ± 2.10

LOD = 0.037 µg g^{-1} LOQ = 0.147 µg g^{-1}

RSD %

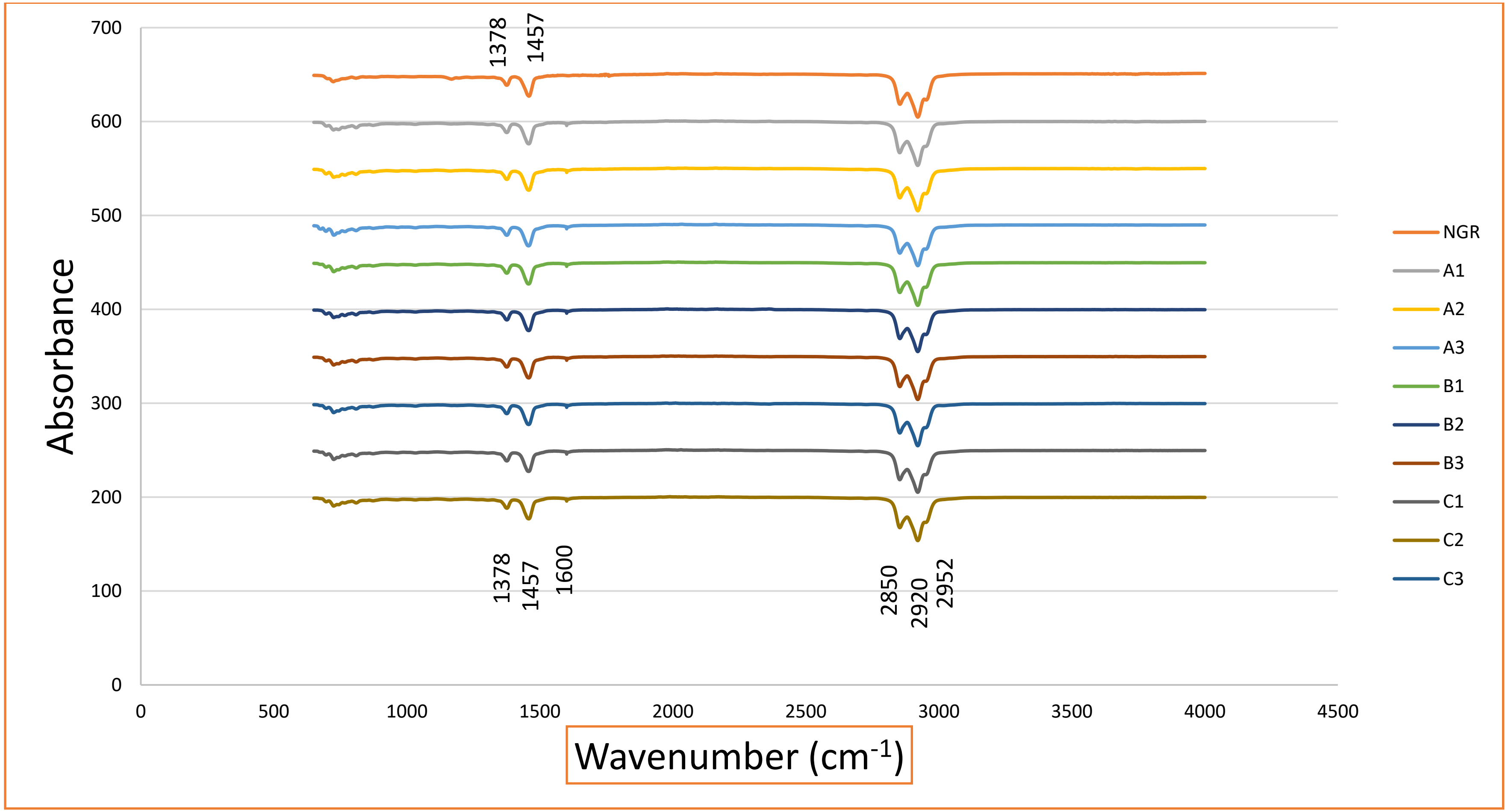


Figure 6-10. Infrared spectra of all test sample

6.4 Discussion

The GCMS and FTIR analyses were able to determine the chemical composition of the nine non-standard refined diesel fuel oils and the control sample. The quantity of BTX and n-alkane concentrations from the GCMS analysis are presented in Table 6-2. The concentration of benzene in the control sample was insignificant (LOD), compared to the NRD samples. The result for toluene showed a substantial difference between the NRD fuel oils and the control samples. The quantity of toluene in the NRD fuel oils was over 170% higher than the control sample (Table 6-3). There is variation in the result for the benzene and toluene within camps and across the three different camps.

Also, the results for xylenes showed significant differences between the NRD fuel oils compared to the control sample. The quantities of m- and p-xylenes in the NRD fuel oils were between 123% and 153% higher than the control sample (Table 6-3). The concentration of o-xylenes in the NRD fuel oils was between 99% and 141% higher than the control sample (Table 6-3). Result for the xylenes also show variations within camps and across the three different camps.

Results for the n-alkanes showed some differences between the NRD oils and the control sample. For nC_8 (Octane) the results showed a substantial difference between the NRD fuel oils compared to the control sample. The quantity of nC_8 (Octane) in the NRD fuel oils was 175%-184% higher than the control sample (Table 6-3). While the result for nC_{13} (Tridecane) showed only a small difference between the control sample and the NRD fuel oils with the control sample slightly higher. The quantity of nC_{13} (Tridecane) in the control sample was between 7% and 52% higher than the NRD fuel oils (Table 6-3). Also, the result for Octane and Tridecane showed variations is the refining process within camps and across the three different camps.

When used as fuel in internal combustion engines, the higher VOCs concentration in the non-standard refined diesel fuel oils will contribute to high levels of unregulated emissions like benzene, toluene, and xylene in the environment (Latif et al. 2019), with increases in photochemical oxidants, specifically ozone in the atmosphere which is hazardous to the environment and human health (Hazrati et al. 2016). Also, the increased BTX concentration of the NRD fuel oil changes the physical and chemical properties of the fuel. This could result in the low flash points of the NRD fuel oil as presented in Table 5-3 in Chapter 5. This was also reported by Özer (2020) in a study to determine the effect of toluene addition on diesel fuel oil properties, with the results showing a decrease in flash point and kinematic viscosity. According to Jeihouni et al. (2011), aromatic hydrocarbon content in fuels increases PM emissions. High heat release rates, ignition delay, and rise in maximum pressure at medium and high engine loads have been attributed to the effect of different aromatic hydrocarbons blended with diesel fuel (Qian et al. 2017; Sun et al. 2019).

The VOCs results showed inconsistency in the refining process within and across the three different camps. With this, people who make purchase of the non-standard refined products may be faced with a different quality of product each time. The inconsistency in product could be damaging to internal engine components, such as injectors, injection pump, valves, pistons, and liners. Crankcase dilution would be a common occurrence if any of the fuel bought is like those of samples C1 and C3, where the entrained water is above the designated standard. This could also be attributed to damages to car/generator engines, and some spending a lot to maintain their car/generator engines given by questionnaire participants. The result from the Gas Chromatography Mass Spectrometry (GCMS) and Fourier transform infrared spectroscopy (FTIR) study suggest that further investigation into engine performance and emission analysis when using NRD fuel oil is required. This is as the high levels of VOCs found in the non-standard refined diesel fuel oil when used in engines could lead to increased levels of unregulated emissions in the environment. They can be split up into five parts, which are alkenes, carbonyls, alcohols, aromatics, and carboxylic acids respectively (Zuo et al., 2021). Unregulated emissions coming from diesel fuel engines lead to severe environmental pollution which could lead to serious health risks for humans (Chen et al., 2022). Although the unregulated emissions have a very small concentration when compared to regulated emissions, however, their accumulated quantity will become significant in the long term (Zuo et al., 2021).

Table 6-3. The percentage difference of BTX between the NRD fuel oils and the control sample

Samples	Sample	% Toluene	% m- & p-Xylene	o-Xylene	% nC_8	% nC_{13}
A1	NGR	178	136	117	178	44
A2	NGR	178	149	140	180	7
A3	NGR	182	148	139	177	47
B1	NGR	175	129	105	177	42
B2	NGR	176	153	141	184	20
B3	NGR	179	143	124	181	15
C1	NGR	174	123	99	175	52
C2	NGR	177	130	104	178	40
C3	NGR	179	138	118	180	27

6.5 Summary

This chapter has determined the chemical composition of the NRD fuel oils and the control sample using GC-MS and their functional groups using FTIR. The GC-MS was able to identify and quantify the volatile organic compounds (benzene, toluene, and xylene), and n-Alkanes. There was a significant difference in VOCs concentration between the NRD fuel oils as compared to the control sample. The high concentration of benzene, toluene, and xylenes in the NRD fuel oil samples as compared to the control sample (NGR) can be attributed to the crude refining process. This leaves the NRD fuel with more front-end components that are usually found in gasoline. Also, the low flash point for the NRD fuel oils discovered in the physicochemical properties study in Chapter 5 is the consequence of their high VOCs concentration.

Results showed inconsistency in the refining process from the three different camps. Also, there was observed inconsistency in refining within the three different camps. The observed inconsistencies means the refining process changes every time they are set to produce new product. This also implies that citizens who purchase the refined products for use in their generators/cars get a different quality of product every time they make a purchase and therefore, no unique treatment or engine adjustment can be considered due to the uncertainty in these fuels. The observed differences will affect engine performance since the products do not conform to standard and also contribute immensely to environmental pollution. As a result of the substantial quantity of VOCs in the NRD fuel oil from each of the camps compared to the control sample a further investigation is presented in Chapter 7 to determine the effect of the fuels on the performance and combustion characteristics of a diesel engine.

Chapter 7 Performance and combustion characteristics

7.1 Introduction

In Chapter 6 the chemical compositions of the 9 NRD fuel oils and the control sample were determined using the GC-MS and their functional groups using the FTIR. Results obtained showed significant differences for BTX (Benzene, toluene, and xylenes) between the NRD fuels and the control sample. The FTIR spectra showed an aromatic stretch that revealed the presence of BTX. The higher abundance of low molecular weight compounds like benzene, toluene, and xylenes could be the reason for the low flash point of the NRD fuel oil reported in Chapter 5. Unregulated emissions like benzene, toluene, and xylenes are dangerous environmental pollutants that are emitted daily through several sources, such as standby power generators, vehicles, paints (Garzón et al. 2015), and diesel engines of ships and barges (Mihajlović et al. 2016). Thus, this study will determine the performance and combustion characteristics of a single-cylinder diesel engine fuelled with the NRD fuel oils. The study will determine the brake thermal efficiency (BTE), brake specific fuel consumption (BSFC), the peak cylinder pressure, and unregulated emissions like oxides of nitrogen (NO_x), carbon monoxide (CO), and carbon dioxide (CO_2).

7.2 Experimental methods

The collection, preparation, and storage of the NRD fuel samples and the control sample are presented in section 3.3.2 in Chapter 3. The physicochemical properties of the test fuel samples are also presented in Tables 5-3 in Chapter 5.

7.2.1 Experimental setup and procedure

The experiment was conducted with a single-cylinder Cussons Engine Test Bed P8252 with a 3.5kW (4.8 hp) Lombardini engine as presented in Figure 7-1. The engine is a naturally aspirated fuel-injected four-stroke compression ignition engine. It drives a 3-phase alternator via a toothed pulley and a toothed belt. The engine has a bore of 69mm, a 60mm stroke, and a maximum output of 3.5kW at

3500 rpm. The engine’s specifications are listed in Table 7-1. This type of engine is most widely used for the processing of farm produce, in fishing boats as a prime mover, and for power generation around the coastal regions of Nigeria.

To make sure the engine was running in a steady-state condition during the tests, it was started and allowed to run in a no-load condition for 5-10 minutes until the exhaust gas temperature stabilised. The test was conducted at four different engine loads of 0.12kW, 0.43kW, 0.95 kW, and 1.7 kW and a rated speed of 2500rpm. The loads were selected because of the size of the engine, to replicate generating sets used in the creeks of the Niger Delta, and to find the percentage difference which the power range could provide. Engine load of 1.7 kW at the speed of 2500 kw was the maximum capacity of the engine. Any higher load would only be possible at lower engine speed, which would have deviated from the aim of this experiment, replicating generating sets running at constant speed. The speed was held constant to replicate and determine the performance of a standby constant speed generator using the non-standard refined diesel fuel oils. To make sure there was no contamination in the fuel system of the test engine, a different external fuel tank, and fuel filter were used for each test case. At the end of each experiment, the fuel line was purged using clean diesel oil, and the engine was allowed to run for sufficient time to burn off any residual fuel from the previous experiment. This was to make sure there was no contamination in the process of fuel replacement. Three measurements were taken to then average the data for each operating situation because of the pulsed characteristics of the engine. This helped determine the repeatability of the processed data with an estimate of the measured accuracy (Qi et al., 2009).

A piezoelectric transducer (6052 Kistler high-temperature pressure sensor) was installed in the engine cylinder head to measure the in-cylinder pressure, and its output signal fed to a Type 5018A Kistler single channel charge amplifier. The signal from the single-channel charge amplifier was fed to a 100MHz GW INSTEK GDS-1102A-U Digital Storage Oscilloscope (Figure 7-1). The specification of the piezoelectric transducer, the charge amplifier, and the digital oscilloscope are presented in Table 7-2 and Table 7-3. The test were conducted three times for each fuel sample. The repeatability analysis was based on the technical standard ISO/IEC 17025:2017 (Trishch et al. 2019).

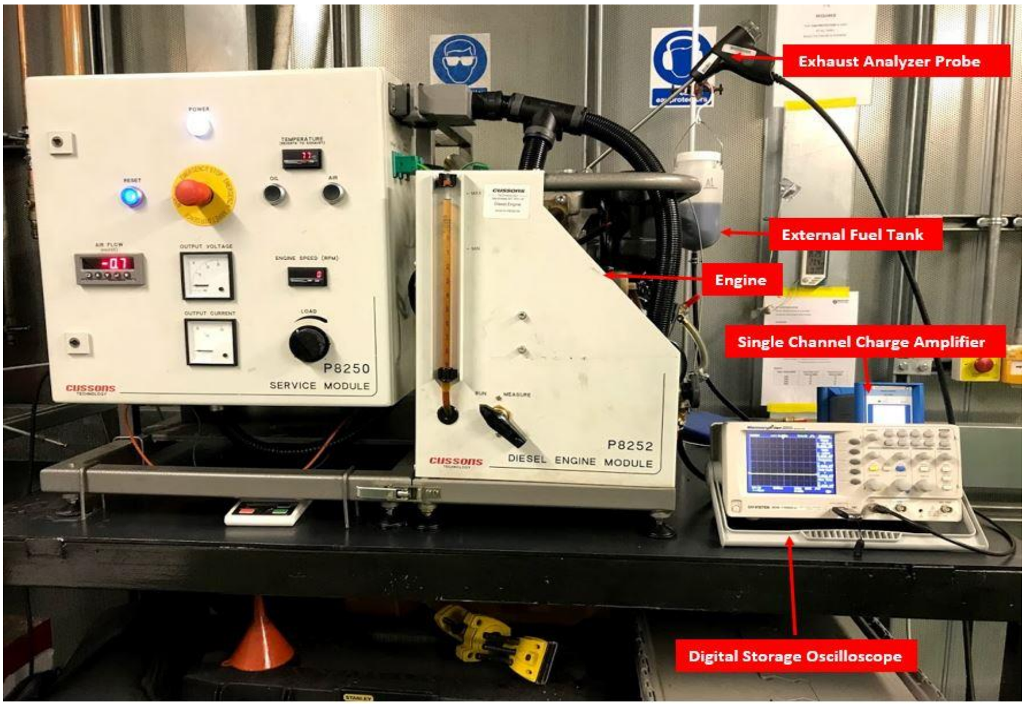


Figure 7-1. Experimental setup

Table 7-1. Specification of the test engine

Manufacturer		
Model		P8252
Engine type		4-stroke
Number of cylinders	N	1
Bore	mm	69
Stroke	mm	60
Swept volume	cm^3	224
Compression ratio		21.1
RPM		3600
Power	kW	3.5
Fuel consumption	g/kW.hr	267

Table 7-2. Specification of the Kistler 5018A single-channel charge amplifier

Connector Type	BNC neg. or TRIAX neg.	
Measuring range FS	pC ±2 - 2 200 000	
Measurement uncertainty	FS<10 pC <±2 FS<100 pC <±0,6 FS≥100 pC <±0,3	% % %
Sensor sensitivity	-20.00 pC/bar	
Sensor Sensitivity change 200˚C ± 50˚C 23……….350˚C		 % %
Overload	300	bar
Operating temperature range Temperature min./max.	-20…….350 -50…….400	˚C ˚C

Table 7-3. Specification of the GDS-1102A-U Digital Storage Oscilloscope

Instrument	Horizontal
GDS-1102A-U (DC~100MHz (-3dB) <3.5ns Approx	
Range	1ns/div ~ 50s/div (1 -2.5-5 increments); ROLL: 50ms/div ~ 50s/div
Accuracy	±0.01%
Modes	MAIN, WINDOW, WINDOW ZOOM, ROLL, X-Y
Pre-Trigger	10 div maximum
Post-Trigger	1000 div
Maximum Input	300V (DC+AC peak), CATII

A Testo 350 exhaust gas analyser was utilized to determine the concentrations of oxides of nitrogen (NO_x), carbon monoxide (CO), and carbon dioxide (CO_2) in the exhaust emissions. The Testo 350 analyser unit is comprised of the sensor system and the electronics that are required for emission measurement. The specification of the Testo 350 analyzer is presented in Table 7-4.

Table 7-4. Specification of Testo 350 exhaust gas analyser

Measurement Parameter	Range	Accuracy	Resolution
CO, H_2- Compensated	0-10000ppm	±10ppm (0-199ppm) ±5% of mv (200-2000ppm) ±10% of mv (rest of range)	1 ppm
CO_{low}, H_2- Compensated	0-500ppm	±2ppm (0-39.9ppm CO) ±5% of mv	0.1ppm
NO	0-4000ppm	±5ppm (0-99) ±5% of mv (100-1999.9ppm) ±10% of mv (2000-4000ppm)	1ppm
NO_{low}	0-300ppm	±2ppm (0-39.9ppm) ±5% of mv (40-300ppm)	0.1ppm
NO_2	0-500ppm	±5ppm (0-99.9ppm) ±5% of mv (100-500ppm)	0.1ppm

*mv stands for the measured value.

7.3 Results

Results for the engine performance including brake thermal efficiency, brake specific fuel consumption, and in-cylinder pressure are discussed in this section. Also, the results for the emission analysis for NOx, CO, and CO_2, will be discussed.

7.3.1 Brake thermal efficiency (BTE)

The brake thermal efficiency is a vital parameter when analysing engine performance. It is the ability to convert a fuel's chemical energy into actual work (Elkelawy et al. 2021). The changes in the BTE for the NRD fuel and the control sample with different engine brake power are presented in Figure 7-2. The BTE relies on characteristics of the fuel such as calorific value (Rajak et al. 2020). The BTE increased with the increase in load for all test samples. At the lowest loading condition of 0.12kW, the BTE was highest for samples A1, A3, B2, C2 compared to the control sample. This could be attributed to maximum power being developed as a result of the proper combustion of fuel (Mohapatra et al. 2021), which is also a result of better atomization, mixing of air-fuel, and spray characteristics (Rajak et al. 2020).

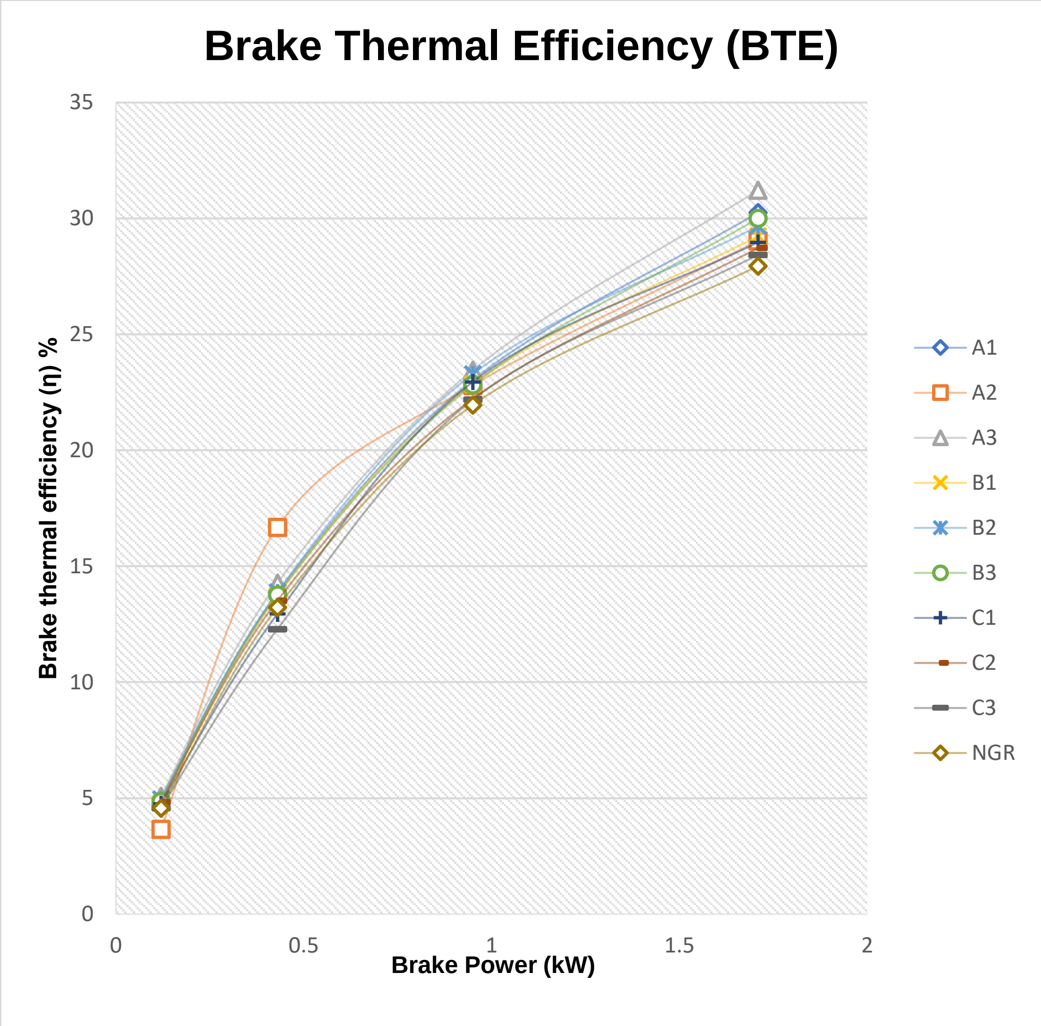


Figure 7-2. Brake Thermal Efficiency (BTE)

As the load increased to 0.43kW, it was observed that the BTE values for the NRD samples A2, A3, B2, and C2 were higher than for the control sample (NGR). The BTE at full load condition (1.71kW) revealed a higher brake thermal efficiency for all the NRD fuel oils compared to the control sample. This could be attributed to their calorific values. A more accurate measure of engine performance is the specific fuel consumption (SFC), which will be dealt with in the next subsection.

Table 7-5 % BTE at full load

	A1	A2	A3	B1	B2	B3	C1	C2	C3	NGR
BP	%η	%η	%η	%η	%η	%η	%η	%η	%η	%η
0.12kW	4.98	3.65	5.07	4.79	4.95	4.85	4.76	4.83	4.57	4.73
0.43kW	13.85	16.68	14.27	13.74	13.88	13.76	12.95	13.52	12.29	13.23
0.95kW	23.03	22.80	23.45	22.85	23.29	22.82	22.95	22.22	22.18	21.95
1.71kW	30.25	29.04	31.22	29.24	29.67	30.00	28.97	28.73	28.43	27.95

*BP- Brake Power

7.3.2 Brake specific fuel consumption (BSFC)

The brake-specific fuel consumption for all test fuels is illustrated in Figure 7-3. It is a measure of the fuel's efficiency measured in g/kW-hr (Raman and Kumar, 2020). For all test cases, the BSFC increased with increasing load. Slight differences were observed between the control sample (NGR) and the NRD fuel oils at all load conditions. However, at the load condition of 0.12kW sample A2 had a higher fuel consumption compared to the control sample and other NRD fuel samples. Comparing the BSFC from the fuels from the three different camps, fuel samples from camp C had the highest BSFC closely followed by the fuels from camp B and camp A which had the lowest BSFC (see Table 7-6). The high BSFC from camp C could be attributed to the high entrained water in the non-standard refined diesel fuel oils from camp C. The usage of the NRD fuel oil with high water content could lead to users refilling their fuel tanks often. From the questionnaire instrument on usage, respondents reported that they spend more when they make use of the NRD fuel oil. The monies spent could be for maintenance of the car/generator engine.

Table 7-6 BSFC at all load conditions

	A1	A2	A3	B1	B2	B3	C1	C2	C3
BP	g/kW-hr	g/kW-hr	g/kW-hr	g/kW-hr	g/kW-hr	g/kW-hr	g/kW-hr	g/kW-hr	g/kW-hr
0.12kW	1.705	2.324	1.677	1.776	1.711	1.753	1.779	1.763	1.854
0.43kW	0.613	0.509	0.596	0.619	0.61	0.617	0.653	0.63	0.657
0.95kW	0.369	0.373	0.363	0.373	0.363	0.353	0.369	0.383	0.383
1.71kW	0.281	0.292	0.272	0.291	0.285	0.283	0.292	0.296	0.298

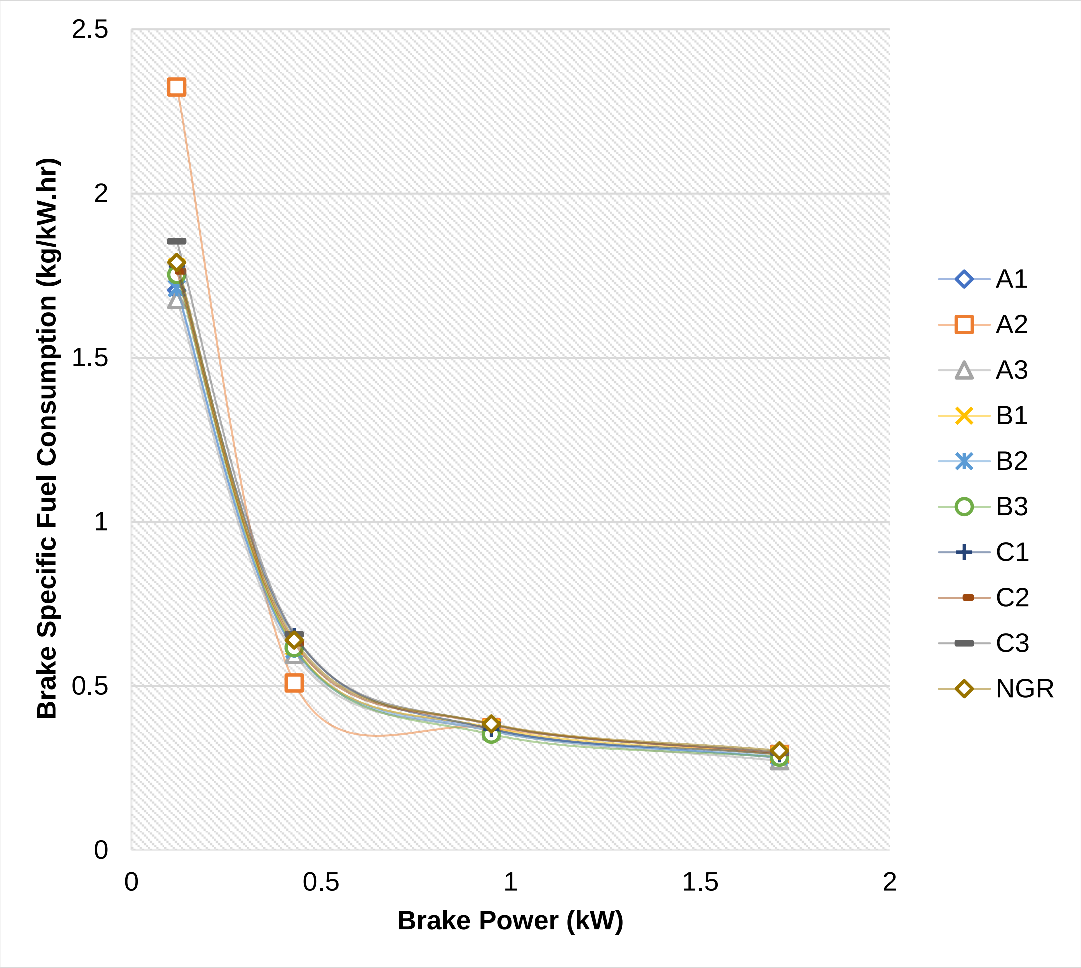


Figure 7-3. Brake Specific Fuel Consumption (BSFC)

7.3.3 Cylinder pressure

The variation in the cylinder pressure under different loading conditions for all test fuels is presented in Figure 7-4. There is a noticeable increase in-cylinder pressure as the engine load is increased for all test fuels. At 0.12kW and 0.43kW brake power, the cylinder pressure for the NRD fuel oils was slightly higher than that of the control sample. At 0.95kW brake power, fuel samples A2, C1, C2, and C3 were higher than the other NRD fuel oils and the control sample. At 1.71kW brake power, there were slight differences observed between the NRD fuel oils and the control sample. Comparing the cylinder pressure for the three different camps to that of the control sample as shown in Figure 7-5, it was observed that at all load conditions the NRD fuel oils from camp C were higher than the control sample.

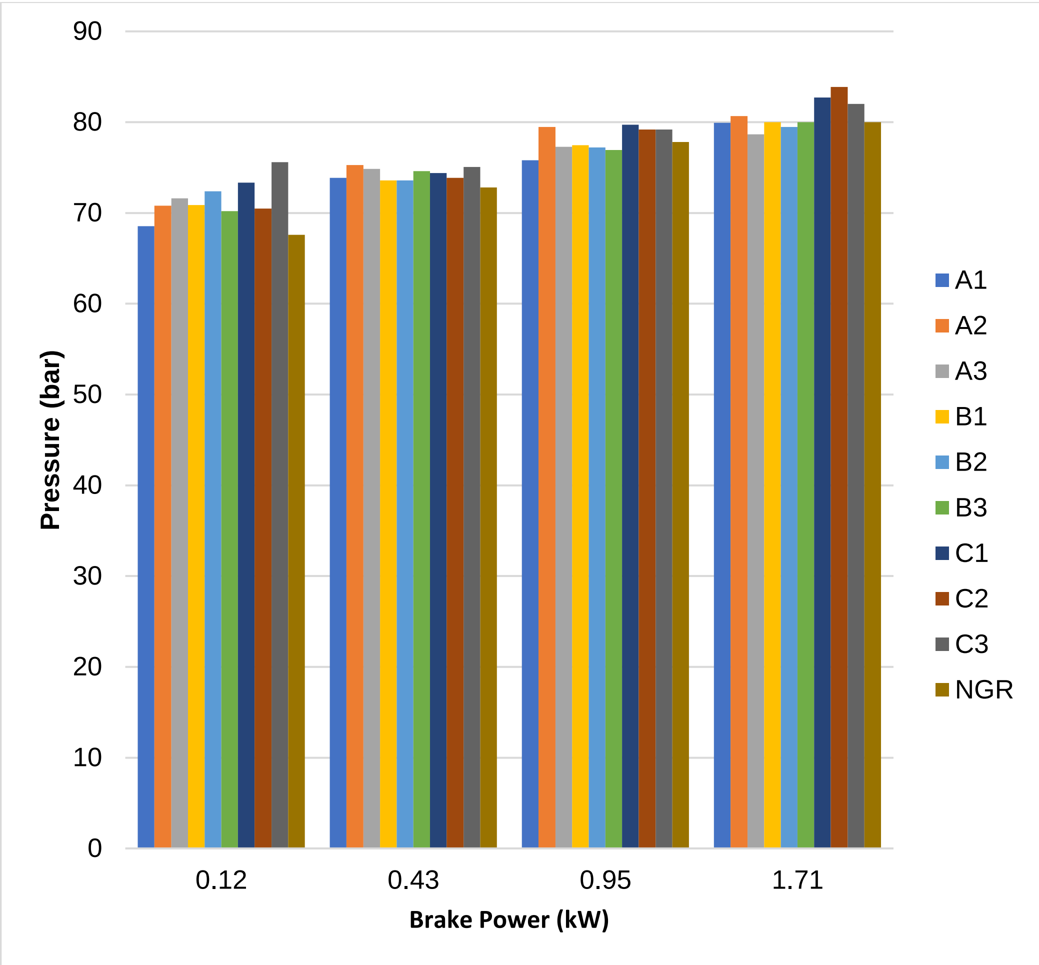


Figure 7-4. Cylinder Pressure

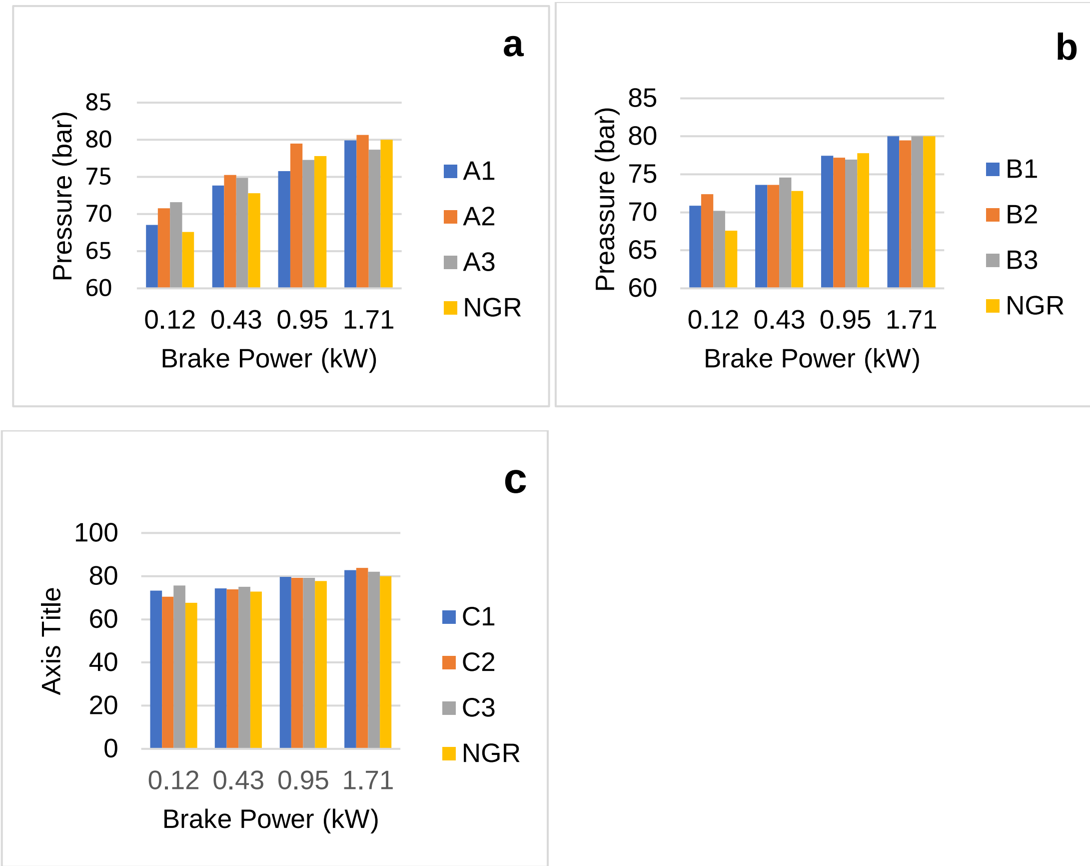


Figure 7-5. Cylinder Pressure (a) fuel samples from camps A and the control sample (b) fuel samples from camp B and the control sample (c) fuel samples from camp C and the control sample

The higher pressure when using the NRD fuel oil may reflect shortened ignition delay time. The shortened ignition delay time could be attributed to the high level of toluene in the NRD fuel oils (see Table 6-2). According to Özer (2020) the addition of toluene to soyabean oil biodiesel, and diesel fuel oil results in shortened ignition delay; toluene reduces the flash, and ignition point of fuel. The addition of toluene is believed to start the burning in the first phase of the spray before the target point, possibly reducing the duration of the combustion (Şimşek and Çolak, 2019). Due to its very low boiling point, toluene is easily gasified, and mixed with the charged air at the end of compression, could lead to a higher rate of combustion and higher cylinder pressure.

7.3.3.1 Maximum cylinder pressure

Figure 7-6 shows the maximum cylinder pressure at the maximum loading condition of 1.71kW for the various NRD fuel oils and the control sample. NRD fuel oils from camp C had the highest peak cylinder pressure of 83.87 bar. As discussed in subsection 7.3.3, high cylinder pressure could be attributed to the presence of an increased level of toluene and perhaps other volatile compounds in the NRD fuel oils. High maximum cylinder pressure is damaging to engines. There is a tendency for increased wear and tear of internal engine parts like bearings, pistons, rings, valves, and liners. This could be a reason for the damage to cars/generator engines experienced by respondents of the questionnaire instrument on usage where 56.2% agreed that the non-standard refined diesel fuel oils were damaging to engines. Respondents fell into the group that does not make use of diesel fuel oils. Respondents also reported that usage of the non-standard refined diesel fuel oil made users spend a lot in the maintenance of their car/generator engines. This was attested to by 53.1% of respondents.

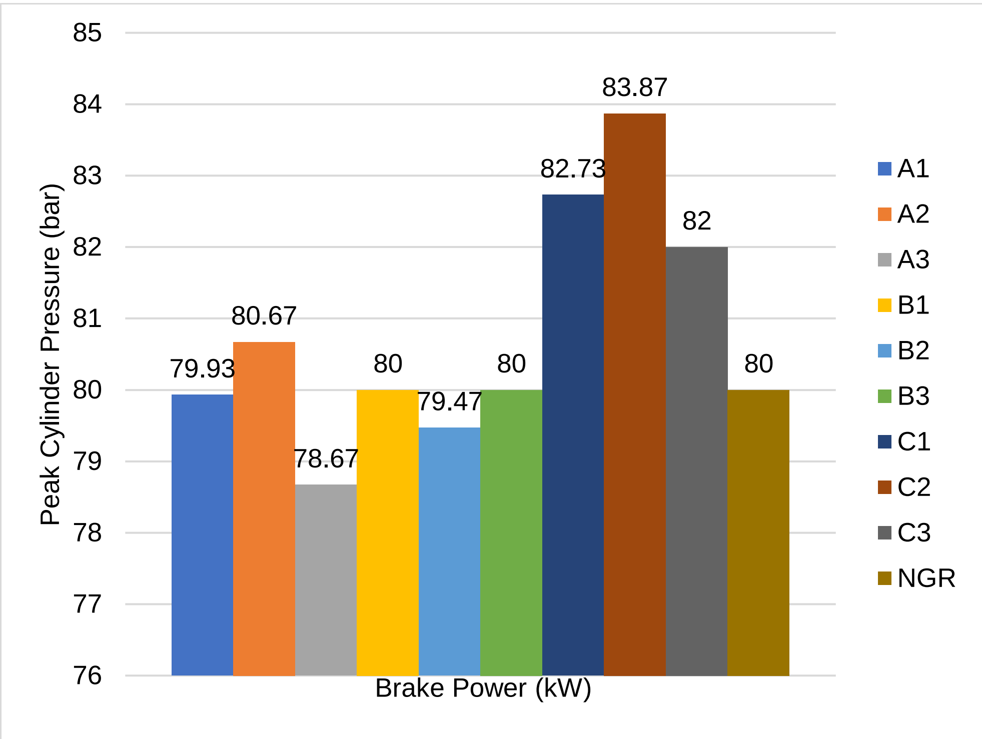


Figure 7-6. Maximum cylinder pressure

7.3.4 Exhaust gas temperature

The exhaust gas temperature (EGT) was measured for all samples. The variations in the exhaust gas temperature (EGT), at different loads, are illustrated in Figure 7-7. There was an increase in the EGT for all the tested fuels with increasing engine load. This could be attributed to an increased supply of fuel into the combustion chamber as a result of the higher load. Samples B1, C1, C3, and the control sample had high EGT (Table 7-7), while the others showed lower EGT as compared with the control sample. The lower EGT is closely related to the early ignition of the fuel in the engine cylinder

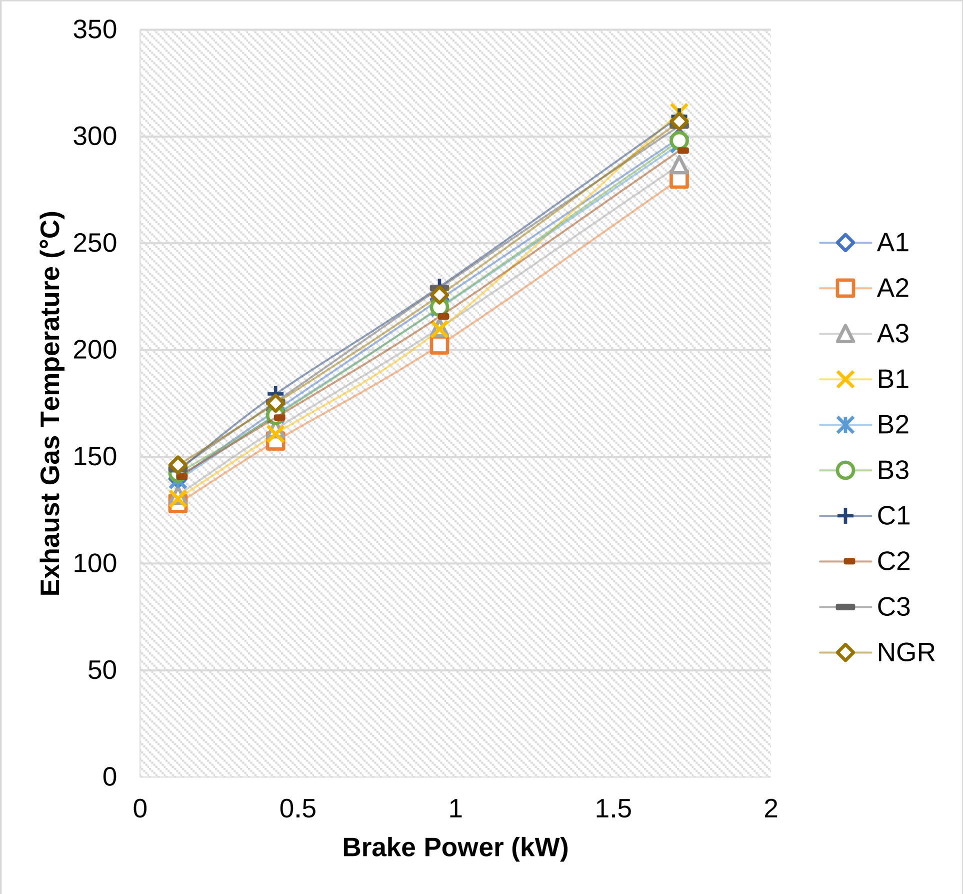


Figure 7-7. Exhaust Gas Temperature (EGT)

Table 7-7 Exhaust gas temperature at full load

	A1	A2	A3	B1	B2	B3	C1	C2	C3	NGR
BP	°C	°C	°C	°C	°C	°C	°C	°C	°C	°C
1.71kW	299.33	280	286.67	311.3	296.33	298	309.33	293.33	305	307

*BP-Brake Power

7.3.5 Oxides of nitrogen (NOx) emissions

Figure 7-8 shows the variations in NO_x emissions for the NRD fuel oils and the control sample at different load conditions and a constant engine speed of 2500 rpm. The results showed an increase in the NO_x emission at increased load for the different test samples. Samples A1, B3, C1, C2, and C3 (see Table 7-8) had high values of NO_x emission compared to the control sample. The high oxides of nitrogen emission could be attributed to the early ignition, and high combustion temperature experienced with some of the samples.

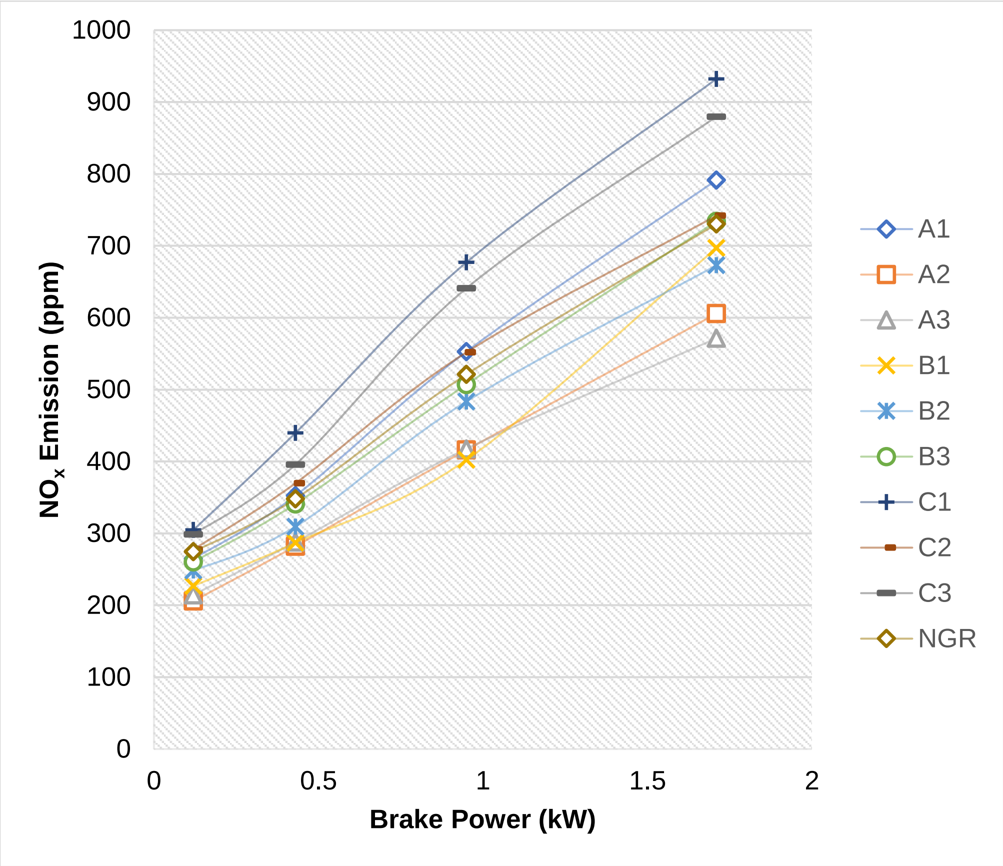


Figure 7-8. Oxides of Nitrogen (NO_x)

Table 7-8 NO_x emission at full load in ppm

	A1	A2	A3	B1	B2	B3	C1	C2	C3	NGR
BP	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm
1.71kW	791.53	605.7	571.36	696.8	672.9	734.1	932.27	742.03	879.77	730.37

ppm – parts per million

7.3.6 Carbon monoxide emissions (CO)

The results for CO emissions for the non-standard refined diesel fuel oils and the control sample are presented in Figure 7-9. Results revealed a reduction of CO emissions with an increase in load for all test fuels. Table 7-9 presents the CO emission results at 0.12kW and 1.7kW brake power.

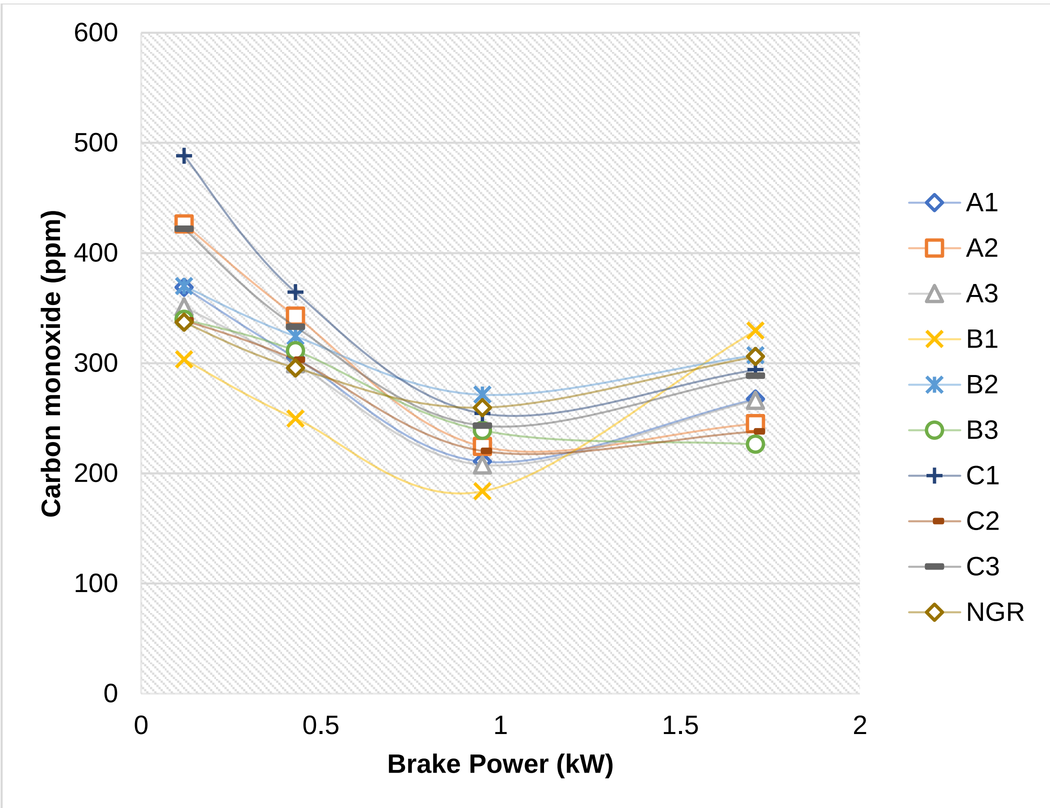


Figure 7-9. Carbon monoxide (CO)

Table 7-9 CO emission at part load (0.12kW) and full load (1.71kW) in ppm

	A1	A2	A3	B1	B2	B3	C1	C2	C3	NGR
BP	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm
0.12kW	368.67	426.33	351	303.33	370	339.67	488.33	339	422	337
1.71kW	267.33	245	266.33	329.67	307.33	226.33	294	238	288.67	306

*ppm-parts per million

*BP- Brake Power

At 0.12kW brake power the samples A2, C1, and C3 had high carbon monoxide emissions, while sample C1 had the highest CO emissions of 488.33 ppm, compared to NGR with a percentage difference of 36.67%. At 1.71kW full load, samples B1, B2, C1, C3, and NGR had high carbon monoxide emissions, while sample B1 had the highest CO emissions of 329.67 ppm, compared to NGR with a percentage difference of 7.45%.

7.3.7 Carbon dioxide emissions (CO_2)

Figure 7-10 shows the variation in carbon dioxide emissions for the test fuel samples. There was an increase in CO_2 emissions with increasing load for all the test fuels. The increase in CO_2 with load is attributable to an increase in fuel injection into the combustion chamber. At 0.12kW brake power (see Table 7-9) the samples A1, C1, and C3 had high CO_2 emissions compared to the control sample (NGR) with percentage differences of 2.45%, 19.64%, and 15.1% respectively. At the full load condition (see Table 7-10) samples A1, B3, C1, and C3 had high CO_2 emissions compared to the control sample (NGR) with percentage differences of 2.76%, 1.71%, 21.20%, and 17.32% respectively. Sample C1 from camp C had the highest CO_2 emissions overall.

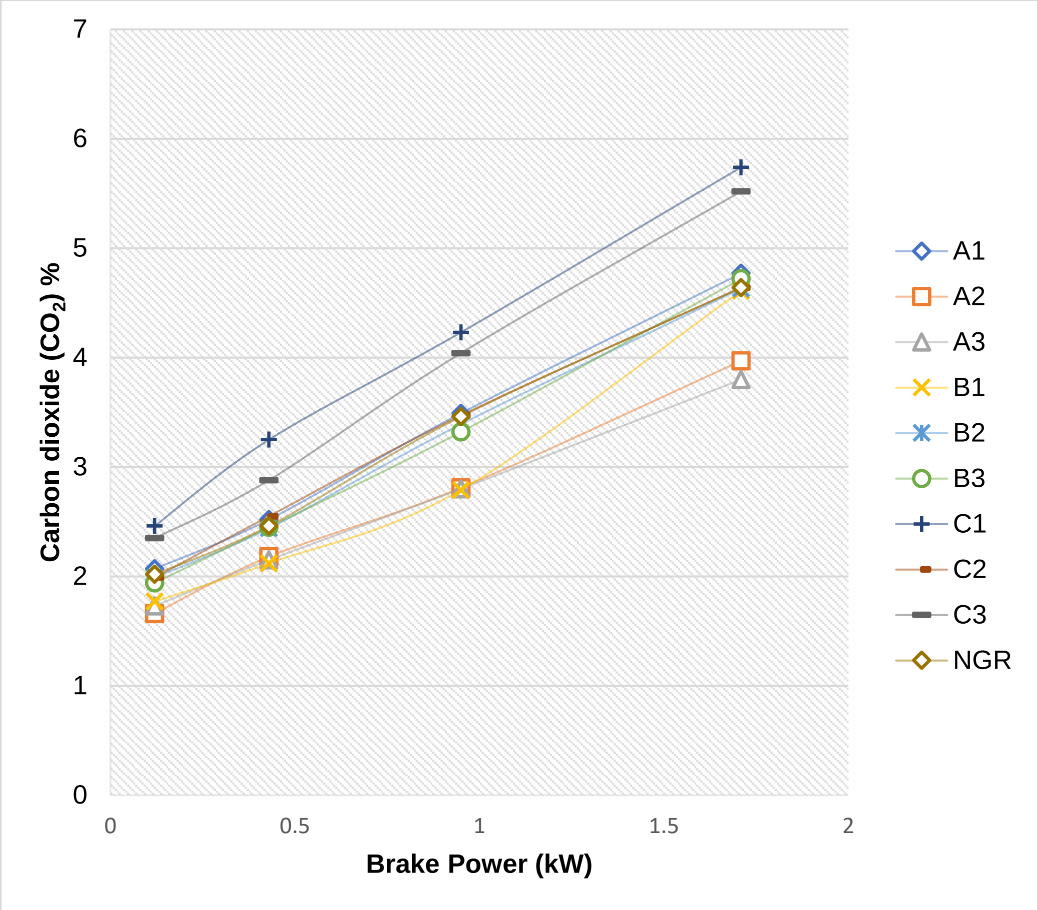


Figure 7-10. Carbon dioxide (CO_2)

Table 7-10 CO_2 emission at part load (0.12kW) and full load (1.71kW) in %

	A1	A2	A3	B1	B2	B3	C1	C2	C3	NGR
BP	%	%	%	%	%	%	%	%	%	%
0.12kW	2.07	1.66	1.73	1.77	1.99	1.94	2.46	1.99	2.35	2.02
1.71kW	4.77	3.97	3.8	4.61	4.63	4.72	5.74	4.64	5.52	4.64

7.4 Discussion

The brake thermal efficiency varied for the various NRD fuel oils compared to the control sample. While the BTE for all the test fuels increased with load, which is expected for diesel fuel, at full load conditions it was observed that samples A1 (28.26%), A3 (33.04%), B2 (28.6%), B3 (28.2%), and C2 (28.68%), were all significantly higher than the control sample. The percentage differences in BTE for samples A1, A3, B2, B3, and C2, compared to the control sample NGR, were 2.29%, 17.87%, 3.48%, 2.07%, and 3.76%.

Slight differences were observed for the BSFC for the test fuels. The NRD fuel oils from camp C had higher fuel consumption compared to the other NRD fuel oils from camps A, and B. The high BSFC from camp C is the indication of lower efficiency as more fuel is required per kW/hr. This may be attributed to the comparatively higher water content. Cylinder gas maximum pressure at full load conditions revealed high maximum pressure for samples A2, C1, C2, and C3, compared to the control sample. This could be attributed to ignition delay, which brings about the collection of fuel inside the combustion chamber thereby increasing the uncontrolled combustion phase, consequently leading to high cylinder pressure (Santhoshkumar et al. 2019). Though the ignition delay was not measured in this study, the high maximum pressure from some of the samples could indicate the variation in ignition delay.

The exhaust gas temperature (EGT) showed variations at full load conditions for the 9 NRD fuel oil samples compared to the control sample. The differences observed in the EGT could be attributed to an increased supply of fuel into the combustion chamber as a result of higher load (Shrivastava et al. 2019). The exhaust gas temperature also indicates the quality of combustion in the combustion chamber. Sample C1 from camp C had the highest EGT of 309.33 °C with a 0.76% difference from the control sample. High levels of NO_x emission were observed at all load conditions for the NRD fuel oils A1, B3, C1, C2, and C3 compared to the control sample (NGR) at full load conditions as presented in Table 7-8. This could be attributed to high combustion temperature, availability of oxygen. Also, the high level of NOx might be a result of the high maximum cylinder pressure developed by some of the samples. The percentage difference in NO_x emissions between samples A1, B3, C1, C2, and C3 compared to the control sample is presented in Table 7-11. Samples A1 (8.04%), C1 (24.29%), and C3 (18.56%) were quite higher than the control sample, while samples B3, and C2 were slightly higher than the control sample. The non-standard refining also revealed inconsistencies in the refining processes within, and across the different camps. The inconsistencies is seen in the refining process from all three camps. Camp C had the highest production of oxides of nitrogen emission.

Table 7-11. The percentage difference in NOx emission at full load condition

Sample	Sample	% Difference
A1	NGR	8.04
B3	NGR	0.52
C1	NGR	24.29
C2	NGR	1.59
C3	NGR	18.56

Given the high level of NO_x emissions obtained from samples A1, B3, C1, C2, and C3, at full load conditions under a controlled experimental environment, the use of these fuels would contribute significantly to NOx levels in the Niger Delta Region of Nigeria. With the NRD fuels being used daily to power marine craft, stand-by power generators, automobiles, and farm machinery there will be high levels of environmental pollution.

Carbon monoxide emission at the initial load condition of 0.12kW was relatively high in most of the NRD fuel oils compared to the control sample (NGR) as presented in Table 7-9. CO is produced as a result of incomplete combustion of diesel fuel and is a toxic gas that is extremely poisonous to humans, and must be controlled (Ning et al., 2020). The percentage difference between the NRD fuel oils compared to the control sample is presented in Table 7-12. With the lack of emission control in Nigeria, the continuous use of NRD fuel oils will produce carbon monoxide that is harmful to the population and the environment. Samples A1 (8.98%), A2 (23.39%), B2 (9.33%), C1 (36.66%) and C3 (22.39%) were quite higher than the control sample, while samples A3 (4.06%), B3 (0.79%), and C2 (0.52%) were slightly higher than the control sample. The non-standard refining also revealed inconsistencies in the refining processes within, and across the different camps for CO. The inconsistencies is seen in the refining process from all three camps. Camps A and C had the highest production of carbon monoxide emission.

Table 7-12. The percentage difference in CO emission at initial load condition of 0.12kW

Sample	Sample	% Difference
A1	NGR	8.98
A2	NGR	23.39
A3	NGR	4.06
B2	NGR	9.33
B3	NGR	0.79
C1	NGR	36.66
C2	NGR	0.52
C3	NGR	22.39

There was an increase in CO_2 emissions with an increase in load for all the test fuel samples. At 0.12kW brake power, samples A1, C1 and C3 had higher CO_2 emissions compared to the control sample. Also, at 1.71kW brake power, samples A1, B3, C1, and C3 had higher carbon dioxide compared to the control sample (NGR), with percentage differences of 2.76%, 1.71%, 21.20%, and 17.32% respectively. The results for carbon dioxide, like NO_X, and CO, were obtained in experiments carried out in a controlled environment in the Engine Cell, in the Stephenson Building, Newcastle University. The continuous usage of these fuel in the creeks and other towns and cities in Niger Delta will lead to increased greenhouse gas production, intensification of the greenhouse gas effect and global warming (Frinjo et al., 2022, Mona et al., 2021). The non-standard refining also revealed inconsistencies in the refining processes within, and across the different camps for CO_2. The inconsistencies are seen in the refining process from all three camps. Camps B and C had the highest production of carbon dioxide emissions.

7.5 Summary

This chapter has reported combustion and emission analysis using the 9 NRD fuel oil samples and the control sample as test fuels in a single-cylinder Cussons Engine Test Bed P8252, coupled with a piezoelectric transducer and a Testo 350 exhaust gas analyser. The NRD fuel from the various camps showed inconsistency in their refining process. Also, there was inconsistency in the refining process within camps. The high cylinder maximum pressure observed in some of the non-standard refined diesel fuel oils, would be damaging to engines which is in line with the comments of the questionnaire respondents on usage, and the expenditure on engine maintenance. The situation could be likened to buying the non-standard refined diesel fuel oils at a cheap rate but spending more to maintain the engine.

The environment of the Niger Delta region is unsafe with the continuous usage of these fuels with their high levels of regulated emissions like NO_x, CO and CO_2 observed in the study. Also, with the high levels of VOCs (benzene, toluene, and xylenes) observed in the various samples in Chapter 6, the burning of the NRD fuel could lead to high levels of unregulated emissions in the environment.

Chapter 8 Conclusions, Recommendations, and Future Research

8.1 Introduction

This thesis has offered a holistic study into the sustained impact of the activities of non-standard crude oil refiners on their host communities and the effect of the NDR fuel oils on diesel engines, and the resultant emission on the environment of Nigeria's NDR.

The research questions were established to determine:

1. The implications of the activities of the non-standard crude oil refiners in the NDR on their host community?
2. How the non-standard refining of crude oil affect the Niger Delta people? And to what extent?
3. How the activities of the non-standard crude oil refiners could be mitigated?
4. How different, in terms of standard parameters, is the Nigeria refined diesel fuel oil from the non-standard refined diesel fuel oil?
5. How the NRD fuel oil affect engine performance and emissions?

This chapter will present the conclusion of the thesis drawn from the research findings followed by the key recommendations and potential future research.

8.2 Novelty of the study

To reach its final outcome, a novel approach was developed for this thesis, but it could be applied in similar studies elsewhere. The design incorporated the community's opinions in the form of a social study. The community's opinion then set the direction for the scientific research. The results from the scientific research were then fed into the engineering research. The results from the scientific and engineering research could then be fed back to the community to raise awareness of the wider impact and provide evidenced based results for policy makers and environmental agencies. The feedback will help keep communities informed of the inherent danger in the activities of the non-standard crude oil refiners and that of the refined products. Policy makers and government agencies should take necessary precautions when carrying out enforcement duties. Government authorities will also be properly informed of the level of damage to the environment arising from the activities of the non-standard crude oil refiners. This research study has brought to the fore the poor quality and inconsistency in the refining process of the non-standard refined diesel fuel oils which was not known to society. Also, the lack of societal knowledge on the damaging effect of using the non-standard refined diesel fuel on engines has also been revealed. Society was unaware of the damaging effect of using the NRD fuel oil.

8.3 Summary of findings

This study used multiple methods of research to reach its outcome. The use of a convergent method in this research study to determine the impact of the non-standard refining of crude oil on the NDR of Nigeria, while at the same time determining the physical and chemical properties of the fuel, and its impact on diesel engines is novel. This is because other studies had looked to address the myriad of issues facing the NDR of Nigeria as a result of crude oil exploration and exploitation from one perspective only. The study found evidence that the activities of the non-standard refiners have led to high levels of environmental pollution in their host communities. This could be attributed to the poor refining techniques applied by the refiners and their refined waste disposal methods. The disposal of refined waste into nearby streams, rivers, and vegetation has proved to be dangerous to the environment and the ecosystem. This has greatly affected the livelihood of the farmers, and fishermen/fisherwomen, leading to reduced farm harvest and fishing yields, thereby reducing their expected income. Water sources have not been left out in the damaging effect arising from the non-standard refining of crude oil. The waste disposal methods of the non-standard refiners are damaging to both surface water and underground water.

It was determined that while some of the fuel properties were within the internationally acceptable limit in ASTM D975 as compared to the control sample, others like the pour point, flash point, and water content showed some differences.

This is dangerous and affects the transportation and storage of the fuels. The high level of entrained water in these samples could lead to the damage of engine parts.

There is a significant difference between the volatile organic compounds present in the non-standard refined diesel fuel oil as compared to the control sample. These VOCs are known to be dangerous to the environment. The disposal of the refinery waste which contains substances like benzene, toluene, and xylenes into nearby vegetations, rivers, and streams is not only harmful to humans but also harmful to aquatic life, cash crops, and farmlands. This could be a reason for the reduced farm produce, fishing yields, and polluted rivers.

The study reported a high level of NO_x and carbon monoxide emission under a controlled experimental environment. The continuous usage of the non-standard diesel fuel oil for engines in Nigeria will contribute immensely to environmental pollution. A high level of CO_2 emission was also recorded at full load conditions from some of the non-standard refined diesel fuel oil samples. The continuous usage of these fuels in an unregulated environment will lead to an increase in greenhouse gases. High peak cylinder pressure observed from some of the samples will cause damage to engine cylinder components like pistons, valves, engine liners, and piston rings. The high level of entrained water observed in some of the samples, see (Figure 5-5) could lead to crankcase dilution when used in diesel engines, see (Yu et al. 2021).

Also, there was inconsistencies in the refining process within and across the three different camps. With these inconsistencies, people who make use of the fuels could be buying a different quality of product whenever they go out to purchase the non-standard refined diesel fuel oil.

8.4 Recommendations

The study makes several key recommendations to policy makers, environmental agencies, government agencies saddled with the responsibility of enforcement and orientation, oil multinationals, DPR, NNPC, NOSDRA and community stakeholders as detailed below.

8.4.1 Remediation of affected soil, water

This thesis recommends that the Federal Ministry of Petroleum Resources, the Directorate of Petroleum Resources (DPR), the National Oil Spill Detection and Response Agency (NOSDRA), and Oil Multinationals carry out an urgent Environmental Impact Assessment (EIA) to determine the areas in the NDR affected by the high level of crude oil pollution to the land, water bodies, flora and fauna and the findings from the EIA being acted upon by the necessary agencies of government. This is to ensure that crude oil contaminated soil and rivers by the activities of the non-standard crude oil refiners be attended to, and for both to be in line with the United Nations Sustainable Development Goals 14 and 15 (UNDP, 2021). Goal 14 aims to “manage and protect marine and coastal ecosystems from pollution” and Goal 15 aims to “manage and protect the loss of natural habitats and biodiversity which are part of our common heritage and support global food and water security”. For heavily contaminated soils, phytoremediation will have to be carried out, (Adesipo et al. 2020) and an urgent clean-up is required for the streams and rivers that have been heavily polluted. This will ensure that damaged soils and water bodies are restored so farmers and fishermen/fisherwomen could return to their farms and fishing areas. This will help boost farm harvest and fish yields.

8.4.2 Fish restocking and water supply

Fish species that have been heavily affected by the pollution of the streams, and rivers in particular areas in the NDR by crude oil pollution from the activities of non-standard crude oil refiners have to be restocked. The Department of Fisheries in the Federal Ministry of Agriculture in conjunction with the State Department of Fisheries should work with affected communities and stakeholders to restore fish species that were affected. Also, the governments at the state and federal levels should endeavour to provide potable drinking water for communities in the Niger Delta, by drilling boreholes and installing water taps with properly reticulated pipeline networks. This will reduce their dependence on river and stream water for drinking purposes. It will also ensure that the United Nations Sustainable Development Goal 6 is met. Goal 6 ensures that there is safe and affordable drinking water for all by 2030 (UNDP, 2021). This will also reduce sickness arising from the drinking of polluted water.

8.4.3 Enforcement and funding

The study recommends that agencies of government like the National Oil Spill Detection and Response Agency (NOSDRA), the Directorate of Petroleum Resources (DPR), and the National Environmental Standards and Regulation Enforcement Agency (NESREA), see (section 2.1.7) be properly funded to carry out their constitutional roles. With required funding, operational facilities will be available for monitoring and detection of crude oil pollution, cleaning of polluted land and water, and public enlightenment. Also, the military authorities, the police and the Nigeria Security and Civil Defence Corps (NSCDC) should change their approach to the destruction of non-standard crude oil refineries, see (section 2.1.7). The process where confiscated refined and unrefined products are poured into nearby streams and rivers is damaging to the environment. Non-standard refineries should not be set ablaze as a means of destroying them. Seized products both refined and unrefined should be handed over to the Nigerian National Petroleum Corporation (NNPC) operator of the nation's refineries.

There is a need for the military and other security apparatus of government to purge their rank and file of corrupt personnel, who collaborate with the non-standard refiners in the sabotage carried out on oil pipelines in the search for crude oil for their refining. Also, special courts should be set up to speedily prosecute crude oil theft cases, including military and police personnel discovered providing covert support for the illegal refiners.

8.4.4 Public enlightenment

The study recommends that the National Orientation Agency (NOA) should carry out continuous public enlightenment in the NDR to inform residents of the dangers of buying and storing the NRD fuel oil in their homes. This is as a result of the physiochemical property analysis, see (Chapter 5) which revealed a low flash point for the 9 NRD fuel oil samples compared to the control sample, and the GC-MS analysis which revealed the presence of high levels of volatile organic compounds (Benzene, toluene, and xylenes). With the variety of health effects associated with VOCs, education of the people regarding the inherent dangers associated with the refining, usage and emissions from the refined products should be undertaken.

As a signatory to the Kyoto protocol and the Paris agreement on climate change, the Nigerian government owes a duty to the citizens to continuously enlighten the nation and the Niger Delta people in particular through the print, electronic and social media platforms, on the inherent dangers of using the non-standard refined diesel fuel in their engines. This is as some of the respondents in the questionnaire survey said they do not mind the damage to their engines arising from the usage of the non-standard refined diesel fuel oil and the cost of maintenance, see (subsection 4.3.3). Due to the high level of unregulated emissions like, NOx, CO, and CO2 (as reported in Subsections 7.3.5, 7.3.6 and 7.3.7) observed from the emission analysis and the high level of VOCs, the continuous usage of the NRD fuel oil will cause tremendous damage to the environment. The more the fuel is burnt the more it damages the environment, contributing to poor air quality and leading to respiratory sicknesses in humans. The population should be encouraged to buy refined diesel fuel oil from government accredited fuel retail outlets.

8.4.5 Establishment of mini refineries

The study recommends the establishment of mini refineries. The establishment of mini refineries will provide employment for the present operators of the non-standard refineries. This will reduce unemployment amongst the youths of the NDR. It will also reduce environmental pollution, boost the nation's economy and the economy of the host communities. Youth restiveness in the NDR could also be reduced. Modalities need to be put in place to ensure crude is supplied (sold) to the mini refineries. This would put a stop to the sabotage of crude oil pipelines in the search for the basic raw material needed for the non-standard refining. Such modalities should include granting of soft loans to potential mini refinery operators as a start-up. Another aspect should be training. Although the refiners use basic distilling techniques to refine the diesel fuel oil, training on how to operate the mini refineries and waste management techniques will help to protect the environment. The inconsistences in the refined products from the three different camps would also be addressed with the mini-refineries and training on how to operate the facility.

8.4.6 Legal Framework

This study recommends that the Federal Government of Nigeria through the Ministry of Justice and the National Assembly enact a law to bring the non-standard refineries into a legal framework. This will not only provide a legal backing for the activities of the refiners, it would also attract prospective investors. With a law legalising the activities of the non-standard crude oil refiners, crude oil will be purchased legally from the Pipelines and Products Marketing Company, a subsidiary of the NNPC.

8.4.7 Revamping and construction of more floating fuel stations

This study recommends that the government revamps the abandoned fuel Mega stations. The revamping of these stations will make for their use. Also, the provision of petroleum products to the floating Mega station will ensure that there is availability of products for boat operators and travellers. In addition, the government should construct more floating Mega stations to add to the 12 presently in the Niger Delta Region. Adding to the 12 floating Mega stations will make more quality petroleum products like diesel, gasoline, and kerosene available to riverine (offshore) communities.

8.4.8 Maintenance of existing refineries

This study recommends that the government as a matter of urgency initiates the process of turn around maintenance for the existing four moribund refineries (see section 1.1). The successful maintenance of the existing refineries will make refined products more available to the general public and the people of the Niger Delta. Also, the government should support the existing private refinery owners to see that the projects are completed timely. Import duty exemptions for parts and heavy machinery for the construction of the private refineries will help to speed up the projects. The completion of the private refinery projects will ensure that their availability of refined petroleum products and create employment for Nigerians.

8.4.9 Infrastructural development of the Niger Delta

This study recommends the construction of roads to link communities in the NDR to their state capitals. The construction of roads will serve as a fast transportation link between the communities and their various capitals. It will also enable speedy and sustainable development within the region.

8.5 Further research

This study suggests the need for more empirical research into some key areas.

8.5.1 What is the level of VOCs in the exhaust emission from engines?

The thesis produced a detailed experimental analysis to determine the compositional variations of the non-standard refined diesel fuel oil. With the result revealing a high level of VOCs (benzene, toluene, and xylenes), in the non-standard diesel fuel oils, there is a need, therefore, for further research to determine the VOCs in the exhaust emissions from engines.

8.5.2 What is the ambient level of VOCs around the host communities?

With the high level of VOC in the non-standard refined diesel fuel oil compared to the control sample coupled with the method of refining where the cooking pots are stoked with crude oil to increase the intensity of the heat, there is a need for further research to determine the ambient level of VOCs around the refining sites and host communities.

References

Abosede, E. E. (2013). Effect of crude oil pollution on some soil physical properties. *Journal of Agriculture and Veterinary Science*, *6*(3), 14-17

Abrar, I., Bhaskarwar, A.N., 2021. Performance and emission characteristics of constant speed diesel engine fueled by surfactant-free microemulsions. Sustainable Energy Technologies and Assessments 47, 101414. https://doi.org/10.1016/j.seta.2021.101414

Abu-Zaid, M., (2004). Performance of single cylinder, direct injection Diesel engine using water fuel emulsions. Energy Conversion and Management 45, 697–705. https://doi.org/10.1016/S0196-8904(03)00179-1

Achudume, A.C., (2009). The Effect of Petrochemical Effluent on the Water Quality of Ubeji Creek in Niger Delta of Nigeria. Bull Environ Contam Toxicol 83, 410–415. https://doi.org/10.1007/s00128-009-9736-2

Acock, A. C., & Stavig, G. R. (1979). A measure of association for nonparametric statistics. *Social Forces*, *57*(4), 1381-1386.

Adaramola, M.S., Oyewola, O.M., Ohunakin, O.S., Akinnawonu, O.O., 2014. Performance evaluation of wind turbines for energy generation in Niger Delta, Nigeria. Sustainable Energy Technologies and Assessments 6, 75–85. https://doi.org/10.1016/j.seta.2014.01.001

Adegbite, I. (2013) Climate Change, Perennial Crude Oil Theft and the Quest for Sustainable Development in Nigeria, OIDA International Journal of Sustainable Development 06: 12

Adeloye O. M., Ekade P. J., 2021. Modeling of pollutants from artisanal refining of crude oil in Port Harcourt: A case study of Eagle Island. World J. Adv. Eng. Tech. Sci. 2, 034–044. https://doi.org/10.30574/wjaets.2021.2.1.0013

Adeola, A.O., Akingboye, A.S., Ore, O.T., Oluwajana, O.A., Adewole, A.H., Olawade, D.B., Ogunyele, A.C., 2022. Crude oil exploration in Africa: socio-economic implications, environmental impacts, and mitigation strategies. Environ Syst Decis 42, 26–50. https://doi.org/10.1007/s10669-021-09827-x

Adesipo, A.A., Freese, D., Nwadinigwe, A.O., 2020. Prospects of in-situ remediation of crude oil contaminated lands in Nigeria. Scientific African 8, e00403. https://doi.org/10.1016/j.sciaf.2020.e00403

Adewuyi, A., 2020. Challenges and prospects of renewable energy in Nigeria: A case of bioethanol and biodiesel production. Energy Reports 6, 77–88. https://doi.org/10.1016/j.egyr.2019.12.002

Adewuyi, A.O., 2016. Determinants of import demand for non-renewable energy (petroleum) products: Empirical evidence from Nigeria. Energy Policy 95, 73–93. https://doi.org/10.1016/j.enpol.2016.04.035

Adeyemo, O.K., (2003). Consequences of Pollution and Degradation of Nigerian Aquatic Environment on Fisheries Resources. The Environmentalist 23, 297–306. https://doi.org/10.1023/B:ENVR.0000031357.89548.fb

Adow M., (2012) The looting and 'cooking' of Nigeria's crude [Online] Available from < https://www.aljazeera.com/features/2012/8/3/the-looting-and-cooking-of-nigerias-crude > 16/03/2022

Adunbi, O., 2020. Crafting Spaces of Value. The Cambridge Journal of Anthropology 38, 38–52. https://doi.org/10.3167/cja.2020.380204

Afshar-Mohajer, N., Lam, A., Dora, L., Katz, J., Rule, A.M., Koehler, K., (2020). Impact of dispersant on crude oil content of airborne fine particulate matter emitted from seawater after an oil spill. Chemosphere 256, 127063. https://doi.org/10.1016/j.chemosphere.2020.127063

Agarwal, A. K. (2007). Biofuels (alcohols and biodiesel) applications as fuels for internal combustion engines. *Progress in energy and combustion science*, *33*(3), 23

Agarwal, A.K., and Das, L.M., (2001). Biodiesel Development and Characterization for Use as a Fuel in Compression Ignition Engines. Journal of Engineering for Gas Turbines and Power 123, 440. http://doi.org/10.1115/1.1364522

Agarwal, S., Kumari, S., Mudgal, A., Khan, S., (2020). Green synthesized nano-additives in jojoba biodiesel-diesel blends: An improvement of engine performance and emission. Renewable Energy 147, 1836–1844. https://doi.org/10.1016/j.renene.2019.09.139

Agbonifo, P.E., 2016. Risk Management and Regulatory Failure in the Oil and Gas Industry in Nigeria: Reflections on the Impact of Environmental Degradation in the Niger Delta Region. JSD 9, 1. https://doi.org/10.5539/jsd.v9n4p1

Agbonifo, P.E., 2022. Socio-economic implications of poor environmental management: a framework on the Niger Delta questions. Environ Dev Sustain 24, 2453–2470. https://doi.org/10.1007/s10668-021-01541-7

Ahmed, U., 2020. Techno-economic feasibility of methanol synthesis using dual fuel system in a parallel process design configuration with control on green house gas emissions. International Journal of Hydrogen Energy 45, 6278–6290. https://doi.org/10.1016/j.ijhydene.2019.12.169

Ajuonuma, L., (2011) NNPC Alerts on Adulterated Kerosene in Delta, Edo States, [Online] Available from http://www.nnpcgroup.com/PublicRelations/NNPCinthenews/tabid/92/articleType/ArticleView/articleId/275/NNPC-Alerts-on-Adulterated-Kerosene-in-Delta-Edo-States.aspx [29/10/2016]

Akinleye A., (2013) Update 1- Nigeria's oil thieves say government leaves them no choice [Online] Available from https://www.reuters.com/article/nigeria-oil-theft-idUSL6N0AK68Q20130115 16/03/2022

Ako, R.T., 2009. Nigeria's Land Use Act: An Anti-Thesis to Environmental Justice. J. Afr. law 53, 289–304. https://doi.org/10.1017/S0021855309990076

Akpan-Idio, A.U., Ibrahim, A., Udo, I.A., (2012). Water Quality Assessment of Okpauku River for Drinking and Irrigation Uses in Yala, Cross River State, Nigeria. Research J. of Environmental Sciences 6, 210–221. https://doi.org/10.3923/rjes.2012.210.221

Akpoghomeh, O.S., Badejo, D., 2006. Petroleum product scarcity: a review of the supply and distribution of petroleum products in Nigeria. OPEC Review 30, 27–40. https://doi.org/10.1111/j.1468-0076.2006.00159.x

Akpomera, E., (2015). International crude oil theft: elite predatory tendencies in Nigeria. Review of African Political Economy 42, 156–165. doi:10.1080/03056244.2014.988696

Akpomrere, O.R., Uguru, H., 2020. Potential Ecological Risk of Swamps Sediments in Illegal Refineries Sites: A Case Study of Isoko South, Delta State, Nigeria. JERR 1–9. https://doi.org/10.9734/jerr/2020/v16i217160

Alaba, O. C., and Agbalajobi, S. A. (2014). Evaluation of private refineries and depots in distribution of petroleum products in Nigeria. *International Journal of Engineering and Technology*, *4*(2), 118-126.

Ale, B. B. (2003). Fuel adulteration and tailpipe emissions. *Journal of the Institute of Engineering*, *3*(1), 12-16.

Aleme, H.G., and Barbeira, P.J.S., (2012). Determination of flash point and cetane index in diesel using distillation curves and multivariate calibration. Fuel 102, 129–134. https://doi.org/10.1016/j.fuel.2012.06.015

Aleme, H.G., Corgozinho, C.N.C., Barbeira, P.J.S., 2010. Diesel oil discrimination by origin and type using physicochemical properties and multivariate analysis. Fuel 89, 3151–3156. https://doi.org/10.1016/j.fuel.2010.05.010

Aleme, H.G., Assunção, R.A., Carvalho, M.M.O., Barbeira, P.J.S., 2012. Determination of specific gravity and kinematic viscosity of diesel using distillation curves and multivariate calibration. Fuel Processing Technology 102, 90–95. https://doi.org/10.1016/j.fuproc.2012.04.016

Ali, B., Kumar, A., (2017). Life cycle water demand coefficients for crude oil production from five North American locations. Water Research 123, 290–300. https://doi.org/10.1016/j.watres.2017.06.076

Ali, Y., Hanna, M. A., & Cuppett, S. L. (1995). Fuel properties of tallow and soybean oil esters. *Journal of the American Oil Chemists' Society*, *72*(12), 1557-1564.

Allen, F. (2012). The enemy within: Oil in the Niger Delta. *World Policy Journal*, *29*(4), 46-53.

Alptekin, E., Canakci, M., (2009). Characterization of the key fuel properties of methyl ester–diesel fuel blends. Fuel 88, 75–80. https://doi.org/10.1016/j.fuel.2008.05.023

Amaeze, N., Adetoro, F., Adegboro, O., (2015). Toxicity evaluation of effluent from the de-oiling works of a decommissioned Nigerian crude oil pipeline using *Palaemonetes africanus*. African Journal of Aquatic Science 40, 57–61. https://doi.org/10.2989/16085914.2015.1019827

Amangabara, G. T., and Njoku, J. D. (2012). Assessing groundwater vulnerability to the activities of artisanal refining in Bolo and environs, Ogu/Bolo Local Government Area of Rivers State; Nigeria. *British Journal of environment and climate change*, *2*(1), 28.

Ana, G.R., Sridhar, M.K., Bamgboye, E.A., 2009. Environmental risk factors and health outcomes in selected communities of the Niger delta area, Nigeria. Perspectives in Public Health 129, 183–191. https://doi.org/10.1177/1466424008094803

Anejionu, O. C., Ahiarammunnah, P. A. N., & Nri-ezedi, C. J. (2015). Hydrocarbon pollution in the Niger Delta: Geographies of impacts and appraisal of lapses in extant legal framework. *Resources Policy*, *45*, 65-77.

Aniefiok E. Ite, Usenobong F. Ufot, Margaret U. Ite, Idongesit O. Isaac, and Udo J. Ibok,(2016) "Petroleum Industry in Nigeria: Environmental Issues, National Environmental Legislation and Implementation of International Environmental Law." American Journal of Environmental Protection, vol. 4, no. 1 : 21-37. doi: 10.12691/env-4-1-3

Anifowose, B., Lawler, D.M., van der Horst, D., and Chapman, L., (2012). Attacks on oil transport pipelines in Nigeria: A quantitative exploration and possible explanation of observed patterns. Applied Geography 32, 636–651. https://doi.org/10.1016/j.apgeog.2011.07.012

Anifowose, B., Lawler, D., van der Horst, D., Chapman, L., 2014. Evaluating interdiction of oil pipelines at river crossings using Environmental Impact Assessments: Evaluating interdiction of oil pipelines at river crossings. Area 46, 4–17. https://doi.org/10.1111/area.12065

Antonopoulos, A.K., Hountalas, D.T., 2012. Effect of instantaneous rotational speed on the analysis of measured diesel engine cylinder pressure data. Energy Conversion and Management 60, 87–95. https://doi.org/10.1016/j.enconman.2012.01.020

Armbruster, D. A., & Pry, T. (2008). Limit of blank, limit of detection and limit of quantitation. *The Clinical biochemist. Reviews*, *29 Suppl 1*(Suppl 1), S49–S52

Aroh, K.N., Ubong, I.U., Eze, C.L., Harry, I.M., Umo-Otong, J.C., Gobo, A.E., (2010). Oil spill incidents and pipeline vandalization in Nigeria: Impact on public health and negation to attainment of Millennium development goal: the Ishiagu example. Disaster Prevention and Management: An International Journal 19, 70–87. Doi: 10.1108/09653561011022153

Arouni, H., Farooq, U., Goswami, P., Kapur, N., Russell, S.J., (2019). Coalescence efficiency of surface modified PBT meltblown nonwovens in the separation of water from diesel fuel containing surfactants. Results in Engineering 4, 100048. https://doi.org/10.1016/j.rineng.2019.100048

Arouni, H., Farooq, U., Goswami, P., Kapur, N., Russell, S.J., (2018). Limitations of Monoolein in Simulating Water-in-Fuel Characteristics of EN590 Diesel Containing Biodiesel in Water Separation Testing. SAE Int. J. Fuels Lubr. 11, 229–238. https://doi.org/10.4271/04-11-03-0012

Asimiea, A., and Omokhua, G. (2013). Environmental impact of illegal refineries on the vegetation of the Niger delta, Nigeria. *Journal of Agriculture and Social Research (JASR)*, *13*(2), 121-126.

ASTM D613-17ce1 Standard Test Method for Cetane Number of Diesel Fuel Oils, ASTM International, West Conshohocken, PA, 2017, http://doi.org/10.1520/D0613-17CE01

ASTM D4057-19, Standard Practice for Manual Sampling of Petroleum and Petroleum Products, ASTM International, West Conshohocken, PA, 2019, www.astm.org

ASTM D3828-16a, Standard Test Methods for Flash Point by Small Scale Closed Cup Tester, ASTM International, West Conshohocken, PA, 2016, www.astm.org

ASTM D86-20b, Standard Test Method for Distillation of Petroleum Products and Liquid Fuels at Atmospheric Pressure, ASTM International, West Conshohocken, PA, 2020, www.astm.org

ASTM D4052-18a, Standard Test Method for Density, Relative Density, and API Gravity of Liquids by Digital Density Meter, ASTM International, West Conshohocken, PA, 2018, www.astm.org

ASTM D4737-10(2016), Standard Test Method for Calculated Cetane Index by Four Variable Equation, ASTM International, West Conshohocken, PA, 2016, www.astm.org

ASTM D975-20c, Standard Specification for Diesel Fuel, ASTM International, West Conshohocken, PA, 2020, www.astm.org

ASTM D975-21, Standard Specification for Diesel Fuel, ASTM International, West Conshohocken, PA, 2020, www.astm.org. DOI: 10.1520/D0975-21

ASTM D4809-18, Standard Test Method for Heat of Combustion of Liquid Hydrocarbon Fuels by Bomb Calorimeter (Precision Method), ASTM International, West Conshohocken, PA, 2018, www.astm.org

ASTM E1252-98(2013)e1, Standard Practice for General Techniques for Obtaining Infrared Spectra for Qualitative Analysis, ASTM International, West Conshohocken, PA, 2013, www.astm.org

ASTM D5950-14(2020), Standard Test Method for Pour Point of Petroleum Products (Automatic Tilt Method), ASTM International, West Conshohocken, PA, 2020, www.astm.org

ASTM D6304-20, Standard Test Method for Determination of Water in Petroleum Products, Lubricating Oils, and Additives by Coulometric Karl Fischer Titration, ASTM International, West Conshohocken, PA, 2020, www.astm.org

ASTM D445-19a, Standard Test Method for Kinematic Viscosity of Transparent and Opaque Liquids (and Calculation of Dynamic Viscosity), ASTM International, West Conshohocken, PA, 2019, www.astm.org

Atabani, A.E., Silitonga, A.S., Ong, H.C., Mahlia, T.M.I., Masjuki, H.H., Badruddin, I.A., Fayaz, H., (2013). Non-edible vegetable oils: A critical evaluation of oil extraction, fatty acid compositions, biodiesel production, characteristics, engine performance and emissions production. Renewable and Sustainable Energy Reviews 18, 211–245. https://doi.org/10.1016/j.rser.2012.10.013

Audu, A., Jimoh, A., Abdulkareem, S. A., & Lawrence, O. (2016). Economics and environmental impacts of oil exploration and exploitation in Nigeria. *Energy Sources, Part B: Economics, Planning, and Policy*, *11*(3), 251-257.

Ayeni, A. O. (2019). Environmental Policies for Emergency Management and Public Safety: Implementing Green Policy and Community Participation. In *Emergency and Disaster Management: Concepts, Methodologies, Tools, and Applications* (pp. 903-922). IGI Global.

Babatunde, A.O., 2020. Oil pollution and water conflicts in the riverine communities in Nigeria's Niger Delta region: challenges for and elements of problem-solving strategies. Journal of Contemporary African Studies 38, 274–293. https://doi.org/10.1080/02589001.2020.1730310

Babatunde, B.B., Sikoki, F.D., Avwiri, G.O., Chad-Umoreh, Y.E., 2019. Review of the status of radioactivity profile in the oil and gas producing areas of the Niger delta region of Nigeria. Journal of Environmental Radioactivity 202, 66–73. https://doi.org/10.1016/j.jenvrad.2019.01.015

Babatunde, A.O., 2020. Local perspectives on food security in Nigeria's Niger delta. The Extractive Industries and Society 7, 931–939. https://doi.org/10.1016/j.exis.2020.07.011

Babatunde, A.O., 2012. An Analytical Evaluation of the Cost of the Conflict in Nigeria's Niger Delta. Journ. of Confl. 3. https://doi.org/10.7238/joc.v3i1.1327

Babu, V., Krishna, R., and Mani, N., (2017). Review on the Detection of Adulteration in Fuels through Computational Techniques. Materials Today: Proceedings 4, 1723–1729. https://doi.org/10.1016/j.matpr.2017.02.013

Badmus, I., Oyewola, M.O., Fagbenle, R.O., (2012). A Review of Performance Appraisals of Nigerian Federal Government-Owned Refineries. Energy and Power Engineering 04, 47–52. https://doi.org/10.4236/epe.2012.41007

Balogun, T.F., (2015). Mapping Impacts of Crude Oil theft and Illegal Refineries on Mangrove of the Niger Delta of Nigeria with Remote Sensing Technology. Mediterranean Journal of Social Sciences. doi:10.5901/mjss. 2015.v6n3p150

Barra, I., Mansouri, M.A., Cherrah, Y., Kharbach, M., Bouklouze, A., (2019). FTIR fingerprints associated to a PLS-DA model for rapid detection of smuggled non-compliant diesel marketed in Morocco. Vibrational Spectroscopy 101, 40–45. https://doi.org/10.1016/j.vibspec.2019.02.001

Barra, I., Kharbach, M., Qannari, E.M., Hanafi, M., Cherrah, Y., Bouklouze, A., 2020. Predicting cetane number in diesel fuels using FTIR spectroscopy and PLS regression. Vibrational Spectroscopy 111, 103157. https://doi.org/10.1016/j.vibspec.2020.103157

Bartholomew, D.J., 1980. Factor Analysis for Categorical Data. Journal of the Royal Statistical Society: Series B (Methodological) 42, 293–312. https://doi.org/10.1111/j.2517-6161.1980.tb01128.x

BBC News Pidgin, (2021). Fuel Scarcity Abuja: NNPC dismiss long queues for petrol stations inside Nigeria capital- Fotos [Online] Available from < https://www.bbc.com/pidgin/tori-56827247> [15/06/2021].

Bebeteidoh, O.L., Kometa, S., Pazouki, K., Norman, R., 2020a. Sustained impact of the activities of local crude oil refiners on their host communities in Nigeria. Heliyon 6, e04000. https://doi.org/10.1016/j.heliyon.2020.e04000

Bebeteidoh, O.L., Pazouki, K., Norman, R., 2020b. An experimental investigation of the physio-chemical properties of locally refined diesel oil. Sustainable Chemistry and Pharmacy 15, 100200. https://doi.org/10.1016/j.scp.2019.100200

Beg, R. A., Sarker, M. R. I., & Pervez, M. R. (2010). Production of diesel fuel from used engine oil. *International Journal of Mechanical & Mechatronics Engineering IJMME-IJENS*, *10*(02), 103602-1717.

Belkhode, P.N., Ganvir, V.N., Shende, A.C., Shelare, S.D., 2021. Utilization of waste transformer oil as a fuel in diesel engine. Materials Today: Proceedings S2214785321010610. https://doi.org/10.1016/j.matpr.2021.02.008

Bell, J., Gotor, R., Rurack, K., 2018. Fluorescent Paper Strips for the Detection of Diesel Adulteration with Smartphone Read-out. JoVE 58019. https://doi.org/10.3791/58019

Blessing I., (2022) Wike Demands Redeployment of DPO, NSCDC Officer Fingered in Illegal Refinery Activities [Online] Available from < https://www.thisdaylive.com/index.php/2022/01/15/wike-demands-redeployment-of-dpo-nscdc-officer-fingered-in-illegal-refinery-activities/ > [16/03/2022]

Bodo, T., Gimah, B.G., 2020. The Pollution and Destruction of the Niger Delta Ecosystem in Nigeria: Who is to be blamed? ESJ 16. https://doi.org/10.19044/esj.2020.v16n5p161

Boone, H. N., & Boone, D. A. (2012). Analyzing likert data. *Journal of extension*, *50*(2), 1-5.

Boris, O.H., (2015). The Upsurge of Oil Theft and Illegal Bunkering in the Niger Delta Region of Nigeria: Is There a Way Out? Mediterranean Journal of Social Sciences. https://doi.org/10.5901/mjss.2015.v6n3s2p563

Brelsford R., (2021). Azikel selects EPC contractor for Nigerian modular refinery [Online] Available from < https://www.ogj.com/refining-processing/refining/construction/article/14199510/azikel-selects-epc-contractor-for-nigerian-modular-refinery > [28/07/2021].

Briggs, I.L., Briggs, B.C., (2018). Petroleum Industry Activities and Human Health, in: The Political Ecology of Oil and Gas Activities in the Nigerian Aquatic Ecosystem. Elsevier, pp. 143–147. https://doi.org/10.1016/B978-0-12-809399-3.00010-0

Business Day 2016. Motorist in Lagos decry lack of petrol in most filling stations [Online] Available from < https://businessday.ng/uncategorized/article/motorists-in-lagos-decry-lack-of-petrol-in-most-filling-stations/ > [29/06/2021]

Câmara, A.B.F., de Carvalho, L.S., de Morais, C.L.M., de Lima, L.A.S., de Araújo, H.O.M., de Oliveira, F.M., de Lima, K.M.G., (2017). MCR-ALS and PLS coupled to NIR/MIR spectroscopies for quantification and identification of adulterant in biodiesel-diesel blends. Fuel 210, 497–506. https://doi.org/10.1016/j.fuel.2017.08.072

Campese, J., Sunderland, T., Greiber, T., and Oviedo, G., (2009). *Rights-based approaches: Exploring issues and opportunities for conservation*. CIFOR.

Channels TV (2015) Navy's Air Patrol Uncovers Illegal Refineries in Niger Delta [Online] Available from https://www.youtube.com/watch?v=u5ffBEQzVD8 [10/01/2018]

Chen, F., Liu, J., Yang, T., Yin, S., Su, B., Xie, M., Dai, B., Han, S., Xue, Y., 2020. Influence of maleic anhydride-co-methyl benzyl acrylate copolymers modified with long-chain fatty amine and long-chain fatty alcohol on the cold flow properties of diesel fuel. Fuel 268, 117392. https://doi.org/10.1016/j.fuel.2020.117392

Chen, H., Cheng, Y., He, Q., Wang, X., 2022. Experimental study on combustion and unregulated emission characteristics of a diesel engine fueled with light hydrocarbon/diesel blends. Fuel 315, 123075. https://doi.org/10.1016/j.fuel.2021.123075

Cheung, C.S., Di, Y., Huang, Z., 2008. Experimental investigation of regulated and unregulated emissions from a diesel engine fueled with ultralow-sulfur diesel fuel blended with ethanol and dodecanol. Atmospheric Environment 42, 8843–8851. https://doi.org/10.1016/j.atmosenv.2008.09.009

Chikere, C. B., Okpokwasili, G. C., & Chikere, B. O. (2009). Bacterial diversity in a tropical crude oil-polluted soil undergoing bioremediation. *African Journal of Biotechnology*, *8*(11).

Chikere, C.B., Obieze, C.C., Chikere, B.O., 2020. Biodegradation of artisanally refined diesel and the influence of organic wastes on oil-polluted soil remediation. Scientific African 8, e00385. https://doi.org/10.1016/j.sciaf.2020.e00385

Chinenyeze, M. A. J., and Ekene, U. R. (2017) Physical and Chemical Properties of Crude Oils and Their Geologic Significances. *International Journal of Science and Research,* Vol. 6, Issue 6

Chowdhury, M., Gholizadeh, A., Agah, M., 2021. Rapid detection of fuel adulteration using microfabricated gas chromatography. Fuel 286, 119387. https://doi.org/10.1016/j.fuel.2020.119387

Chu Van, T., Ramirez, J., Rainey, T., Ristovski, Z., Brown, R.J., 2019. Global impacts of recent IMO regulations on marine fuel oil refining processes and ship emissions. Transportation Research Part D: Transport and Environment 70, 123–134. https://doi.org/10.1016/j.trd.2019.04.001

Clothier, P.Q.E., Aguda, B.D., Moise, A., Pritchard, H.O., (1993). How do diesel-fuel ignition improvers work? Chem. Soc. Rev. 22, 101. https://doi.org/10.1039/cs9932200101

Corgozinho, C., Pasa, V., Barbeira, P., (2008). Determination of residual oil in diesel oil by spectrofluorimetric and chemometric analysis. Talanta 76, 479–484. https://doi.org/10.1016/j.talanta.2008.03.003

Cronbach, L.J., 1951. Coefficient alpha and the internal structure of tests. Psychometrika 16, 297–334. https://doi.org/10.1007/BF02310555

Cunha, D.A., Montes, L.F., Castro, E.V.R., Barbosa, L.L., (2016). NMR in the time domain: A new methodology to detect adulteration of diesel oil with kerosene. Fuel 166, 79–85. https://doi.org/10.1016/j.fuel.2015.10.078

Cunha, D.A., Neto, Á.C., Colnago, L.A., Castro, E.V.R., Barbosa, L.L., (2019). Application of time-domain NMR as a methodology to quantify adulteration of diesel fuel with soybean oil and frying oil. Fuel 252, 567–573. https://doi.org/10.1016/j.fuel.2019.04.149

Curl, H. C., & O'Donnell, K. (1977). *Chemical and physical properties of refined petroleum products* (No. ERL MESA-17). US Department of Commerce, National Oceanic and Atmospheric Administration, Environmental Research Laboratories.

Datta, A., Saha, A., 2021. Investigation of an ultra-sensitive fiber-optic fuel adulteration sensor by propagating a higher-order Bessel-Gauss beam. Optik 243, 167408. https://doi.org/10.1016/j.ijleo.2021.167408

de Aguiar, L.M., Galvan, D., Bona, E., Colnago, L.A., Killner, M.H.M., 2022. Data fusion of middle-resolution NMR spectroscopy and low-field relaxometry using the Common Dimensions Analysis (ComDim) to monitor diesel fuel adulteration. Talanta 236, 122838. https://doi.org/10.1016/j.talanta.2021.122838

de Oliveira, E.C., Lourenço, F.R., 2021. Risk of false conformity assessment applied to automotive fuel analysis: A multiparameter approach. Chemosphere 263, 128265. https://doi.org/10.1016/j.chemosphere.2020.128265

DeCoster, J. (1998). *Overview of Factor Analysis*. Retrieved May 27, 2021 from http://www.stat-help.com/notes.html

Denzin, N.K., 2007. Triangulation, in: Ritzer, G. (Ed.), The Blackwell Encyclopedia of Sociology. John Wiley & Sons, Ltd, Oxford, UK, p. wbeost050. https://doi.org/10.1002/9781405165518.wbeost050

Devarajan, Y., Beemkumar, N., Ganesan, S., Arunkumar, T., (2020). An experimental study on the influence of an oxygenated additive in diesel engine fuelled with neat papaya seed biodiesel/diesel blends. Fuel 268, 117254. https://doi.org/10.1016/j.fuel.2020.117254

DeVellis, R. F. (2016). *Scale development: Theory and applications* (Vol. 26). Sage publications.

Dilip kumar, S., Sivasubramonia Pillai, T.V., 2020. Estimating fuel adulteration in automobiles using robust optical fiber sensors. Microprocessors and Microsystems 79, 103289. https://doi.org/10.1016/j.micpro.2020.103289

Dobrzyńska, E., Szewczyńska, M., Puchałka, B., Szczotka, A., Woodburn, J., 2021. The Effect of Nano-Additives on Diesel EngineExhaust Emissions. Pol. J. Environ. Stud. 31, 25–33. https://doi.org/10.15244/pjoes/138209

Dominic, A. A. (2016). Impact of illegal oil business and Nigeria economy: the experience of crude oil theft, bunkering and pipeline vandalism in the 21st century. *International Journal of Advanced Academic Research, Arts, Humanities & Education*, *2*(8).

DPR, 2021. Reuters: Petroleum Refineries and Petrochemicals. [Online] Available from < https://www.dpr.gov.ng/downstream/refinery/> [15/06/2021].

Dunmade, I., 2019. Social Lifecycle Impact Assessment of Informal Petroleum Products Retailing in Nigeria. Procedia Manufacturing 35, 459–464. https://doi.org/10.1016/j.promfg.2019.05.067

Ebeku, Kaniye S.A. "Oil and the Niger Delta People: The Injustice of the Land Use Act." *Verfassung Und Recht in Übersee / Law and Politics in Africa, Asia and Latin America* 35, no. 2 (2002): 201–31. http://www.jstor.org/stable/43239024.

Edino, M. O., Nsofor, G. N., & Bombom, L. S. (2010). Perceptions and attitudes towards gas flaring in the Niger Delta, Nigeria. *The Environmentalist*, *30*(1), 67-75.

Ehsan, M., Rahman, M. M., & Saadi, H. (2010). Effect of fuel adulteration on engine crankcase dilution. *Journal of Mechanical Engineering*, *41*(2), 114-120.

EIA (2016) Country Analysis Brief: Nigeria, U.S. Energy Information Administration [Online] Available from< https://www.eia.gov/beta/international/analysis_includes/countries_long/Nigeria/nigeria.pdf > 03/02/2018

E. Ite, A., A. Harry, T., O. Obadimu, C., R. Asuaiko, E., J. Inim, I., 2018. Petroleum Hydrocarbons Contamination of Surface Water and Groundwater in the Niger Delta Region of Nigeria. JEPHH 6, 51–61. https://doi.org/10.12691/jephh-6-2-2

Ejiba, I., Onya, S., Adams, O., (2016). Impact of Oil Pollution on Livelihood: Evidence from the Niger Delta Region of Nigeria. JSRR 12, 1–12. https://doi.org/10.9734/JSRR/2016/26633

Ejofodomi, O., Ofualagba, G., Onyishi, D.U., 2021. Adulteration Detection of Petroleum Products at Point of Sale POS Terminals, in: Day 2 Tue, August 03, 2021. Presented at the SPE Nigeria Annual International Conference and Exhibition, SPE, Lagos, Nigeria, p. D021S010R006. https://doi.org/10.2118/207101-MS

Elendu Reporters 2017. NSCDC arrest 26 marketers for selling fuel above N145 [Online] Available from < https://www.elendureportsonline.com/nscdc-arrests-26-marketers-selling-fuel-n145/ > [29/06/2021]

Elenwo, E., and Urho, C., (2017). Challenges and Prospects of Enforcement of Environmental Laws in Port Harcourt Metropolis Rivers State, Nigeria. British Journal of Applied Science & Technology 19, 1–29. https://doi.org/10.9734/BJAST/2017/31447

Elkelawy, M., Alm-Eldin Bastawissi, H., Esmaeil, K.K., Radwan, A.M., Panchal, H., Sadasivuni, K.K., Ponnamma, D., Walvekar, R., 2019. Experimental studies on the biodiesel production parameters optimization of sunflower and soybean oil mixture and DI engine combustion, performance, and emission analysis fueled with diesel/biodiesel blends. Fuel 255, 115791. https://doi.org/10.1016/j.fuel.2019.115791

Emiroğlu, A.O., Şen, M., (2018). Combustion, performance and emission characteristics of various alcohol blends in a single cylinder diesel engine. Fuel 212, 34–40. https://doi.org/10.1016/j.fuel.2017.10.016

Emmanuel O., (2013) How crude oil is stolen, refined, sold in Niger Delta [Online] Available from < https://www.premiumtimesng.com/news/150075-crude-oil-stolen-refined-sold-niger-delta.html > 15/03/2022

Eneh, O.C., (2011). A Review on Petroleum: Source, Uses, Processing, Products, and the Environment. Journal of Applied Sciences 11, 2084–2091. https://doi.org/10.3923/jas.2011.2084.2091

Energy.Gov (2011) The How's and Why's of Replacing the Whole Barrel [Online] Available from < https://energy.gov/articles/hows-and-whys-replacing-whole-barrel> [13/02/2018]

Evbuomwan and Alete (2020) Comparative Analysis of Locally Refined Petroleum Products (Diesel) in Niger Delta Region, Nigeria. *American Journal of Engineering Research (AJER)*, Vol. 9, Issue 2, pp- 25-32

Ferreira, V.H.C., Hantao, L.W., Poppi, R.J., 2021. Use of color based chromatographic images obtained from comprehensive two-dimensional gas chromatography in authentication analyses. Talanta 234, 122616. https://doi.org/10.1016/j.talanta.2021.122616

Fetter, N., Blichert-Toft, J., Télouk, P., Albarède, F., (2019). Extraction of Pb and Zn from crude oil for high-precision isotopic analysis by MC-ICP-MS. Chemical Geology 511, 112–122. https://doi.org/10.1016/j.chemgeo.2019.02.021

Fingas, M., (2011). Introduction to Oil Chemistry and Properties, in: Oil Spill Science and Technology. Elsevier, pp. 51–59. https://doi.org/10.1016/B978-1-85617-943-0.10003-6

Frinjo Emma, A., Sathyabhama, A., Kumar Yadav, A., 2022. Extraction and characterization of coffee husk biodiesel and investigation of its effect on performance, combustion, and emission characteristics in a diesel engine. Energy Conversion and Management: X 100214. https://doi.org/10.1016/j.ecmx.2022.100214

Gao, Z., Lin, S., Ji, J., Li, M., 2019. An experimental study on combustion performance and flame spread characteristics over liquid diesel and ethanol-diesel blended fuel. Energy 170, 349–355. https://doi.org/10.1016/j.energy.2018.12.130

Garg, N., Mohan, S., Pal, A., & Mishra, R. S. (2015). Fuel Adulteration, problem, and mitigation strategies: A Review. *Methods*, *48*(48), 51.

Garzón, J.P., Huertas, J.I., Magaña, M., Huertas, M.E., Cárdenas, B., Watanabe, T., Maeda, T., Wakamatsu, S., Blanco, S., 2015. Volatile organic compounds in the atmosphere of Mexico City. Atmospheric Environment 119, 415–429. https://doi.org/10.1016/j.atmosenv.2015.08.014

Gaspar, D.J., Phillips, S.D., Polikarpov, E., Albrecht, K.O., Jones, S.B., George, A., Landera, A., Santosa, D.M., Howe, D.T., Baldwin, A.G., Bays, J.T., 2019. Measuring and predicting the vapor pressure of gasoline containing oxygenates. Fuel 243, 630–644. https://doi.org/10.1016/j.fuel.2019.01.137

Gaylarde, CC, Bento, FM, & Kelley, J. (1999). Microbial contamination of stored hydrocarbon fuels and its control. *Microbiology Journal* , *30* (1), 01-10.

Geng, P., Tan, Q., Zhang, C., Wei, L., He, X., Cao, E., Jiang, K., 2016. Experimental investigation on NOx and green house gas emissions from a marine auxiliary diesel engine using ultralow sulfur light fuel. Science of The Total Environment 572, 467–475. https://doi.org/10.1016/j.scitotenv.2016.08.047

Ghazvinian, J., 2007. The curse of oil. Virginia Quarterly Review, Winter, Charlottesville, VA: University of Virginia, 5 –27.

Gilbert, G.E., Prion, S., 2016. Making Sense of Methods and Measurement: The Chi-Square Test. Clinical Simulation in Nursing 12, 145–146. https://doi.org/10.1016/j.ecns.2015.12.013

Glory, B. (2016). Unethical marketing practices by petroleum marketers in Nigeria. *British Journal of Marketing Studies*, *4*(5), 37-50.

Gonca, G., (2014). Investigation of the effects of steam injection on performance and NO emissions of a diesel engine running with ethanol–diesel blend. Energy Conversion and Management 77, 450–457. https://doi.org/10.1016/j.enconman.2013.09.031

Google Map (2021) Ologbobiri Community [Online] Available from < https://www.google.co.uk/maps/place/560103,+Olugbobiri,+Nigeria/@4.6588759,5.973357,11.4z/data=!4m5!3m4!1s0x106a4162a7e7b871:0x18a34b893fb64b6e!8m2!3d4.6504034!4d5.9870705> [23/06/2021]

Google Map (2021) Akinima and Okarki Community [Online] Available from < https://www.google.co.uk/maps/place/Okarki+Engenni+Rivers+Nigeria/@4.982131,6.3599232,11.85z/data=!4m5!3m4!1s0x1069ff07651d53b3:0x4dc1beb113ac3681!8m2!3d4.9786827!4d6.4785326> [23/06/2021]

Górski, K., Przedlacki, M., 2014. Evaluation of the Influence of Diethyl Ether (DEE) Addition on Selected Physicochemical Properties of Diesel Oil and Ignition Delay Period. Energy Fuels 28, 2608–2616. https://doi.org/10.1021/ef4025036

Gouveia, L., Oliveira, A.C., Congestri, R., Bruno, L., Soares, A.T., Menezes, R.S., Filho, N.R.A., Tzovenis, I., 2017. Biodiesel from microalgae, in: Microalgae-Based Biofuels and Bioproducts. Elsevier, pp. 235–258. https://doi.org/10.1016/B978-0-08-101023-5.00010-8

Gowda, S.H., Avinash, A., Raju, K., 2021. Production optimization of Vateria Indica biodiesel and performance evaluation of its blends on compression ignition engine.

Sustainable Chemistry and Pharmacy 22, 100475.
https://doi.org/10.1016/j.scp.2021.100475

Groysman, A., 2017. Physicochemical Properties of Crude Oils, in: Corrosion Problems and Solutions in Oil Refining and Petrochemical Industry. Springer International Publishing, Cham, pp. 9–15. https://doi.org/10.1007/978-3-319-45256-2_2

Gundlach, E. R., & Hayes, M. O. (1978). Vulnerability of coastal environments to oil spill impacts. *Marine technology society Journal*, *12*(4), 18-27.

Gundlach, E.R., Giadom, F.D., Akpokodje, E.G., Bonte, M., Tse, A.C., Ekeocha, N.E., Story, K.T., Acra, E.J., 2021. Core sediments and oil chemistry from contaminated mangroves in eastern Niger Delta, Ogoniland, Nigeria. Marine Pollution Bulletin 171, 112714. https://doi.org/10.1016/j.marpolbul.2021.112714

Gungah, A., Emodi, N.V., Dioha, M.O., 2019. Improving Nigeria's renewable energy policy design: A case study approach. Energy Policy 130, 89–100. https://doi.org/10.1016/j.enpol.2019.03.059

Harbach, J.A., Agosta, V., 1991. Effects of Emulsified Fuel on Combustion in a Four-Stroke Diesel Engine. Journal of Ship Research 35, 356–363. https://doi.org/10.5957/jsr.1991.35.4.356

Harpe, S.E., 2015. How to analyze Likert and other rating scale data. Currents in Pharmacy Teaching and Learning 7, 836–850. https://doi.org/10.1016/j.cptl.2015.08.001

Harris, A., Soban, D., Smyth, B.M., Best, R., 2020. A probabilistic fleet analysis for energy consumption, life cycle cost and greenhouse gas emissions modelling of bus technologies. Applied Energy 261, 114422. https://doi.org/10.1016/j.apenergy.2019.114422

Hassan, Z. A., Schattner, P., & Mazza, D. (2006). Doing a pilot study: why is it essential? *Malaysian family physician: the official journal of the Academy of Family Physicians of Malaysia*, *1*(2-3), 70.

Hazrati, S., Rostami, R., Fazlzadeh, M., Pourfarzi, F., 2016. Benzene, toluene, ethylbenzene, and xylene concentrations in atmospheric ambient air of gasoline and CNG refueling stations. Air Qual Atmos Health 9, 403–409. https://doi.org/10.1007/s11869-015-0349-0

Hoang, A.T., 2019. Experimental study on spray and emission characteristics of a diesel engine fueled with preheated bio-oils and diesel fuel. Energy 171, 795–808. https://doi.org/10.1016/j.energy.2019.01.076

Hoang, A.T., 2018. Prediction of the density and viscosity of biodiesel and the influence of biodiesel properties on a diesel engine fuel supply system. Journal of Marine Engineering & Technology 1–13. https://doi.org/10.1080/20464177.2018.1532734

Howard, I., Okpara, K., Techato, K., 2021. Toxicity and Risks Assessment of Polycyclic Aromatic Hydrocarbons in Riverbed Sediments of an Artisanal Crude Oil Refining Area in the Niger Delta, Nigeria. Water 13, 3295. https://doi.org/10.3390/w13223295

Hua, R., Li, Y., Liu, W., Zheng, J., Wei, H., Wang, J., Lu, X., Kong, H., Xu, G., (2003). Determination of sulfur-containing compounds in diesel oils by comprehensive two-dimensional gas chromatography with a sulfur chemiluminescence detector. Journal of Chromatography A 1019, 101–109. https://doi.org/10.1016/j.chroma.2003.08.048

Human Rights Watch (2003) The Warri Crisis: Fuelling Violence [Online] Available from < https://www.hrw.org/reports/2003/nigeria1103/nigeria1103.pdf > [21/03/2022]

Ibaba, I. S. (2010). Environmental protection laws and sustainable development in the Niger Delta. *Africana*, *4*(1).

Ickes, A. M., Bohac, S. V., and Assanis, D. N. (2009). Effect of fuel cetane number on a premixed diesel combustion mode. *International Journal of Engine Research*, *10*(4), 251-263.

IBM, 2014. KMO and Bartlett's test [online] Available from < https://www.ibm.com/docs/en/spss-statistics/23.0.0?topic=detection-kmo-bartletts-test> [27/05/2021]

Ickes, A.M., Bohac, S.V., and Assanis, D.N., (2009) Effect of a fuel cetane number on a premixed diesel combustion mode. *International Journal of Engine Research*, Vol. 10, Issue 04, pg 251-263

Igbani, S., & Lucky, B. O. (2015). Experimental Investigation of API Gravity of Gasoline in Dispensing Stations and its Effects on Gasoline Engines in Bayelsa State, Nigeria. *International Journal of Applied*, *5*(4).

Igben, J.L., 2021. Artisanal Petroleum Refining and Occupational Dynamics in the Niger Delta Region, Nigeria. jasem 25, 341–349. https://doi.org/10.4314/jasem.v25i3.6

Ijah, U.J., and Antai, S., (2003). Removal of Nigerian light crude oil in soil over a 12-month period. International Biodeterioration & Biodegradation 51, 93–99. https://doi.org/10.1016/S0964-8305(01)00131-7

Ikezam, P., Elenwo, E.I., Oyegun, C.U., 2021. Effects of Artisanal Refinery on the Environment, Public Health and Socio-Economic Development of Communities in the Niger Delta Region. EMSD 10, 97. https://doi.org/10.5296/emsd.v10i3.18921

Iloeje, A. F., Nwagbara, A. O., and Chijioke, E. O. (2015). Assessment of Impact Significance of Oil Spill in the Niger Delta, Nigeria, *International Journal of Development Research,* Vol. 5, Issue 03, pp. 3755-3760

Imoobe, T. O., & Aganmwonyi, I. (2021). IMPACT OF OIL POLLUTION ON THE WATER QUALITY OF EKEHUAN RIVER, EDO STATE, NIGERIA. *Research Journal of Biotechnology and Life Science*, *1*(1), 1-17.

Iovleva, E.L., Borisov, A.A., Stepanov, P.A., 2020. Development of Arctic Diesel Fuel with Optimal Composition. IOP Conf. Ser.: Earth Environ. Sci. 459, 052009. https://doi.org/10.1088/1755-1315/459/5/052009

Ite, A. E., Ibok, U. J., Ite, M. U., & Petters, S. W. (2013). Petroleum exploration and production: past and present environmental issues in the Nigeria's Niger Delta. *American Journal of Environmental Protection*, *1*(4), 78-90.

Ithnin, A.M., Ahmad, M.A., Bakar, M.A.A., Rajoo, S., Yahya, W.J., (2015). Combustion performance and emission analysis of diesel engine fuelled with water-in-diesel emulsion fuel made from low-grade diesel fuel. Energy Conversion and Management 90, 375–382. https://doi.org/10.1016/j.enconman.2014.11.025

Ithnin, A.M., Noge, H., Abdul Kadir, H., Jazair, W., (2014). An overview of utilizing water-in-diesel emulsion fuel in diesel engine and its potential research study. Journal of the Energy Institute 87, 273–288. https://doi.org/10.1016/j.joei.2014.04.002

Itsekor, L., (2020). A Need for Investment in Nigerian Crude Oil Refining and Infrastructures: A Panacea to Refined Petroleum Shortages and Economic Growth. ABR 8, 31–46. https://doi.org/10.14738/abr.84.7951

Iturbe-Espinoza, P., Bonte, M., Gundlach, E., Brandt, B.W., Braster, M., van Spanning, R.J.M., 2022. Adaptive changes of sediment microbial communities associated with cleanup of oil spills in Nigerian mangrove forests. Marine Pollution Bulletin 176, 113406. https://doi.org/10.1016/j.marpolbul.2022.113406

Jafarmadar, S., (2013). The Effect of Split Injection on the Combustion and Emissions in DI and IDI Diesel Engines, in: Bari, S. (Ed.), Diesel Engine - Combustion, Emissions and Condition Monitoring. InTech. https://doi.org/10.5772/55232

James O., (2019) CSO: Federal Government must clamp down on illegal oil refineries- otherwise soot pollution won't stop [Online] Available from < https://www.thecable.ng/cso-fg-must-clamp-down-on-illegal-oil-refineries-otherwise-soot-pollution-wont-stop > [21/03/2022]

Jeihouni, Y., Pischinger, S., Ruhkamp, L., & Koerfer, T. (2011). *Relationship between fuel properties and sensitivity analysis of non-aromatic and aromatic fuels used in a single cylinder heavy duty diesel engine* (No. 2011-01-0333). SAE Technical Paper.

Jon G., (2013) Oil bunkering threatens Nigeria's economy, environment [Online] Available from < https://www.washingtonpost.com/national/oil-bunkering-threatens-nigerias-economy-environment/2013/07/18/e38cb4a0-e273-11e2-aef3-339619eab080_story.html > 17/03/2022

Joshi, R.M., Pegg, M.J., (2007). Flow properties of biodiesel fuel blends at low temperatures. Fuel 86, 143–151. https://doi.org/10.1016/j.fuel.2006.06.005

Julius Berger Nigeria (2020), Floating stations for the Niger Delta [Online] Available from < https://www.facebook.com/JuliusBergerNigeria/ > [24/07/2021]

Kadafa, A. A. (2012). Environmental impacts of oil exploration and exploitation in the Niger Delta of Nigeria. *Global Journal of Science Frontier Research Environment & Earth Sciences*, *12*(3), 19-28.

Kadhim, N. S. (2015). Study the Effect of Blending Kerosene with Diesel Fuel on the Performance and Emissions of Diesel Engine.

Kaisan, M.U., Anafi, F.O., Nuszkowski, J., Kulla, D.M., Umaru, S., (2020). Calorific value, flash point and cetane number of biodiesel from cotton, jatropha and neem binary and multi-blends with diesel. Biofuels 11, 321–327. https://doi.org/10.1080/17597269.2017.1358944

Kalligeros, S., Zannikos, F., Stournas, S., & Lois, E. (2003). Fuel adulteration issues in Greece. *Energy*, *28*(1), 15-26.

Kaltschmitt, T., & Deutschmann, O. (2012). Fuel processing for fuel cells. In *Advances in Chemical Engineering* (Vol. 41, pp. 1-64). Academic Press.

Karonis, D., and Stournas, S. (2006). Impact of Using Adulterated Automotive Diesel on the Exhaust Emissions of a Stationary Diesel Engine. *Global NEST Journal, Vol 8, No 3, pp 291-296*

Katsouris, C., and Sayne, A. (2013). *Nigeria's Criminal Crude: International Options to Combat the Export of Stolen Oil* (pp. 1-39). London: Chatham House.

Kanyathare, B., Kuivalainen, K., Räty, J., Silfsten, P., Bawuah, P., Peiponen, K.-E., 2018. A prototype of an optical sensor for the identification of diesel oil adulterated by kerosene. J. Eur. Opt. Soc.-Rapid Publ. 14, 3. https://doi.org/10.1186/s41476-018-0071-2

Keshavarz, S., Ghasemi-Fasaei, R., Ronaghi, A., Zarei, M., (2020). Nutritional composition, growth and enzymatic response of vetiver grass grown under crude oil contamination as influenced by gibberellic acid and surfactant. Journal of Plant Nutrition 43, 418–428. https://doi.org/10.1080/01904167.2019.1683191

Khan, M.A.I., Biswas, B., Smith, E., Naidu, R., Megharaj, M., (2018). Toxicity assessment of fresh and weathered petroleum hydrocarbons in contaminated soil- a review. Chemosphere 212, 755–767. https://doi.org/10.1016/j.chemosphere.2018.08.094

Khan, M.Z.H., Sultana, M., Al-Mamun, M.R., Hasan, M.R., 2016. Pyrolytic Waste Plastic Oil and Its Diesel Blend: Fuel Characterization. Journal of Environmental and Public Health 2016, 1–6. https://doi.org/10.1155/2016/7869080

Kharaka, Y. K., & Dorsey, N. S. (2005). Environmental issues of petroleum exploration and production: Introduction. *Environmental Geosciences*, *12*(2), 61-63.

Kharaka, Y. K., and J. S. Hanor, (2003). Deep fluids in the continents: I. Sedimentary basins, in J. I. Drever, ed., Treatise on Geochemistry, v. 5, p. 499–540.

Khasnobish, A., Bhattacharyya, S., Konar, A., Tibarewala, D.N., Nagar, A.K., 2011. A Two-fold classification for composite decision about localized arm movement from EEG by SVM and QDA techniques, in: The 2011 International Joint Conference on Neural Networks. Presented at the 2011 International Joint Conference on Neural Networks (IJCNN 2011 - San Jose), IEEE, San Jose, CA, USA, pp. 1344–1351. https://doi.org/10.1109/IJCNN.2011.6033380

Kim, M., Oh, J., Lee, C., 2018. Study on Combustion and Emission Characteristics of Marine Diesel Oil and Water-In-Oil Emulsified Marine Diesel Oil. Energies 11, 1830. https://doi.org/10.3390/en11071830

Kizza, R., Banadda, N., Seay, J., 2021. Qualitative and energy recovery potential analysis: plastic-derived fuel oil versus conventional diesel oil. Clean Techn Environ Policy. https://doi.org/10.1007/s10098-021-02028-9

Knothe, G., Matheaus, A. C., & Ryan, T. W. (2003). Cetane numbers of branched and straight-chain fatty esters determined in an ignition quality tester☆. *Fuel*, *82*(8), 971-975

Knothe, G., Steidley, K.R., 2005. Kinematic viscosity of biodiesel fuel components and related compounds. Influence of compound structure and comparison to petrodiesel fuel components. Fuel 84, 1059–1065. https://doi.org/10.1016/j.fuel.2005.01.016

Koebel, M., Elsener, M., Kleemann, M., 2000. Urea-SCR: a promising technique to reduce NOx emissions from automotive diesel engines. Catalysis Today 59, 335–345. https://doi.org/10.1016/S0920-5861(00)00299-6

Kojima, M., and Bacon, R. (2001). Abuses in Fuel Markets. *World Bank Viewpoint Note*, *220*.

KPMG, (2019). Downstream Oil and Gas Sector Watch [Online] Available from < https://assets.kpmg/content/dam/kpmg/ng/pdf/tax/Downstream-Oil-and-Gas-Sector-Watch.pdf > [24/07/2021]

Kulathunga, D. R., and Mahanama, K. R. R. (2013). Fingerprinting diesel and petrol fuels for adulteration in Sri Lanka. *Journal of the National Science Foundation of Sri Lanka*, *41*(4).

Lao, J., Song, H., Wang, C., Zhou, Y., Wang, J., 2020. Reducing atmospheric pollutant and greenhouse gas emissions of heavy-duty trucks by substituting diesel with hydrogen in Beijing-Tianjin-Hebei-Shandong region, China. International Journal of Hydrogen Energy S0360319920335722. https://doi.org/10.1016/j.ijhydene.2020.09.132

Latif, M.T., Abd Hamid, H.H., Ahamad, F., Khan, M.F., Mohd Nadzir, M.S., Othman, M., Sahani, M., Abdul Wahab, M.I., Mohamad, N., Uning, R., Poh, S.C., Fadzil, M.F., Sentian, J., Tahir, N.M., 2019. BTEX compositions and its potential health impacts in Malaysia. Chemosphere 237, 124451. https://doi.org/10.1016/j.chemosphere.2019.124451

Lavrakas, P.J. (Ed.), 2008. Encyclopedia of survey research methods. SAGE Publications, Thousand Oaks, Calif. https://dx.doi.org/10.4135/9781412963947.n91

Leghrib, R., Ouacha, E., Zouida, A., Faiz, B., Amghar, A., 2020. Monitoring automobile fuel adulteration using ultrasound technique for environmental issues. Measurement 150, 107004. https://doi.org/10.1016/j.measurement.2019.107004

Leonardo, R.S., Murta Valle, M.L., Dweck, J., (2020). Thermovolumetric and thermogravimetric analysis of diesel S10: Comparison with ASTM D86 standard method. J Therm Anal Calorim 139, 1507–1514. https://doi.org/10.1007/s10973-019-08528-7

Li, D., Zhen, H., Xingcai, L., Wu-gao, Z., and Jian-guang, Y., (2005). Physico-chemical properties of ethanol–diesel blend fuel and its effect on performance and emissions of diesel engines. Renewable Energy 30, 967–976. https://doi.org/10.1016/j.renene.2004.07.010

Li, Y., Cai, J., Zhang, L., Yuan, T., Zhang, K., Qi, F., 2011. Investigation on chemical structures of premixed toluene flames at low pressure. Proceedings of the Combustion Institute 33, 593–600. https://doi.org/10.1016/j.proci.2010.05.033

Li, Y., Wei, M., Liu, L., Xue, Q., Yu, B., 2020. Adsorption of toluene on various natural soils: Influences of soil properties, mechanisms, and model. Science of The Total Environment 740, 140104. https://doi.org/10.1016/j.scitotenv.2020.140104

Lindén, O., Pålsson, J., (2013). Oil Contamination in Ogoniland, Niger Delta. AMBIO 42, 685–701. https://doi.org/10.1007/s13280-013-0412-8

LN. 71 of 1965. Hydrocarbon Oil Refineries Act [online] Available from < https://lawsofnigeria.placng.org/laws/H5.pdf > 19/03/2022

Loegel, T.N., Cramer, J.A., Hammond, M.H., Leska, I.A., Morris, R.E., Johnson, K.J., (2019). Detection, Identification, and Quantification of Nonpolar High Molecular Weight Contaminants in Jet and Diesel Fuels by Liquid Chromatography. Energy Fuels 33, 868–876. https://doi.org/10.1021/acs.energyfuels.8b03746

Lopez-Echartea, E., Strejcek, M., Mukherjee, S., Uhlik, O., Yrjälä, K., (2020). Bacterial succession in oil-contaminated soil under phytoremediation with poplars. Chemosphere 243, 125242. https://doi.org/10.1016/j.chemosphere.2019.125242

Lubi, S.P., Akinluyi, F.O., 2022. Groundwater hydrocarbon contamination spatial pattern in Opuama, Western Niger-Delta, Nigeria. Environ Earth Sci 81, 121. https://doi.org/10.1007/s12665-022-10250-x

Luke, M. E., & Odokuma, L. O. (2021). Acute toxicity of crude oil from NNPC and artisanal refineries in Niger Delta on selected aquatic biota.

Lukoil (2013) Global Trends in Oil and Gas Markets to 2025 [Online] Available from < https://www.lukoil.be/pdf/Trends_Global_Oil_ENG.pdf > [28/10/2017]

Luo, Z., Wang, X., Yang, D., Zhang, S., Zhao, T., Qin, L., Yu, Z.-Z., (2020). Photothermal hierarchical carbon nanotube/reduced graphene oxide microspherical aerogels with radially orientated microchannels for efficient cleanup of crude oil spills. Journal of Colloid and Interface Science 570, 61–71. https://doi.org/10.1016/j.jcis.2020.02.097

Maamar, A., Lucchesi, M.-E., Debaets, S., Nguyen van Long, N., Quemener, M., Coton, E., Bouderbala, M., Burgaud, G., Matallah-Boutiba, A., (2020). Highlighting the Crude Oil Bioremediation Potential of Marine Fungi Isolated from the Port of Oran (Algeria). Diversity 12, 196. https://doi.org/10.3390/d12050196

Maawa, W.N., Mamat, R., Najafi, G., De Goey, L.P.H., (2020). Performance, combustion, and emission characteristics of a CI engine fueled with emulsified diesel-biodiesel blends at different water contents. Fuel 267, 117265. https://doi.org/10.1016/j.fuel.2020.117265

Mabood, F., Boqué, R., Hamaed, A., Jabeen, F., Al-Harrasi, A., Hussain, J., Alameri, S., Albroumi, M., Al Nabhani, M.M.O., Naureen, Z., Al Rawahi, M., Al Futaisi, F.A.S., (2017). Near-Infrared Spectroscopy Coupled with Multivariate Methods for the Characterization of Ethanol Adulteration in Premium 91 Gasoline. Energy & Fuels 31, 7591–7597. https://doi.org/10.1021/acs.energyfuels.7b00870

Madu I, U.A., (2015). Evidence of Petroleum Resources on Nigerian Economic Development (2000-2009). Business and Economics Journal 06. https://doi.org/10.4172/2151-6219.1000149

Mahmodi, K., Mostafaei, M., Mirzaee-Ghaleh, E., 2019. Detection and classification of diesel-biodiesel blends by LDA, QDA and SVM approaches using an electronic nose. Fuel 258, 116114. https://doi.org/10.1016/j.fuel.2019.116114

Mahmoudi, M.R., Baleanu, D., Band, S.S., Mosavi, A., 2021. Factor analysis approach to classify COVID-19 datasets in several regions. Results in Physics 25, 104071. https://doi.org/10.1016/j.rinp.2021.104071

Majekodunmi, A. (2013). The political economy of fuel subsidy removal in Nigeria. *International Journal of Management and Social Sciences Research (IJMSSR). 2 (7)*.

Mamudu, A.O., Igwe, G.J., Okonkwo, E., 2019. Process design evaluation of an optimum modular topping refinery for Nigeria crude oil using hysys® aspen software. Cogent Engineering 6. https://doi.org/10.1080/23311916.2019.1659123

Mancini, M., Rinnan, å., Pizzi, A., and Toscano, G., (2018). Prediction of gross calorific value and ash content of woodchip samples by means of FT-NIR spectroscopy. Fuel Processing Technology 169, 77–83. https://doi.org/10.1016/j.fuproc.2017.09.021

Mani, M., Subash, C., Nagarajan, G., 2009. Performance, emission and combustion characteristics of a DI diesel engine using waste plastic oil. Applied Thermal Engineering 29, 2738–2744. https://doi.org/10.1016/j.applthermaleng.2009.01.007

Marketing, G. (2007). Diesel Fuels Technical Review.

Martínez, G., Sánchez, N., Encinar, J.M., González, J.F., (2014). Fuel properties of biodiesel from vegetable oils and oil mixtures. Influence of methyl esters distribution. Biomass and Bioenergy 63, 22–32. https://doi.org/10.1016/j.biombioe.2014.01.034

Mathew, G.M., Raina, D., Narisetty, V., Kumar, V., Saran, S., Pugazhendi, A., Sindhu, R., Pandey, A., Binod, P., 2021. Recent advances in biodiesel production: Challenges and solutions. Science of The Total Environment 794, 148751. https://doi.org/10.1016/j.scitotenv.2021.148751

Mendes, G., and Barbeira, P.J.S., (2013). Detection and quantification of adulterants in gasoline using distillation curves and multivariate methods. Fuel 112, 163–171. https://doi.org/10.1016/j.fuel.2013.04.077

Mihajlović, M., Jovanović, M., Pešić, R., Jovanović, J., Milanović, Z., 2016. Volatile organic compounds (VOC) policy innovation in petrochemicals river barge transportation. Journal of Cleaner Production 112, 1559–1567. https://doi.org/10.1016/j.jclepro.2015.04.080

Milinkovitch, T., Thomas-Guyon, H., Lefrançois, C., & Imbert, N. (2013). Dispersant use as a response to oil spills: toxicological effects on fish cardiac performance. *Fish physiology and biochemistry*, *39*(2), 257-262.

Mis Solval, K., Chouljenko, A., Theegala, C., Sathivel, S., 2021. Physicochemical Properties of Purified Biodiesel Based on Oil Recovered from Catfish (*ICTALURUS PUNCTATUS*) Viscera. J Am Oil Chem Soc aocs.12467. https://doi.org/10.1002/aocs.12467

Mitra, S., Roy, P., 2011. BTEX : A Serious Ground-water Contaminant. Research J. of Environmental Sciences 5, 394–398. https://doi.org/10.3923/rjes.2011.394.398

Modak, N.M., Ghosh, D.K., Panda, S., Sana, S.S., 2018. Managing green house gas emission cost and pricing policies in a two-echelon supply chain. CIRP Journal of Manufacturing Science and Technology 20, 1–11. https://doi.org/10.1016/j.cirpj.2017.08.001

Mohapatra, S.S., Rath, M.K., Singh, R.K., Murugan, S., 2021. Performance and emission analysis of co-pyrolytic oil obtained from sugarcane bagasse and polystyrene in a CI engine. Fuel 298, 120813. https://doi.org/10.1016/j.fuel.2021.120813

Mona, S., Malyan, S.K., Saini, N., Deepak, B., Pugazhendhi, A., Kumar, S.S., 2021. Towards sustainable agriculture with carbon sequestration, and greenhouse gas mitigation using algal biochar. Chemosphere 275, 129856. https://doi.org/10.1016/j.chemosphere.2021.129856

Monteiro, M. R., Ambrozin, A. R., Liao, L. M., Boffo, E. F., Tavares, L. A., Ferreira, M. M., and Ferreira, A. G. (2008). Study of Brazilian gasoline quality using hydrogen nuclear magnetic resonance (1H NMR) spectroscopy and chemometric. *Energy & Fuels*, *23*(1), 272-279.

Monfreda, M., Gregori, A., 2011. Differentiation of Unevaporated Gasoline Samples According to Their Brands, by SPME-GC-MS and Multivariate Statistical Analysis:

DIFFERENTIATION OF UNEVAPORATED GASOLINE SAMPLES. Journal of Forensic Sciences 56, 372–380. https://doi.org/10.1111/j.1556-4029.2010.01644.x

Monteiro, M.R., Ambrozin, A.R.P., da Silva Santos, M., Boffo, E.F., Pereira-Filho, E.R., Lião, L.M., Ferreira, A.G., 2009. Evaluation of biodiesel–diesel blends quality using 1H NMR and chemometrics. Talanta 78, 660–664. https://doi.org/10.1016/j.talanta.2008.12.026

Moolla, R., Curtis, C., Knight, J., (2015). Occupational Exposure of Diesel Station Workers to BTEX Compounds at a Bus Depot. IJERPH 12, 4101–4115. https://doi.org/10.3390/ijerph120404101

Moreno-Gutiérrez, J., Durán-Grados, V., 2021. Calculating ships' real emissions of pollutants and greenhouse gases: Towards zero uncertainties. Science of The Total Environment 750, 141471. https://doi.org/10.1016/j.scitotenv.2020.141471

Muralikrishna, M. V., Kishor, K., & Venkata, R. R. C. (2006). Studies on exhaust emissions of catalytic coated spark ignition engine with adulterated gasoline. *Journal of environmental science & engineering*, *48*(2), 97-102.

Murtada, K., Bowman, D., Edwards, M., Pawliszyn, J., 2022. Thin-film microextraction combined with comprehensive two-dimensional gas chromatography time-of-flight mass spectrometry screening for presence of multiclass organic pollutants in drinking water samples. Talanta 242, 123301. https://doi.org/10.1016/j.talanta.2022.123301

Naanen, B., 2019. When extractive governance fails: Oil theft as resistance in Nigeria. The Extractive Industries and Society 6, 702–710. https://doi.org/10.1016/j.exis.2019.03.019

Ngada, T., Bowers, K., 2018. Spatial and temporal analysis of crude oil theft in the Niger delta. Secur J 31, 501–523. https://doi.org/10.1057/s41284-017-0112-3

Nandy, A., Radović, J.R., Novotnik, B., Sharma, M., Larter, S.R., Thangadurai, V., (2020). Investigation of crude oil degradation using a microbial fuel cell using metal oxide based anode. Bioresource Technology Reports 100449. https://doi.org/10.1016/j.biteb.2020.100449

Narayan, S., Moravec, D.B., Hauser, B.G., Dallas, A.J., Dutcher, C.S., (2018). Removing Water from Diesel Fuel: Understanding the Impact of Droplet Size on Dynamic Interfacial Tension of Water-in-Fuel Emulsions. Energy Fuels 32, 7326–7337. https://doi.org/10.1021/acs.energyfuels.8b00502

Nespeca, M.G., Hatanaka, R.R., Flumignan, D.L., Oliveira, J.E. de, 2018. Rapid and Simultaneous Prediction of Eight Diesel Quality Parameters through ATR-FTIR Analysis. Journal of Analytical Methods in Chemistry 2018, 1795624. https://doi.org/10.1155/2018/1795624

Network, S. D. (2013). Communities Not Criminals: Illegal Oil Refining in the Niger Delta [Online] Available from http://www.stakeholderdemocracy.org/wp-content/uploads/2015/04/CommunitiesNotCriminals.pdf [03/02/2018]

Ngada, T., & Bowers, K. (2018). Spatial and temporal analysis of crude oil theft in the Niger Delta. *Security Journal*, *31*(2), 501-523.

Nganje, T.N., Edet, A.E., Ibok, U.J., Ukpabio, E.J., Ibe, K.A., Neji, P., (2012). Polycyclic aromatic hydrocarbons in surface water and soil in the vicinity of fuel-oil spillage from a tank farm distribution facility, Esuk Utan, Calabar Municipality, Nigeria. Environ Earth Sci 67, 81–90. https://doi.org/10.1007/s12665-011-1481-2

Nigerian Air Force 2016., Operation Delta Safe: Nigerian Airforce Destroys Illegal Refineries and Barges [Online] Available from < https://www.youtube.com/watch?v=HAIk798BYFo > [28/06/2021]

Ning, L., Duan, Q., Chen, Z., Kou, H., Liu, B., Yang, B., Zeng, K., (2020). A comparative study on the combustion and emissions of a non-road common rail diesel engine fueled with primary alcohol fuels (methanol, ethanol, and n-butanol)/diesel dual fuel. Fuel 266, 117034. https://doi.org/10.1016/j.fuel.2020.117034

NNPC 2016, Nigerian National Petroleum Corporation, *Refineries and Petrochemicals,* [Online] Available from < http://nnpcgroup.com/NNPCBusiness/MidstreamVentures/RefineriesPetrochemicals.aspx > 23/01/2018

NNPC Retail, (2021) Want to know more about us? [Online] Available from < https://nnpcretail.com.ng/about-us/ > [24/07/2021]

NOSDRA (2020). About NOSDRA [online] Available from < https://www.nosdra.gov.ng/about.php> [02/06/2020]

Nriagu, J., (2019). Oil Industry and the Health of Communities in the Niger Delta of Nigeria, in: Encyclopedia of Environmental Health. Elsevier, pp. 758–766. https://doi.org/10.1016/B978-0-12-409548-9.11443-5

NS Energy, (ND). Waltersmith Modular Refinery, [Online], Available from < https://www.nsenergybusiness.com/projects/waltersmith-modular-refinery/ > [24/07/2021]

Nwachukwu, M.O., Azorji, J.N., Adjero, L.A., Green, M.C., Igwe, C.E., Nnadozie, R.I.A., (2020). Influence of Spent Engine Oil Pollution and Organic Amendment on Soil Physicochemical Properties, Microbial Population and Growth of Capsicum annuum (L.). ASRJ 17–25. https://doi.org/10.9734/asrj/2020/v3i130064

Nwaejije, E.C., Hamidu, I., Obiosio, E.O., 2017. Early to middle miocene sequence stratigraphy of well-5 (OML 34), Niger Delta, Nigeria. Journal of African Earth Sciences 129, 519–526. https://doi.org/10.1016/j.jafrearsci.2017.01.026

Nwajiaku-Dahou, K., (2012). The political economy of oil and ‘rebellion’ in Nigeria’s Niger Delta. Review of African Political Economy 39, 295–313. https://doi.org/10.1080/03056244.2012.688805

Nwogwugwu, N., Emmanuel, A. O., & Egwuonwu, C. (2012). Militancy and Insecurity in the Niger Delta: impact on the inflow of foreign direct investment to Nigeria. *Kuwait Chapter of the Arabian Journal of Business and Management Review*, *2*(1), 23.

Nwozor, A., Olanrewaju, J., Ake, M., Okidu, O., 2020. Oil and its discontents: the political economy of artisanal refining in Nigeria. Review of African Political Economy 47, 662–675. https://doi.org/10.1080/03056244.2020.1835631

Obasi, V. U., Ezenkwa, E. C., Onwa, D. O., & Nwogbaga, D. M. (2017). THE POLITICAL ECONOMY OF FUEL SUBSIDY REMOVAL IN NIGERIA. *African Journal of Politics and Adminstrative Studies*, *10*(1).

Obenade, M., & Amangabara, G. T. (2014). The Socioeconomic Implications of Oil Theft and Artisanal Refining in the Niger Delta Region of Nigeria. *International Journal of Science and Research (IJSR)*, *3*(7), 2390-2394.

Obenade, M., & Amangabara, G. T. (2014). Perspective: The environmental implications of oil theft and artisanal refining in the Niger Delta Region. *Asian Review of Environmental and Earth Sciences*, *1*(2), 25-29.

Obi, C. I. (2010). Oil extraction, dispossession, resistance, and conflict in Nigeria's oil-rich Niger Delta. *Canadian Journal of Development Studies/Revue canadienne d'études du développement*, *30*(1-2), 219-236.

Obodeh, O., and Isaac, F. O. (2011). Investigation of performance characteristics of diesel engine fuelled with diesel-kerosene blends. *Journal of Emerging Trends in Engineering and Applied Sciences (JETEAS)*, *2*(2), 318-322.

Ochoterena, R., Lif, A., Nydén, M., Andersson, S., Denbratt, I., (2010). Optical studies of spray development and combustion of water-in-diesel emulsion and microemulsion fuels. Fuel 89, 122–132. https://doi.org/10.1016/j.fuel.2009.06.039

Odeyemi, O., Ogunseitan, O.A., (1985). Petroleum industry and its pollution potential in Nigeria. Oil and Petrochemical Pollution 2, 223–229. https://doi.org/10.1016/S0143-7127(85)90218-2

Odiyi, B.O., Giwa, G.O., Abiya, S.E., Babatunde, O.S., (2020). Effects of crude oil pollution on the morphology, growth and heavy metal content of maize (*Zea mays* Linn.). Journal of Applied Sciences and Environmental Management 24, 119. https://doi.org/10.4314/jasem.v24i1.17

Odjuvwuederhie E.I., Douglason G. O., & Felicia N. A. (2006). The effect of oil spillage on crop yield and farm income in Delta State, Nigeria. *Journal of Central European Agriculture*, *7*(1), 41-48.

Odalonu, B. (2016). Oil theft and insecurity in post amnesty era in the Niger Delta Region of Nigeria: implications on national security. *E3 J. Environ. Res. Manag*, *7*, 1-12.

Ogbeibu, A.E., Akpogheneta, S.E., Zagi, M.M., (2020). The Effects of Crude Oil Production Activities on Surface and Groundwater Quality in Sapele, Delta State, Nigeria. OALib 07, 1–15. https://doi.org/10.4236/oalib.1106245

Ogbeifun, B. (2014) Why Nigeria should not treat oil theft with kid gloves—Ogbeifun. Vanguard in Sweet Crude, January 7, 2014 Retrieved on February 02, 2018 [available from] https://www.vanguardngr.com/2014/01/nigeria-treat-oil-theft-kid-gloves-ogbeifun/

Ogala E., (2013). How crude oil is stolen, refined, sold in Niger Delta [Online] Available from < https://www.premiumtimesng.com/news/150075-crude-oil-stolen-refined-sold-niger-delta.html > [22/03/2022]

Ogbon, N.O., Otanocha, O.B., Rim-Rukeh, A., 2018. An assessment of the economic viability and competitiveness of modular refinery in Nigeria. Nig. J. Tech. 37, 1015. https://doi.org/10.4314/njt.v37i4.22

Ogbuigwe, A., 2018. Refining in Nigeria: history, challenges and prospects. Appl Petrochem Res 8, 181–192. https://doi.org/10.1007/s13203-018-0211-z

Ogele, E. P., & Egobueze, A. (2020). The Artisanal Refining and Socioeconomic Development in Rivers State, Nigeria, 2007-2017. *International Journal of Research and Innovation in Social Science IV (IV)*, 16-25.

Ogu Kelechukwu (2021), Nigerians Generated Over N10bn To Ease Petrol Supply To Non-functional NNPC Floating Stations in Three Years [Online] Available from < http://saharareporters.com/2021/04/12/nigerians-generated-over-n10bn-ease-petrol-supply-non-functional-nnpc-floating-stations > [24/07/2021]

Ogunleye S., (2016) Angry motorist queue for fuel across Nigeria [Online] Available from < https://www.reuters.com/article/us-nigeria-oil-idUSKCN0X21R8> [15/06/2021].

Oh, J., Im, M., Oh, S., Lee, C., 2019. Comparison of NOx and Smoke Characteristics of Water-in-Oil Emulsion and Marine Diesel Oil in 400-kW Marine Generator Engine. Energies 12, 228. https://doi.org/10.3390/en12020228

Ojimba, T. P., & Iyagba, A. G. (2012). Effects of crude oil pollution on Horticultural crops in Rivers State, Nigeria. *Global Journal of Science Frontier Research Agriculture and Biology*, *12*(4), 37-43.

Okafor, C.P., Udemang, N.L., Chikere, C.B., Akaranta, O., Ntushelo, K., 2021. Indigenous microbial strains as bioresource for remediation of chronically polluted Niger Delta soils. Scientific African 11, e00682. https://doi.org/10.1016/j.sciaf.2020.e00682

Okafor-Yarwood, I., 2018. The effects of oil pollution on the marine environment in the Gulf of Guinea—the Bonga Oil Field example. Transnational Legal Theory 9, 254–271. https://doi.org/10.1080/20414005.2018.1562287

Okafor P., Why illegal refineries persist in Niger Delta region – Sylva [Online] Available from < https://www.vanguardngr.com/2021/06/why-illegal-refineries-persist-in-niger-delta-region-sylva/#:~:text=NCDMB%20and%20NNPC%20own%2030,operate%20the%20terminal%20upon%20completion. > 16/03/2022

Okonkwo, T., and Etemire, U., (2017). “Oil Injustice” in Nigeria’s Niger Delta Region: A Call for Responsive Governance. Journal of Environmental Protection 08, 42–60. https://doi.org/10.4236/jep.2017.81005

Okpo, O. C., and R. C. Eze. "Vandalization of oil pipelines in the Niger Delta region of Nigeria and poverty: An overview." *Studies in Sociology of Science* 3, no. 2 (2012): 13-21.

Olajuyigbe, F.M., Adeleye, O.A., Kolawole, A.O., Bolarinwa, T.O., Fasakin, E.A., Asenuga, E.R., Ajele, J.O., 2020. Bioremediation treatment improves water quality for Nile tilapia (Oreochromis niloticus) under crude oil pollution. Environ Sci Pollut Res. https://doi.org/10.1007/s11356-020-09020-8

Olalekan, E.O., Adebiyi, F.M., 2020. Measurement of radioactivity levels in oil impacted soils around petroleum products retailing stations. Petroleum Science and Technology 38, 53–63. https://doi.org/10.1080/10916466.2019.1656240

Olaniyan, A. (2015). The Law and Multi-Agency Response to Oil Spill Incidents in Nigeria. *Conference Proceedings of Interspill, Amsterdam 2015.*

Olujobi, O.J., 2021. Deregulation of the downstream petroleum industry: An overview of the legal quandaries and proposal for improvement in Nigeria. Heliyon 7, e06848. https://doi.org/10.1016/j.heliyon.2021.e06848

Olujobi, O.J., Olusola-Olujobi, T., 2020. Comparative appraisals of legal and institutional framework governing gas flaring in Nigeria's upstream petroleum sector: How satisfactory? Environmental Quality Management tqem.21680. https://doi.org/10.1002/tqem.21680

Omontuemhen, Pedro, Darrell, McGraw. 2018. Nigeria's Refining Revolution (PwC Research Report) [Online] Available from < https://www.pwc.com/ng/en/assets/pdf/nigerias-refining-revolution.pdf > 02/11/20

Onakpohor, A., Fakinle, B.S., Sonibare, J.A., Oke, M.A., Akeredolu, F.A., 2020. Investigation of air emissions from artisanal petroleum refineries in the Niger-Delta Nigeria. Heliyon 6, e05608. https://doi.org/10.1016/j.heliyon.2020.e05608

Ong, H.C., Silitonga, A.S., Masjuki, H.H., Mahlia, T.M.I., Chong, W.T., Boosroh, M.H., (2013). Production and comparative fuel properties of biodiesel from non-edible oils: Jatropha curcas, Sterculia foetida and Ceiba pentandra. Energy Conversion and Management 73, 245–255. https://doi.org/10.1016/j.enconman.2013.04.011

Onuh, P.A., Omenma, T.J., Onyishi, C.J., Udeogu, C.U., Nkalu, N.C., Iwuoha, V.O., 2021. Artisanal refining of crude oil in the Niger Delta: A challenge to clean-up and remediation in Ogoniland. Local Economy 36, 468–486. https://doi.org/10.1177/02690942211071075

Onyekakeyah. L (2017) Promoting private refineries in the Niger Delta, The Guardian Newspaper [Online] Available from < https://guardian.ng/opinion/promoting-private-refineries-in-the-niger-delta/> 02/02/2018

Onyena, A.P., Sam, K., 2020. A review of the threat of oil exploitation to mangrove ecosystem: Insights from Niger Delta, Nigeria. Global Ecology and Conservation 22, e00961. https://doi.org/10.1016/j.gecco.2020.e00961

Onyena, A.P., Nkwoji, J.A., Chukwu, L.O., 2021. Evaluation of hydrochemistry and benthic macroinvertebrates in Chanomi Creek, Niger Delta Nigeria. Regional Studies in Marine Science 46, 101907. https://doi.org/10.1016/j.rsma.2021.101907

Ordinioha, B., Brisibe, S., 2013. The human health implications of crude oil spills in the Niger delta, Nigeria: An interpretation of published studies. Niger Med J 54, 10. https://doi.org/10.4103/0300-1652.108887

Orisakwe, O.E., 2021. Crude oil and public health issues in Niger Delta, Nigeria: Much ado about the inevitable. Environmental Research 194, 110725. https://doi.org/10.1016/j.envres.2021.110725

Orubu, C. O., Odusola, A., & Ehwarieme, W. (2004). The Nigerian oil industry: environmental diseconomies, management strategies and the need for community involvement. *Journal of Human Ecology*, *16*(3), 203-214.

Osa O., (2019) Why Illegal Bunkering Thrives in Niger Delta [Online] Available from https://leadership.ng/why-illegal-bunkering-thrives-in-niger-delta/ [16/03/2022]

Osahon, J. (2018) Navy destroys 100 illegal refineries in Bayelsa, The Guardian Newspaper [Online] Available from < https://guardian.ng/navy/-destroys-100-illegal-refineries-in-bayelsa/> 02/06/2020

Owamah, H.I., 2020. A comprehensive assessment of groundwater quality for drinking purpose in a Nigerian rural Niger delta community. Groundwater for Sustainable Development 10, 100286. https://doi.org/10.1016/j.gsd.2019.100286

Owolabi T., Nigeria goes after illegal oil refineries to curb pollution [Online] Available from https://www.reuters.com/business/energy/nigeria-goes-after-illegal-oil-refineries-curb-pollution-2022-02-08/ 16/03.2022

Owolabi F., (2018). Undercover: Inside Niger Delta Creeks where oil thieves feed fat after bribing soldiers with millions [Online] Available from < http://petrobarometer.thecable.ng/2018/10/11/undercover-inside-niger-delta-creeks-where-oil-thieves-feed-fat-after-paying-millions-to-soldiers-and-naval-officers/> [08/05/2020]

Owusu, P.A., Banadda, N., Zziwa, A., Seay, J., Kiggundu, N., 2018. Reverse engineering of plastic waste into useful fuel products. Journal of Analytical and Applied Pyrolysis 130, 285–293. https://doi.org/10.1016/j.jaap.2017.12.020

Oyedepo, S. O. (2013). Energy in Perspective of Sustainable Development in Nigeria. *Sustainable Energy*, *1*(2), 14-25.

Oyibo, J.N., Wegwu, M.O., Uwakwe, A.A., Osuoha, J.O., (2018). Analysis of total petroleum hydrocarbons, polycyclic aromatic hydrocarbons and risk assessment of heavy metals in some selected finfishes at Forcados Terminal, Delta State, Nigeria. Environmental Nanotechnology, Monitoring & Management 9, 128–135. https://doi.org/10.1016/j.enmm.2017.11.002

Özer, S., 2020. The effect of adding toluene to increase the combustion efficiency of biodiesel. Energy Sources, Part A: Recovery, Utilization, and Environmental Effects 1–16. https://doi.org/10.1080/15567036.2020.1776421

Pairohakul, S., Olive, P.J.W., Bentley, M.G., Caldwell, G.S., 2021. Trophic upgrading of long-chain polyunsaturated fatty acids by polychaetes: a stable isotope approach using Alitta virens. Mar Biol 168, 67. https://doi.org/10.1007/s00227-021-03874-3

Paiva, E.M., Rohwedder, J.J.R., Pasquini, C., Pimentel, M.F., Pereira, C.F., (2015). Quantification of biodiesel and adulteration with vegetable oils in diesel/biodiesel blends using portable near-infrared spectrometer. Fuel 160, 57–63. https://doi.org/10.1016/j.fuel.2015.07.067

Pangestu, F., and Stanfel, C. (2009). Media for Water Separation from Biodiesel-Ultra Low Sulphur Diesel Blends. *SAE International Journal of Fuels and Lubricants, 2*(1), 305-316. Retrieved June 5, 2020, from www.jstor.org/stable/26273390

Park, J., Shin, M., Lee, Jongchul, Lee, Jongtae, 2021. Estimating the effectiveness of vehicle emission regulations for reducing NOx from light-duty vehicles in Korea using on-road measurements. Science of The Total Environment 767, 144250. https://doi.org/10.1016/j.scitotenv.2020.144250

Pasha, Y., Shrinivasa, U., Swamy, D.R., Muzzamil Ahmed, S., 2020. Experimental analysis of fuel properties and performance analysis of diesel engine with esterified castor oil blended with gasoline. Materials Today: Proceedings S2214785320379426. https://doi.org/10.1016/j.matpr.2020.10.331

Paterson, S., Cordero, R., Burlinson, S., 2004. Screening and semi-quantitative analysis of post mortem blood for basic drugs using gas chromatography/ion trap mass spectrometry. Journal of Chromatography B 813, 323–330. https://doi.org/10.1016/j.jchromb.2004.10.036

Patil, K.R., Thipse, S.S., (2015). Experimental investigation of CI engine combustion, performance and emissions in DEE–kerosene–diesel blends of high DEE concentration. Energy Conversion and Management 89, 396–408. https://doi.org/10.1016/j.enconman.2014.10.022

Payri, F., Olmeda, P., Guardiola, C., Martín, J., 2011. Adaptive determination of cut-off frequencies for filtering the in-cylinder pressure in diesel engines combustion analysis. Applied Thermal Engineering 31, 2869–2876. https://doi.org/10.1016/j.applthermaleng.2011.05.012

Peterson, C. H., Rice, S. D., Short, J. W., Esler, D., Bodkin, J. L., Ballachey, B. E., & Irons, D. B. (2003). Long-term ecosystem response to the Exxon Valdez oil spill. *Science*, *302*(5653), 2082-2086.

Phoon, L.Y., Mustaffa, A.A., Hashim, H., Mat, R., 2014. A Review of Flash Point Prediction Models for Flammable Liquid Mixtures. Ind. Eng. Chem. Res. 53, 12553–12565. https://doi.org/10.1021/ie501233g

Pointer (2018) Destruction of Illegal Refineries: Need for a Rethink [Online] Available from <http://thepointernewsonline.com/?p=61014 > [10/01/2019]

Popa, G., Gheți, M.A., 2020. Locomotive Diesel Engine Operation with Optimal Specific Fuel Consumption. Procedia Manufacturing 46, 440–444. https://doi.org/10.1016/j.promfg.2020.03.064

Prabhu, A., Venkata Ramanan, M., (2020). Emission and performance analysis of pentanol-diesel blends in unmodified diesel engine. International Journal of Ambient Energy 41, 699–702. https://doi.org/10.1080/01430750.2018.1490356

Qi, D.H., Geng, L.M., Chen, H., Bian, Y.Zh., Liu, J., Ren, X.Ch., 2009. Combustion and performance evaluation of a diesel engine fueled with biodiesel produced from soybean crude oil. Renewable Energy 34, 2706–2713. https://doi.org/10.1016/j.renene.2009.05.004

Qian, Y., Qiu, Y., Zhang, Y., Lu, X., 2017. Effects of different aromatics blended with diesel on combustion and emission characteristics with a common rail diesel engine. Applied Thermal Engineering 125, 1530–1538. https://doi.org/10.1016/j.applthermaleng.2017.07.145

Rageh R (2014) Nigeria Oil Theft at highest level in years [Online] Available from <https://www.youtube.com/watch?v=KagZ76EXU_I> [12/01/2019

Rahman, S.M.A., Fattah, I.M.R., Maitra, S., Mahlia, T.M.I., 2021. A ranking scheme for biodiesel underpinned by critical physicochemical properties. Energy Conversion and Management 229, 113742. https://doi.org/10.1016/j.enconman.2020.113742

Rahman, S.M.A., Fattah, I.M.R., Maitra, S., Mahlia, T.M.I., 2021. A ranking scheme for biodiesel underpinned by critical physicochemical properties. Energy Conversion and Management 229, 113742. https://doi.org/10.1016/j.enconman.2020.113742

Rajak, U., Nashine, P., Verma, T.N., (2020). Effect of spirulina microalgae biodiesel enriched with diesel fuel on performance and emission characteristics of CI engine. Fuel 268, 117305. https://doi.org/10.1016/j.fuel.2020.117305

Rajak, U., Nashine, P., Verma, T.N., Pugazhendhi, A., 2020. Performance and emission analysis of a diesel engine using hydrogen enriched n-butanol, diethyl ester and Spirulina microalgae biodiesel. Fuel 271, 117645. https://doi.org/10.1016/j.fuel.2020.117645

Rajak, U., Chaurasiya, P.K., Nashine, P., Verma, M., Reddy Kota, T., Verma, T.N., 2020. Financial assessment, performance, and emission analysis of Moringa oleifera and Jatropha curcas methyl ester fuel blends in a single-cylinder diesel engine. Energy Conversion and Management 224, 113362. https://doi.org/10.1016/j.enconman.2020.113362

Ralby, IM (2017) Downstream Oil Theft: Global Modalities, Trends, and Remedies. Atlantic Council. [Online] Available at: https://www.atlanticcouncil.org/wp-content/uploads/2018/09/Downstream-Oil-Theft-RW-0214.pdf (21/03/2022)

Raman, R., Kumar, N., 2020. Performance and emission characteristics of twin cylinder diesel engine fueled with mahua biodiesel and DEE. Transportation Engineering 2, 100024. https://doi.org/10.1016/j.treng.2020.100024

Ramesh, A., Ashok, B., Nanthagopal, K., Ramesh Pathy, M., Tambare, A., Mali, P., Phuke, P., Patil, S., Subbarao, R., (2019). Influence of hexanol as additive with Calophyllum Inophyllum biodiesel for CI engine applications. Fuel 249, 472–485. https://doi.org/10.1016/j.fuel.2019.03.072

Ramos, K., Riddell, A., Tsiagras, H., Hupp, A.M., 2022. Analysis of biodiesel-diesel blends: Does Ultrafast Gas Chromatography provide for similar separation in a fraction of the time? Journal of Chromatography A 462903. https://doi.org/10.1016/j.chroma.2022.462903

Riaz, M., Abid, M., Bano, Z., 2021. Psychological problems in general population during covid-19 pandemic in Pakistan: role of cognitive emotion regulation. Annals of Medicine 53, 189–196. https://doi.org/10.1080/07853890.2020.1853216

Riccardi, C., Di Filippo, P., Pomata, D., Incoronato, F., Di Basilio, M., Papini, M.P., Spicaglia, S., (2008). Characterization and distribution of petroleum hydrocarbons and heavy metals in groundwater from three Italian tank farms. Science of The Total Environment 393, 50–63. https://doi.org/10.1016/j.scitotenv.2007.12.010

Rim-Rukeh, A., Ikhifa, G.O., Okokoyo, P.A., (2007). Physico-Chemical Characteristics of Some Waters Used for Drinking and Domestic Purposes in the Niger Delta, Nigeria. Environ Monit Assess 128, 475–482. https://doi.org/10.1007/s10661-006-9340-4

Rocha, W.F. de C., Sheen, D.A., 2019. Determination of physicochemical properties of petroleum derivatives and biodiesel using GC/MS and chemometric methods with uncertainty estimation. Fuel 243, 413–422. https://doi.org/10.1016/j.fuel.2018.12.126

Ross W., (2012) Nigeria's booming illegal oil refineries [Online] Available from < https://www.bbc.com/news/world-africa-18973637 > [16/03/2022]

Sadat, A. (2014). Determining the Adulteration of Diesel by an Optical Method. *International Journal of Computer Applications*, *100*(13).

Safarov, J., Ashurova, U., Ahmadov, B., Abdullayev, E., Shahverdiyev, A., Hassel, E., (2018). Thermophysical properties of Diesel fuel over a wide range of temperatures and pressures. Fuel 216, 870–889. https://doi.org/10.1016/j.fuel.2017.11.125

Sakthivel, G., Nagarajan, G., Ilangkumaran, M., Gaikwad, A.B., (2014). Comparative analysis of performance, emission and combustion parameters of diesel engine fuelled with ethyl ester of fish oil and its diesel blends. Fuel 132, 116–124. https://doi.org/10.1016/j.fuel.2014.04.059

Sakthivel, R., Ramesh, K., Purnachandran, R., Mohamed Shameer, P., (2018). A review on the properties, performance, and emission aspects of the third-generation biodiesels. Renewable and Sustainable Energy Reviews 82, 2970–2992. https://doi.org/10.1016/j.rser.2017.10.037

Saleh, H.E., 2009. Effect of exhaust gas recirculation on diesel engine nitrogen oxide reduction operating with jojoba methyl ester. Renewable Energy 34, 2178–2186. https://doi.org/10.1016/j.renene.2009.03.024

Saleh, S.H., Tripp, C.P., 2021. A reagentless and rapid method to measure water content in oils. Talanta 225, 121911. https://doi.org/10.1016/j.talanta.2020.121911

Sam, K., Coulon, F., Prpich, G., 2016. Working towards an integrated land contamination management framework for Nigeria. Science of The Total Environment 571, 916–925. https://doi.org/10.1016/j.scitotenv.2016.07.075

Sam, K., Coulon, F., Prpich, G., 2017. Use of stakeholder engagement to support policy transfer: A case of contaminated land management in Nigeria. Environmental Development 24, 50–62. https://doi.org/10.1016/j.envdev.2017.06.005

Sam, K., Zabbey, N., Onyena, A.P., 2022. Implementing contaminated land remediation in Nigeria: Insights from the Ogoni remediation project. Land Use Policy 115, 106051. https://doi.org/10.1016/j.landusepol.2022.106051

Santhoshkumar, A., Thangarasu, V., Anand, R., 2019. Performance, combustion, and emission characteristics of DI diesel engine using mahua biodiesel, in: Advanced Biofuels. Elsevier, pp. 291–327. https://doi.org/10.1016/B978-0-08-102791-2.00012-X

Santos, S.M., Nascimento, D.C., Costa, M.C., Neto, A.M.B., Fregolente, L.V., 2020. Flash point prediction: Reviewing empirical models for hydrocarbons, petroleum fraction, biodiesel, and blends. Fuel 263, 116375. https://doi.org/10.1016/j.fuel.2019.116375

Saravanan, C.G., Raj Kiran, K., Vikneswaran, M., Rajakrishnamoorthy, P., Yadav, S.P.R., 2020. Impact of fuel injection pressure on the engine characteristics of CRDI engine powered by pine oil biodiesel blend. Fuel 264, 116760. https://doi.org/10.1016/j.fuel.2019.116760

Sayin, C., 2010. Engine performance and exhaust gas emissions of methanol and ethanol–diesel blends. Fuel 89, 3410–3415. https://doi.org/10.1016/j.fuel.2010.02.017

Sayin, C., Canakci, M., (2009). Effects of injection timing on the engine performance and exhaust emissions of a dual-fuel diesel engine. Energy Conversion and Management 50, 203–213. https://doi.org/10.1016/j.enconman.2008.06.007

Šebjan, U., Tominc, P., 2015. Impact of support of teacher and compatibility with needs of study on usefulness of SPSS by students. Computers in Human Behavior 53, 354–365. https://doi.org/10.1016/j.chb.2015.07.022

Sewall, A., (2019). Stata vs. R vs. SPSS for Data Analysis [Online] Available from < http://publish.illinois.edu/commonsknowledge/2019/12/05/stata-vs-r-vs-spss-for-data-analysis/ >

Sharma, R.K., Gupta, A.K., 2007. Detection/ estimation of adulteration in gasoline and diesel using ultrasonics, in: 2007 International Conference on Industrial and Information Systems. Presented at the 2007 International Conference on Industrial and Information Systems, IEEE, Peradeniya, Sri Lanka, pp. 509–512. https://doi.org/10.1109/ICIINFS.2007.4579230

Shehata, M.S., 2013. Emissions, performance, and cylinder pressure of diesel engine fuelled by biodiesel fuel. Fuel 112, 513–522. https://doi.org/10.1016/j.fuel.2013.02.056

Shimamoto, G.G., Tubino, M., (2016). Alternative methods to quantify biodiesel in standard diesel-biodiesel blends and samples adulterated with vegetable oil through UV–Visible spectroscopy. Fuel 186, 199–203. https://doi.org/10.1016/j.fuel.2016.08.076

Shrivastava, P., Verma, T.N., David Samuel, O., Pugazhendhi, A., 2020. An experimental investigation on engine characteristics, cost and energy analysis of CI engine fuelled with Roselle, Karanja biodiesel and its blends. Fuel 275, 117891. https://doi.org/10.1016/j.fuel.2020.117891

Sidjabat, O. (2013). The characteristics of a mixture of kerosene and biodiesel as a substituted diesel fuel. *Sci Contrib Oil Gas*, *36*(1), 37Ā44.

Silitonga, A.S., Masjuki, H.H., Mahlia, T.M.I., Ong, H.C., Chong, W.T., Boosroh, M.H., (2013). Overview properties of biodiesel diesel blends from edible and non-edible feedstock. Renewable and Sustainable Energy Reviews 22, 346–360. https://doi.org/10.1016/j.rser.2013.01.055

Şimşek, D., & Çolak, N. Y. (2019). Investigation of the effect of biodiesel/propanol fuel mixtures on diesel engine emissions. *Al-Cezeri Journal of Science and Engineering*, *6*, 166-174.

Skrobot, V.L., de Sousa Santos, C., Batista Braga, J.W., 2019. Exploratory Analysis of Automotive Diesel Fuel Stability Test Methods by Infrared Spectroscopy and Parallel Factor Analysis. Energy Fuels 33, 6170–6176. https://doi.org/10.1021/acs.energyfuels.9b01001

Skrobot, V.L., Castro, E.V.R., Pereira, R.C.C., Pasa, V.M.D., and Fortes, I.C.P., (2007). Use of Principal Component Analysis (PCA) and Linear Discriminant Analysis (LDA) in Gas Chromatographic (GC) Data in the Investigation of Gasoline Adulteration. Energy & Fuels 21, 3394–3400. https://doi.org/10.1021/ef0701337

Soares, I.P., Rezende, T.F., Fortes, I.C.P., 2009. Study of the Behavior Changes in Physical-Chemistry Properties of Diesel/Biodiesel (B2) Mixtures with Residual Oil and Its Quantification by Partial Least-Squares Attenuated Total Reflection−Fourier Transformed Infrared Spectroscopy (PLS/ATR−FTIR). Energy Fuels 23, 4143–4148. https://doi.org/10.1021/ef900302q

Soares, S., Rocha, F.R.P., 2020. Green volumetric procedure for determining biodiesel content in diesel blends or mixtures with vegetable oils exploiting solubility differences in an ethanol:water medium. Fuel 276, 118042. https://doi.org/10.1016/j.fuel.2020.118042

Sopian, N. A., Jalaludin, J., & Bahri, M. T. S. (2016). Risk of respiratory health impairment among susceptible population living near petrochemical industry-a review article.

Sparkman, O.D., Penton, Z.E., Kitson, F.G., (2011). Introduction and History, in: Gas Chromatography and Mass Spectrometry: A Practical Guide. Elsevier, pp. 2–13. https://doi.org/10.1016/B978-0-12-373628-4.00001-0

Speight, J. G. (2015). *Handbook of Petroleum Product Analysis* (Vol. 182). John Wiley & Sons.

Srivastava, A., Prasad, R., 2000. Triglycerides-based diesel fuels. Renewable and Sustainable Energy Reviews 4, 111–133. https://doi.org/10.1016/S1364-0321(99)00013-1

Stauffer, E., Dolan, J.A., Newman, R., (2008). Interpretation of Data Obtained from Neat Ignitable Liquids, in: Fire Debris Analysis. Elsevier, pp. 295–354. https://doi.org/10.1016/B978-012663971-1.50013-0

Sun, X., Liang, X., Shu, G., Wang, Y., Chen, Y., 2019. Effect of toluene content on the combustion and emissions of large two-stroke marine diesel engine. Applied Thermal Engineering 159, 113909. https://doi.org/10.1016/j.applthermaleng.2019.113909

Suppajariyawat, P., Andrade, A.F.B. de, Elie, M., Baron, M., Gonzalez-Rodriguez, J., 2019. The Use Of Chemical Composition And Additives To Classify Petrol And Diesel Using Gas Chromatography–Mass Spectrometry And Chemometric Analysis: A Uk Study. Open Chemistry 17, 183–197. https://doi.org/10.1515/chem-2019-0021

Sylvester I., and Emmanuel A., (2019) How Perpetrators of Bunkering are Denying Nigeria Enormous Revenue [Online] Available from < https://www.thisdaylive.com/index.php/2019/08/25/how-perpertrators-of-bunkering-are-denying-nigeria-enormous-revenue/ > [21/03/2022]

Takeshita, E.V., Rezende, R.V.P., de Souza, S.M.A.G.U., de Souza, A.A.U., (2008). Influence of solvent addition on the physicochemical properties of Brazilian gasoline. Fuel 87, 2168–2177. https://doi.org/10.1016/j.fuel.2007.11.003

Taksande, A., Hariharan, C., 2006. Synchronous Fluorescence Method to Check Adulteration of Petrol and Diesel by Kerosene. Spectroscopy Letters 39, 345–356. https://doi.org/10.1080/00387010600781340

Tamer, A., Karadağ, F., Ünal, E., Abdulkarim, Y.I., Deng, L., Altintas, O., Bakır, M., Karaaslan, M., (2020). Metamaterial based sensor integrating transmission line for detection of branded and unbranded diesel fuel. Chemical Physics Letters 742, 137169. https://doi.org/10.1016/j.cplett.2020.137169

Tang, D., Sun, J., Zhou, L., Wang, S., Singh, R.P., Pan, G., (2019). Ecological response of phytoplankton to the oil spills in the oceans. Geomatics, Natural Hazards and Risk 10, 853–872. https://doi.org/10.1080/19475705.2018.1549110

Tang, T. W., Ku, Y. Y., & Chen, C. L. (2016). *Impacts of Biodiesel Blends on Fuel Filters of High-Pressure Common Rail (HPCR) System* (No. 2016-01-1280). SAE Technical Paper.

Tharby, Ronald [editor]. 2002. *Catching gasoline and diesel adulteration (English)*. South Asia urban air quality management briefing note ; no. 7. Washington, DC: World Bank.

http://documents.worldbank.org/curated/en/223591468164352248/Catching-gasoline-and-diesel-adulteration

The Guardian UK (2013) Illegal oil refineries in the Niger Delta in Pictures [Online] Available from < https://www.theguardian.com/artanddesign/gallery/2013/jan/17/illegal-oil-refining-nigeria-in-pictures > [30/10/2017]

This Day, (2021) The Much-awaited Dangote Oil Refinery [Online] Available from < https://www.thisdaylive.com/index.php/2021/04/17/the-much-awaited-dangote-oil-refinery/ > [24/07/2021]

Toche, R., Borade, S., Malve, M., & More, B. (2015) Mineral Turpentine Adulterant in Lubricating Oil. *Chemical Science Transactions* Vol. 4, No. 4

Today (2020). NNPC floating petrol stations abandoned in Bayelsa [Online] Available from https://www.today.ng/business/energy/nnpc-floating-petrol-stations-abandoned-bayelsa-276217 [27/08/2021]

Torab, E.S., 2018. A law or just a hypothesis? A critical review of supply and demand effect on the affordable residential markets in developing countries. Alexandria Engineering Journal 57, 4081–4090. https://doi.org/10.1016/j.aej.2018.10.010

Torres-García, M., García-Martín, J.F., Jiménez-Espadafor Aguilar, F.J., Barbin, D.F., Álvarez-Mateos, P., 2020. Vegetable oils as renewable fuels for power plants based on low and medium speed diesel engines. Journal of the Energy Institute 93, 953–961. https://doi.org/10.1016/j.joei.2019.08.006

Torres-Jimenez, E., Jerman, M.S., Gregorc, A., Lisec, I., Dorado, M.P., Kegl, B., (2011). Physical and chemical properties of ethanol–diesel fuel blends. Fuel 90, 795–802. https://doi.org/10.1016/j.fuel.2010.09.045

Trishch, R., Maletska, O., Hrinchenko, H., Artiukh, S., Burdeina, V., Antonenko, N., 2019. Development and validation of measurement techniques according to ISO/IEC 17025:2017, in: 2019 IEEE 8th International Conference on Advanced Optoelectronics and Lasers (CAOL). Presented at the 2019 IEEE 8th International Conference on Advanced Optoelectronics and Lasers (CAOL), IEEE, Sozopol, Bulgaria, pp. 1–6. https://doi.org/10.1109/CAOL46282.2019.9019539

Tsanaktsidis, C.G., Christidis, S.G., Favvas, E.P., 2013. A novel method for improving the physicochemical properties of diesel and jet fuel using polyaspartate polymer additives. Fuel 104, 155–162. https://doi.org/10.1016/j.fuel.2012.09.076

Tukur U., A., Hajj O., M.S., (2017). Causes and consequences of crude oil pipeline vandalism in the Niger delta region of Nigeria: A confirmatory factor analysis approach. Cogent Economics & Finance 5. doi:10.1080/23322039.2017.1353199

Ubeidalah, S. K. (2015). *Assessment of Gasoline Quality Marketed in Accra Metropolis, Ghana* (Doctoral dissertation, University of Ghana).

Udo, E.J., Fayemi, A.A.A., (1975). The Effect of Oil Pollution of Soil on Germination, Growth and Nutrient Uptake of Corn. Journal of Environmental Quality 4, 537–540. https://doi.org/10.2134/jeq1975.00472425000400040023x

Ugboma, C. J., Ibietela, D. S., & Onwukwe, J. O. (2020) Effect of Different Organic Amendments on Fungi Degrading Hydrocarbons from an Artisanal Crude Oil Refining Polluted Soil in Ngia Kiri, Degema, Rivers State.

Ugor, P.U., 2013. Survival Strategies and Citizenship Claims: Youth and the Underground Oil Economy in Post-Amnesty Niger Delta Africa 83, 270–292. https://doi.org/10.1017/S0001972013000041

Ugwu, H. U., Nwankwojike, B. N., Ogbonnaya, E. A., and Ekoi, E. J. (2012). Energy and Economic losses due to constant power outages in Nigeria. *Nigerian Journal of Technology*, *31*(2), 181-188.

Ukhurebor, K.E., Athar, H., Adetunji, C.O., Aigbe, U.O., Onyancha, R.B., Abifarin, O., 2021. Environmental implications of petroleum spillages in the Niger Delta region of Nigeria: A review. Journal of Environmental Management 293, 112872. https://doi.org/10.1016/j.jenvman.2021.112872

Umar, H.A., Abdul Khanan, M.F., Ogbonnaya, C., Shiru, M.S., Ahmad, A., Baba, A.I., 2021. Environmental and socioeconomic impacts of pipeline transport interdiction in Niger Delta, Nigeria. Heliyon 7, e06999. https://doi.org/10.1016/j.heliyon.2021.e06999

Umukoro, N., 2012. Governance and environmental inequality in Nigeria: implications for conflict management strategies in the Niger Delta. International Journal of Environmental Studies 69, 913–920. https://doi.org/10.1080/00207233.2012.731772

UNDP, 2021. What are the Sustainable Development Goals? [Online] Available from < https://www.undp.org/sustainable-development-goals?utm_source=EN&utm_medium=GSR&utm_content=US_UNDP_PaidSearch_Brand_English&utm_campaign=CENTRAL&c_src=CENTRAL&c_src2=GSR&gclid=Cj0KCQjw2tCGBhCLARIsABJGmZ4hV-W6sEp3wZS0QwQAcxEcIrNESr56jg2ZhiMBazvdGb4UlnJaITsaApfXEALw_wcB#life-on-land> [24/06/2021]

Vellaiyan, S., (2020). Combustion, performance, and emission evaluation of a diesel engine fueled with soybean biodiesel and its water blends. Energy 201, 117633. https://doi.org/10.1016/j.energy.2020.117633

Vanguard Newspaper (2018). FG explains the causes of soot in Rivers [Online] Available from https://www.vanguardngr.com/2018/04/fg-explains-causes-soot-rivers/ [08/02/19]

Vempatapu, B.P. and Kanaujia, P.K., (2017). Monitoring petroleum fuel adulteration: A review of analytical methods. TrAC Trends in Analytical Chemistry 92, 1–11. https://doi.org/10.1016/j.trac.2017.04.011

Vempatapu, B.P., Tripathi, D., Kumar, J., Kanaujia, P.K., (2019). Determination of kerosene as an adulterant in diesel through chromatography and high-resolution mass spectrometry. SN Appl. Sci. 1, 614. https://doi.org/10.1007/s42452-019-0637-7

Vempatapu, B.P., Kumar, J., Ray, A., Chhibber, V.K., Kanaujia, P.K., 2020. Determination of biodiesel and used cooking oil in automotive diesel/green diesel fuels through high-performance liquid chromatography. Journal of Chromatography A 1629, 461512. https://doi.org/10.1016/j.chroma.2020.461512

Venkatesan, V., Nallusamy, N., Nagapandiselvi, P., 2021. Performance and emission analysis on the effect of exhaust gas recirculation in a tractor diesel engine using pine oil and soapnut oil methyl ester. Fuel 290, 120077. https://doi.org/10.1016/j.fuel.2020.120077

Venu, H., Raju, V.D., Subramani, L., Appavu, P., 2020. Experimental assessment on the regulated and unregulated emissions of DI diesel engine fuelled with Chlorella emersonii methyl ester (CEME). Renewable Energy 151, 88–102. https://doi.org/10.1016/j.renene.2019.11.010

Verma, R.K., Suwalka, P., Yadav, J., (2018). Detection of adulteration in diesel and petrol by kerosene using SPR based fiber optic technique. Optical Fiber Technology 43, 95–100. https://doi.org/10.1016/j.yofte.2018.04.011

Vidal J., (2013) Nigerians risk death working at illegal refineries [Online] Available from < https://www.theguardian.com/global-development/2013/oct/16/poor-nigerians-risk-refining-stolen-oil > 16/03/2022

Vieira, A.P., Portela, N.A., Neto, Á.C., Lacerda, V., Romão, W., Castro, E.V.R., Filgueiras, P.R., 2019. Determination of physicochemical properties of petroleum using 1H NMR spectroscopy combined with multivariate calibration. Fuel 253, 320–326. https://doi.org/10.1016/j.fuel.2019.05.028

Waheed, M.A., Oni, A.O., Adejuyigbe, S.B., Adewumi, B.A., 2014. Thermoeconomic and environmental assessment of a crude oil distillation unit of a Nigerian refinery. Applied Thermal Engineering 66, 191–205. https://doi.org/10.1016/j.applthermaleng.2014.02.007

Wan Ghazali, W.N.M., Mamat, R., Najafi, G., Sapee, S., (2020). Investigation of Blended Palm Biodiesel-Diesel Fuel Properties with Water Emulsification. JER 57, 65–74.

Wang, S., Liu, S., Yuan, Y., Zhang, J., Wang, J., Kong, D., 2020. Simultaneous detection of different properties of diesel fuel by near infrared spectroscopy and chemometrics. Infrared Physics & Technology 104, 103111. https://doi.org/10.1016/j.infrared.2019.103111

Wang, X., Peng, G., Chen, M., Zhao, M., He, Y., Jiang, Y., Zhang, X., Qin, Y., Lin, S., (2020). Reduced graphene oxide composites and its real-life application potential for in-situ crude oil removal. Chemosphere 249, 126141. https://doi.org/10.1016/j.chemosphere.2020.126141

Wiedemann, L.S.M., d'Avila, L.A., Azevedo, D. de A., 2005. Brazilian gasoline quality: study of adulteration by statistical analysis and gas chromatography. J. Braz. Chem. Soc. 16. https://doi.org/10.1590/S0103-50532005000200003

Wiesen, C., Odum Institute, 2019. Learn to Use the Kaiser-Meyer-Olkin Measure of Sampling Adequacy in SPSS With Data From Lahman's Baseball Database (2017). SAGE Publications, Ltd., 1 Oliver's Yard, 55 City Road, London EC1Y 1SP United Kingdom. https://doi.org/10.4135/9781526489357

Wilson Abali, H., M. Etebu, O., and G. Leton, T., (2018). Corossitivity of Pollutants from Gas Flares on Galvanised Roofing Sheets in Idu, Rivers State, Niger Delta of Nigeria. Journal of Environment Pollution and Human Health 6, 1–6. https://doi.org/10.12691/jephh-6-1-1

Wizor, C. H., & Wali, E. (2020). Crude Oil Theft in the Niger Delta: The Oil Companies and Host Communities Conundrum. *Int. J. Res. Sci. Innov*, *6*(1), 22-32.

Worldometer 2017. Nigeria Oil [Online] Available from < https://www.worldometers.info/oil/nigeria-oil/ > [03/07/2021]

Xiang, Y., Morgan, S.L., Watt, B.E., 1995. TPH and BTEX Quantitation in Gasoline and Diesel Contaminated Soils by Capillary Gas Chromatography-Mass Spectrometry. Journal of Chromatographic Science 33, 98–108. https://doi.org/10.1093/chromsci/33.3.98

Yadav, G.C., Prakash, S., Sharma, G., Kumar, S., Singh, V., 2019. Detection of kerosene adulteration in automobile fuel with a novel metal clad planar waveguide. Optics & Laser Technology 119, 105589. https://doi.org/10.1016/j.optlastec.2019.105589

Yadav, Sh.R., Murthy, V.K., Mishra, D., Baral, B., (2005). Estimation of petrol and diesel adulteration with kerosene and assessment of usefulness of selected automobile fuel quality test parameters. Int. J. Environ. Sci. Technol. 1, 253–255. https://doi.org/10.1007/BF03325839

Yafugborhi E., (2019) We depend on illegally refined diesel to lift fuel at Port Harcourt depot [Online] Available from < https://www.vanguardngr.com/2019/08/we-depend-on-illegally-refined-diesel-to-lift-fuel-at-pharcourt-depot-ipman/ > 15/03/202

Yakubu, O., (2017). Particle (Soot) Pollution in Port Harcourt Rivers State, Nigeria—Double Air Pollution Burden? Understanding and Tackling Potential Environmental Public Health Impacts. Environments 5, 2. https://doi.org/10.3390/environments5010002

Yasin, G., Bhanger, M. I., Ansari, T. M., Naqvi, S. M. S. R., Ashraf, M., Ahmad, K., & Talpur, F. N. (2013). Quality and chemistry of crude oils. *Journal of Petroleum Technology and Alternative Fuels*, *4*(3), 53-63.

Yasin, M.H.M., Mamat, R., Ali, O.M., Yusop, A.F., Hamidi, M.A., Ismail, M.Y., Rasul, M (2017). Study of Diesel-biodiesel Fuel Properties and Wavelet Analysis on Cyclic Variations in a Diesel Engine. Energy Procedia 110, 498–503. https://doi.org/10.1016/j.egypro.2017.03.175

Yeeles, A., Akporiaye, A., 2016. Risk and resilience in the Nigerian oil sector: The economic effects of pipeline sabotage and theft. Energy Policy 88, 187–196. https://doi.org/10.1016/j.enpol.2015.10.018

Yesilyurt, M.K., (2020). A detailed investigation on the performance, combustion, and exhaust emission characteristics of a diesel engine running on the blend of diesel fuel, biodiesel and 1-heptanol (C7 alcohol) as a next-generation higher alcohol. Fuel 275, 117893. https://doi.org/10.1016/j.fuel.2020.117893

Yesilyurt, M.K., Aydin, M., (2020). Experimental investigation on the performance, combustion and exhaust emission characteristics of a compression-ignition engine fueled with cottonseed oil biodiesel/diethyl ether/diesel fuel blends. Energy Conversion and Management 205, 112355. https://doi.org/10.1016/j.enconman.2019.112355

Yong, A. G., & Pearce, S. (2013). A beginner's guide to factor analysis: Focusing on exploratory factor analysis. *Tutorials in quantitative methods for psychology*, *9*(2), 79-94.

Yoshino, F. J., Marques, G. A., & Ferrari, F. (2013). *Water Separation Challenge for Brazilian Diesel Engine* (No. 2013-01-1693). SAE Technical Paper.

Yu, M., Zhang, J., Joedicke, A., Reddyhoff, T., 2021. Experimental investigation into the effects of diesel dilution on engine lubrication. Tribology International 156, 106828. https://doi.org/10.1016/j.triboint.2020.106828

Zabbey, N., Giadom, F.D., Babatunde, B.B., 2019. Nigerian Coastal Environments, in: World Seas: An Environmental Evaluation. Elsevier, pp. 835–854. https://doi.org/10.1016/B978-0-12-805068-2.00042-5

Zabbey, N., Sam, K., and Onyebuchi, A.T., (2017). Remediation of contaminated lands in the Niger Delta, Nigeria: Prospects and challenges. Science of The Total Environment 586, 952–965. https://doi.org/10.1016/j.scitotenv.2017.02.075

Zabbey, N., Kpaniku, N.C., Sam, K., Nwipie, G.N., Okoro, O.E., Zabbey, F.G., Babatunde, B.B., 2021. Could community science drive environmental management in Nigeria's degrading coastal Niger delta? Prospects and challenges. Environmental Development 37, 100571. https://doi.org/10.1016/j.envdev.2020.100571

Zaharin, M.S.M., Abdullah, N.R., Najafi, G., Sharudin, H., Yusaf, T., (2017). Effects of physicochemical properties of biodiesel fuel blends with alcohol on diesel engine performance and exhaust emissions: A review. Renewable and Sustainable Energy Reviews 79, 475–493. https://doi.org/10.1016/j.rser.2017.05.035

Zhang, C., Zhou, A., Shen, Y., Li, Y., Shi, Q., 2017. Effects of combustion duration characteristic on the brake thermal efficiency and NOx emission of a turbocharged diesel engine fueled with diesel-LNG dual-fuel. Applied Thermal Engineering 127, 312–318. https://doi.org/10.1016/j.applthermaleng.2017.08.034

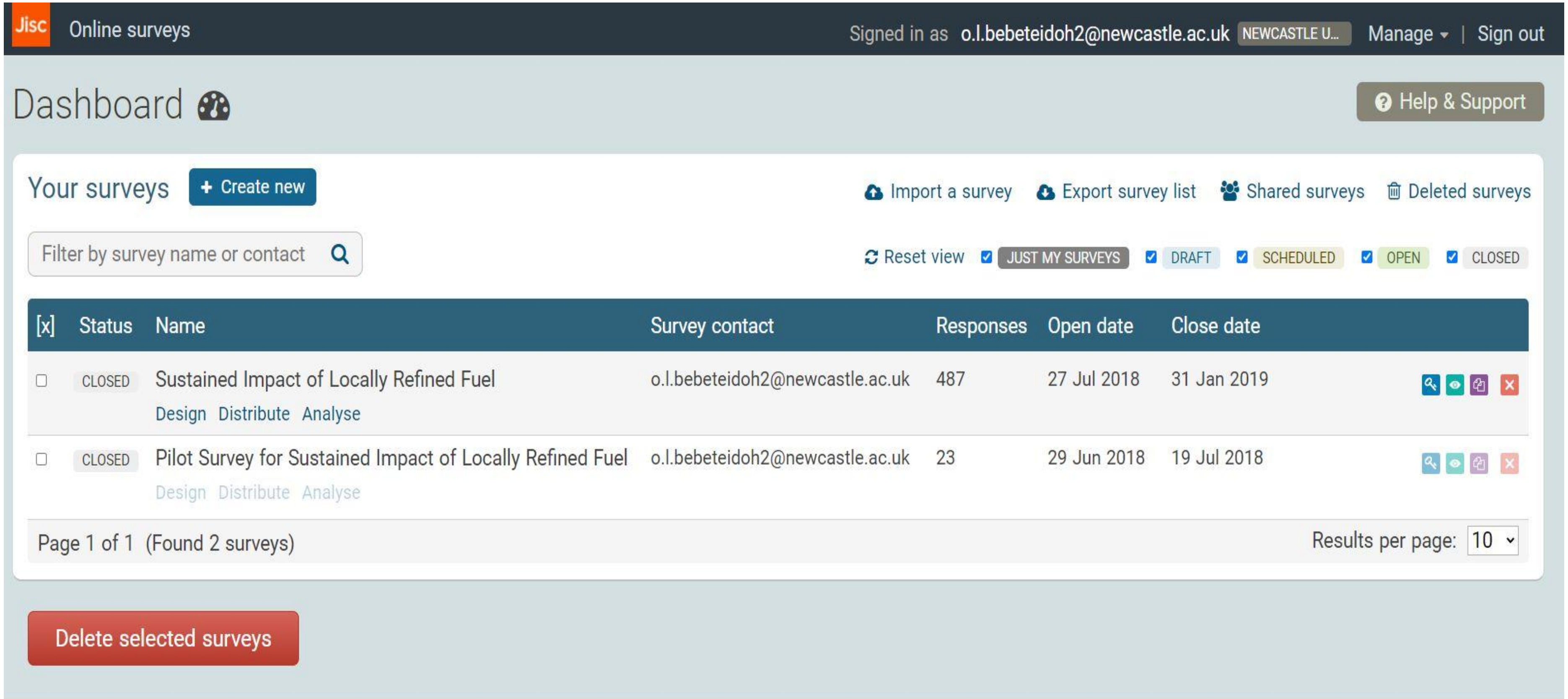
Zhang, Z., Ye, J., Tan, D., Feng, Z., Luo, J., Tan, Y., Huang, Y., 2021. The effects of Fe2O3 based DOC and SCR catalyst on the combustion and emission characteristics of a diesel engine fueled with biodiesel. Fuel 290, 120039. https://doi.org/10.1016/j.fuel.2020.120039

Zhang, Z.-F., Zhang, Xue, Zhang, Xian-ming, Liu, L.-Y., Li, Y.-F., Sun, W., (2020). Indoor occurrence and health risk of formaldehyde, toluene, xylene and total volatile organic compounds derived from an extensive monitoring campaign in Harbin, a megacity of China. Chemosphere 250, 126324. https://doi.org/10.1016/j.chemosphere.2020.126324

Zhao, J., Zhang, A., Héroux, P., Sun, Z., Liu, Y., 2021. Remediation of diesel fuel polluted soil using dielectric barrier discharge plasma. Chemical Engineering Journal 417, 128143. https://doi.org/10.1016/j.cej.2020.128143

Zuo, L., Wang, J., Mei, D., Dai, S., Adu-Mensah, D., 2022. Experimental investigation on combustion and (regulated and unregulated) emissions performance of a common-rail diesel engine using partially hydrogenated biodiesel-ethanol-diesel ternary blend. Renewable Energy 185, 1272–1283. https://doi.org/10.1016/j.renene.2021.12.085

Appendix A: Study questionnaire



Appendix B: Study questionnaire

Sustained Impact of Locally Refined Fuel

Page 1: About the study

Background Information:

This research intends to study the effect of the activities of the local refiners of crude oil in the Niger Delta Region of Nigeria on their host communities and the environment. The region is presently proliferated with local refining camps, where crude oil is refined locally and the products like diesel, kerosene and gasoline are sold in the open market.

This questionnaire is intended to collect data about the social impact of the activities of the local refiners on their host communities. Typically, the ideal respondent will be one of the host communities where the local refineries are located. Most of the questions apply to aquatic pollution, land pollution, air pollution and direct impact on the immediate community.

Who can contribute to this survey?

The survey is soliciting responses from members of the local refinery host communities such as:

- Community chiefs, residing in the host communities and involved in the day to day running of such communities
- Elders and seniors living in the host communities
- Members of the Community Development Committees (CDC) in such communities
- Fishermen, Farmers and traders
- Youths and students
- Commuters
- Visitors

Confidentiality:

1 / 11

Participation in this study is completely voluntary. You have the right to withdraw at any time. The research survey does not capture any confidential information about you, the respondent. Data provided by you will not be traced back to you either in presentations, reports or other forms of dissemination.

Data obtained from participants will only be reported in an aggregated format. This research is strictly for academic purposes. By completing this survey you fully agree to the stated terms

Questions about this research:

If you have any questions about this study, you can contact Oyinkepreye Lucky Bebeteidoh at:

Mobile: +2348037983039

Email ID: o.l.bebeteidoh2@newcastle.ac.uk

Page 2: About the researcher

Name: Oyinkepreye Lucky Bebeteidoh

Year of Study: Stage 2 PhD

Group: Marine, Offshore and Subsea Technology

School: Newcastle University, Newcastle Upon Tyne, NE1 7RU, United Kingdom

Phone Number United Kingdom: +447384040327

Phone Number Nigeria: +2348037983039

Email: o.l.bebeteidoh2@newcastle.ac.uk

Sponsors: Tertiary Education Trust Fund/Niger Delta University

Page 3: Questionnaire

1. What sex are you? * Required

- Male
- Female

2. What is your age bracket? * Required

- 18-25 years
- 26-33 years
- 34-41 years
- 42-55 years
- 56-65 years
- 66 years and above

3. What is your marital status?

- Married
- Single
- Divorced
- Widow/Widower

4. What is your occupation? * Required

- Fisherman/Fisherwomen
- Trader

- Farmer
- Youth/Student
- Business
- Government Employee
- Chief

5. Are you aware of the presence of a non-standard refinery in/around your community? * *Required*

- Yes
- No

6. How long has the non-standard refinery been located in your community? * *Required*

More info

- 0-5 years
- 6-10 years
- 11 years and above
- Not Applicable

7. Are you knowledgeable of the cost of environmental remediation? * *Required*

More info

- Yes
- No

5 / 11

8. The activities of the non-standard refiners has affected my community farm lands? * Required

- Strongly Disagree
- Disagree
- Somewhat Disagree
- Somewhat Agree
- Agree
- Strongly Agree

9. The activities of the non-standard refiners has affected the level of farm yields (harvest)? * Required

- Strongly Disagree
- Disagree
- Somewhat Disagree
- Somewhat Agree
- Agree
- Strongly Agree

10. The activities of the non-standard refiners has affected my community fishing areas? * Required

- Strongly Disagree
- Disagree
- Somewhat Disagree
- Somewhat Agree
- Agree
- Strongly Agree

6 / 11

11. The activities of the non-standard refiners has led to reduction of fishing yields? * Required

- Strongly Disagree
- Disagree
- Somewhat Disagree
- Somewhat Agree
- Agree
- Strongly Agree

12. The major source of water supply is usually polluted by crude oil waste from non-standard refineries? * Required

More info

- Strongly Disagree
- Disagree
- Somewhat Disagree
- Somewhat Agree
- Agree
- Strongly Agree

13. I am concerned about the method of disposal of refined waste by the non-standard crude oil refiners? * Required

- Strongly Disagree
- Disagree
- Somewhat Disagree
- Somewhat Agree
- Agree

- Strongly Agree

14. Do you buy the refined products from the non-standard refineries? * *Required*

More info

- Yes
- No

15. How much quantity of fuel do you buy every month of the non-standard refined products? * *Required*

- 5-10 Liters
- 10-50 Liters
- 50-100 Liters
- 100-500 Liters
- 500 Liters and above
- None

16. The refined products from non-standard refineries have damaged my machine/engine in recent times? * *Required*

- Strongly Disagree
- Disagree
- Somewhat Disagree
- Somewhat Agree
- Agree
- Strongly Agree

- Not applicable

17. The lower cost of the non-standard refined diesel fuel is worth the risk of damage to my engine (car/generator)? * *Required*

More info

- Strongly Disagree
- Disagree
- Somewhat Disagree
- Somewhat Agree
- Agree
- Strongly Agree
- Not applicable

18. I spend so much to maintain my engine (car/generator) as a result of my using non-standard diesel fuel? * *Required*

- Strongly Disagree
- Disagree
- Somewhat Disagree
- Somewhat Agree
- Agree
- Strongly Agree
- Not applicable

19. I experience engine (car/generator) stoppages any time, I use non-standard diesel fuel oil * *Required*

- Strongly Disagree
- Disagree
- Somewhat Disagree
- Somewhat Agree
- Agree
- Strongly Agree
- Not applicable

Page 4: Thank you for participating

Contact o.l.bebeteidoh2@newcastle.ac.uk if any queries

---

11 / 11

Appendix C: Diesel Fuel Oil

Diesel fuel is one of the most commonly used petroleum product in both industries and agriculture (Zhao et al., 2021). Diesel fuel is produced from crude oil by various refining processes, and it is used in compression ignition engines as a fuel (Beg et al., 2010). Diesel fuel oil is a mix of various hydrocarbon blends (Chen et al., 2020). Its composition is influenced by several factors, such as the crude oil's origin, the addition of fractions from the cracking process, operating variables of the refinery, and the insertion of additives to increase engine performance (Nespeca et al. 2018). Diesel fuel, kerosene, and jet fuel (aviation turbine fuel) belong to the petroleum product class commonly known as middle distillates (Speight, 2015). Table 2-4 illustrates the specification of seven different grades of diesel fuel oils appropriate for various types of diesel engines.

With the present attention given to renewable fuels in the transportation and power generation sector, diesel fuel is still significantly used in industries and transportation the world over which keeps its demand high (Abrar and Bhaskarwar, 2021). Diesel fuel is the most used fuel for transportation (Sadat 2014; Kadhim 2015) in industries as fuel for power generators (Ugwu et al. 2012), in household services, and agriculture (Oyedepo 2013).

Table C1-1 Various grades of distillate fuel oil (ASTM D975, 2020; Speight, 2015)

Grade	Description
No. 1-D S15	Ultra-low-sulphur (ULSD) light middle distillate fuel used in diesel engine applications that require higher volatility than No. 2-D S15 (maximum sulphur: 15 ppm)
No. 1-D S500	Low-sulphur light middle distillate fuel used in diesel engine applications that require higher volatility than No. 2-D S500 (maximum sulphur: 500 ppm).
No. 1-D S5000	Regular-sulphur light middle distillate fuel used in diesel engine applications that require higher volatility than No. 2-D S5000 with (maximum sulphur: 5000 ppm).
No. 2-D S15	Ultra-low-sulphur (ULSD) middle distillate fuel used for general-purpose diesel engine applications with varying speed and load (maximum sulphur: 15 ppm).
No. 2-D S500	Low-sulphur middle distillate fuel used for general-purpose diesel engine applications with varying speed and load (maximum sulphur: 500 ppm).
No. 2-D S5000	Low-sulphur middle distillate fuel used for general-purpose diesel engine applications with varying speed and load (maximum sulphur: 5000 ppm).
No. 4-D	Heavy distillate fuel, or a blend of distillate and residual oil, used for low- and medium-speed diesel engine applications involving primarily constant speed and load.

Diesel fuel oil is one of the major products of crude oil refining, only second to gasoline (Sidjabat 2013) and belongs to a group of light non-aqueous phase liquids (LNAPLs), which are not soluble in water and with a density that is also lower than water (Safarov et al. 2018). It is produced from the distillation of crude oil, with a boiling range of approximately 125-328 ^{o}C (Speight 2015). Also, Aleme and Barbeira (2012) reported that diesel is made up of hydrocarbon chains, particularly paraffin's (saturated hydrocarbons), olefins (unsaturated), and aromatic chains which contain from 10 to 19 carbon atoms and with a boiling point of approximately 180-370 ^{o}C. Figure 2-4 shows the fractions of petroleum products obtained from the refining of a barrel of crude oil in a refinery. Thus, in terms of boiling range and carbon number, diesel fuel occurs primarily in the kerosene range, which means the test methods applied to kerosene can also be applied to diesel fuel (Speight 2015).

Furthermore, Mancini et al. (2018) added that while the physiochemical parameters of a fuel divides it into different quality classes, the identification and characterization of its chemical composition is very crucial during the investigation and application of such fuel. A very important characteristic of diesel fuel is its ability to auto-ignite, a characteristic that is quantified by the fuel's cetane index or cetane number (Obodeh and Isaac 2011). Studies have shown that Nigeria's diesel fuel typically has a cetane number in the low 40s whereas European diesel fuel typically has a cetane number in the low 50s (Obodeh and Isaac, 2011). Diesel fuel also has three important cold weather parameters which define its operability, these are the lowest operating temperature in which an engine will operate, the cold filter plugging point, pour point and the temperature where crystals first appear, the cloud point (Sidjabat 2013).

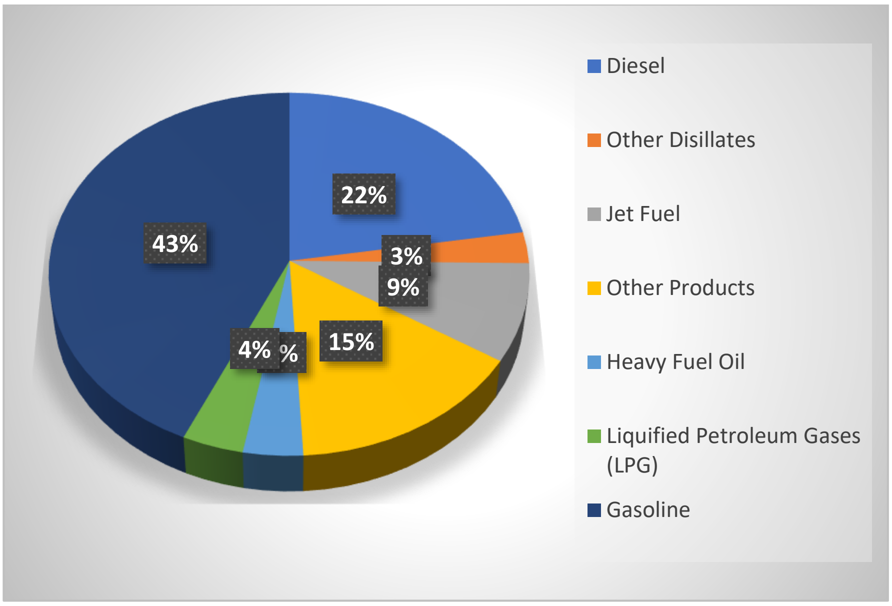


Figure C1-1 Petroleum products made from a barrel of crude oil (Energy.Gov 2011)

C.1 Diesel Fuel Physical and Chemical Properties

The properties of diesel fuel are key pointers to demonstrate the suitability of that particular fuel for usage in a marine diesel engine within approved fuel standards

(Yasin et al. 2017). The properties are strongly connected to engine performance (Wang et al., 2020). Zaharin et al. (2017) in their research added that fuel properties are one of the major factors used in determining the quality of fuel mixing and the combustion process. Likewise, Torres-Jimenez et al., (2011) reported that the fuel injection system of diesel engines depends on the fuel properties and the type of injection system. Poor diesel fuel properties could affect fuel atomization and emission (Devarajan et al., 2020). A fuel's suitability can be altered by contaminants introduced during processing or from other sources and the nature of the fuel components ultimately determines the fuel properties (Knothe, 2005). Calorific value, viscosity, cetane number, density, flash point, cloud point and pour point are properties used in measuring fuel standard and quality (Zaharin et al. 2017; Fingas, 2011). Table 2-5 shows some key properties of standard products commercially available in Nigeria.

Table C1-2 Key properties of standard diesel fuel and kerosene commercially available (Obodeh and Isaac 2011).

Property	**Unit**	**Diesel**	**Kerosene**
Chemical formula	-	$C_{12}H_{26}$	$C_{10}H_{22}$
Calorific value	kJ/kg	44500	45400
Self-ignition temperature	^{O}C	725	640
Final boiling point	^{O}C	369	249
Ignition delay period	s	0.002	0.0015
Flame propagation rate	cm/s	10.5	11.8
Flame temperature	^{O}C	1715	1782
Kinematic Viscosity at 39 ^{O}C	mm^2/s	2.7	2.2
Specific gravity at 15/4 ^{o}C	-	0.893	0.843
Colour	-	Red	Saybolt
Sulphur content by weight	%	0.16	0.04

C.1.1 Density

Density is one of the major fuel properties used in estimating the quantity of fuel injected by the injection systems to provide proper combustion (Sakthivel et al. 2018). Diesel oil density is important because it gives an indication of the energy per unit mass (specific gravity) and the delay between the injection and combustion of the fuel in the diesel engine (Ignition delay) (Atabani et al., 2013). It is an essential fuel property regarding equipment selection and engine performance (Torres-García et al., 2020). According to Kalligeros et al. (2003) density controls the quantity of fuel that is compressed and burned in the combustion chamber of the engine. The higher the quantity of fuel sprayed into the combustion chamber, the higher the output of partially oxidized emitted products.

Changes in fuel density affect its energy content as it gets into the engine at a given injector setting (Marketing, 2007), and any reduction in fuel density tends to reduce NO_x emissions in older models of engines that cannot compensate for this change. The reported densities for kerosene, diesel, and gasoline at 15^{O}C are in the ranges 0.79-0.80 kg/l, 0.835-0.855 kg/l and 0.74-0.75 kg/l (Garg et al., 2015).

C.1.2 Kinematic Viscosity

Kinematic viscosity is a vital parameter that affects the combustion in medium-speed diesel engines (Torres-García et al., 2020). It is an important characteristic of a fuel that signifies the ability of the fuel to flow, being resistant to the flow, and also plays a key role in spray penetration and spray atomization (Sakthivel et al., 2018). It is the thickness of the fuel oil and is determined by the amount of time taken for a specified quantity of oil to pass through an orifice of a specified size (Atabani et al., 2013). Higher viscosity fuels cause insufficient fuel atomization, which in turn results in reduced thermal efficiency and soot deposits. Also, diesel fuels with high viscosity develop problems in cold weather, because the viscosity of fuel increases with decreasing temperature (Martínez et al., 2014). On the other hand, reduced viscosity leads to finer fuel droplets which make it easier for the injector to pump fuel into the combustion chamber (Sakthivel et al., 2018). The viscosity of a fuel in the injection system of an engine ought to stay within a defined range by the manufacturer for good atomisation and hence engine operation (Torres-García et al., 2020).

C.1.3 Cetane Number

Cetane Number (CN) is used in indicating the behaviour of the fuel right after the fuel injection inside the cylinder of a Compression Ignition Engine (CIE), hence its ignition delay (Karonis et al., 2017). Li et al. (2005) while stressing the importance of the cetane number (CN) of fuel in their research, further stated that the CN influences the engine starting ability, its cylinder pressure, combustion noise, and emissions. A high cetane number allows for good starting ability, long engine life, and low noise. According to Sakthivel et al. (2018), the cetane number of a fuel directly influences the ignition delay period of an engine which is the time lag between the beginning of fuel injection into the engine cylinder and the point of first detectable increase in-cylinder pressure due to exothermic release in energy inside the mixture.

Higher Cetane Number shows the ability of the fuel to auto-ignite shortly after being injected into the engines combustion chamber, whereas a lower cetane number results in increased exhaust emissions from the engine, knocking and excessive deposits in the engine due to incomplete combustion (Sakthivel et al. 2018; Atabani et al. 2013). Similarly, Atabani et al. (2013) and Clothier (1993) added that the cetane number is based on two compounds which are heptamethylnonane with a CN of 15 and hexadecane with a CN of 100. Fuel cetane number does not have any effect on gaseous emissions but is just one of many parameters that change the combustion phasing; these changes in combustion phasing drive the subsequent changes in emissions (Ickes et al., 2009).

C.1.4 Pour Point (PP)

The pour point (PP) of a diesel fuel oil is the temperature at which the fuel can no longer be poured because of the formation of a gel (Joshi and Pegg, 2007; Torres-Jimenez et al., 2011). The PP is also used in the characterization of a fuel's cold flow operability as the pour point affects the utility of the fuel in cold climatic conditions (Alptekin and Canakci, 2009).

C.1.5 Flash Point

Sakthivel et al. (2018) describe flash point as the lowest temperature at which a volatile fuel ignites when exposed to a source of ignition. Although the flash point of diesel fuel does not directly affect the engine performance (Alptekin and Canakci, 2009), it does affect its storage classification, and its safe handling and transportation (Li et al., 2005; Torres-Jimenez et al., 2011) particularly in high-temperature environments (Santos et al., 2020). Diesel fuel oil with a low flash point means high fire safety (Iovleva et al., 2020). According to Agarwal and Das (2001) fuels with flash point over 66˚C are safe for use in compression ignition engines. The flash point is also used to characterise the fire hazard of diesel fuel, and a low flash point suggests the presence of extremely volatile materials in the diesel fuel that is a critical safety concern in handling and storage (Khan et al. 2016).

C.1.6 Water Content

The separation of water from diesel is a critical requirement for modern diesel engines (Yoshino et al., 2013). Water is nearly insoluble in diesel but could mix with diesel fuel because of humidity, condensation (Arouni et al., 2019), and during transportation from the point of refining to the fuel retail station (Tang et al., 2016). It can also find its way into diesel fuel during the refining, storage, or during usage in an engine (Yoshino et al., 2013). This entrained water could harm the engine such as through corrosion and rusting of pipes, or fouling resulting from microbial growth, which could all lead to damage to fuel filters and failure of fuel injection mechanisms (Narayan et al., 2018). The presence of water in the diesel fuel storage tank could cause damage to fuel injectors and nozzles (Yoshino et al., 2013). For this reason, the American Society of Testing and Materials (ASTM) diesel specification, D975-20, and the European Union specification, EN 590 limit maximum dissolved water content to 200 mg/kg, with zero tolerance for free water (Pangestu and Stanfel, 2009). Water in diesel fuel could be of three forms: free, dissolved, or emulsified dependent on the situation (Arouni et al., 2018). Ochoterena et al. (2010) reported that water is added to diesel fuel to increase the fuel density and cool the charge. Also, water in diesel fuel lowers the formation of nitrogen oxide inside the combustion chamber and restricts the onset of knock (Ochoterena et al., 2010).

Water could also find its way into diesel fuel by the process of intentional emulsification (Vellaiyan, 2020). In a study to investigate the effect of water emulsification on diesel engine performance, combustion characteristics, and exhaust emissions, Maawa et al. (2020) reported that there was an improvement in engine torque, a reduction in brake specific fuel consumption (BSFC), and a reduction in the NOx emissions. Abu-Zaid (2004) conducted a study to examine the effect of water emulsification on diesel engine performance and discovered that the addition of water in the form of an emulsion enhances combustion efficiency. In another study of water-in-diesel fuel emulsion in diesel engines, Ithnin et al., (2014) observed a reduction in nitrogen oxide (NO_X) and particulate matter but an increase in carbon monoxide (CO) and unburnt hydrocarbons (UHC). Also, Ithnin et al., (2015) in another study to investigate the effect of water-in-diesel originating from low-grade diesel fuel on diesel engine combustion, performance and emission characteristics concluded that water-in-diesel from low-grade diesel fuel is a suitable substitute fuelling method that could bring about greener exhaust emissions.

C.1.7 Calorific Value

An important property of a fuel, on which its efficiency is judged, is its calorific value (Khan et al., 2016). It is an essential property in fuel quality selection (Kaisan et al. 2020), and an important property in diesel fuel characterization (Ong et al. 2013). The calorific value is determined experimentally using an oxygen bomb calorimeter (Silitonga et al., 2013). The calorific value of a fuel is the amount of heat generated by the complete combustion of a given mass (Wan et al. 2020). It relies on the carbon molecules present in the fuel and also on the ratio of hydrogen and carbon to nitrogen and oxygen (Agarwal et al. 2020).

C.1.8 Distillation Range

An important property of ignitable liquids is the distillation boiling point range (Stauffer et al., 2008). Values obtained for the distillation range of diesel fuel are used to determine the calculated cetane index (CCI) (Ali et al. 1995). The distillation range of diesel fuel affects properties such as density, viscosity, and flash point

(Alptekin and Canakci, 2009). Its data provides valuable information on the combustion characteristics of diesel fuel (Leonard et al., 2020).

Appendix D: Diesel Engine Analysis

D.1 Engine analysis

The diesel engine as an internal combustion engine is faced with two major challenges: fuel quality and the increasing stringent emission regulations (Zhang et al. 2017). Diesel engines are used in the power generation industries, transportation (marine, automobile, and train), and agriculture because of their low specific fuel consumption and their tendency to produce lower emissions excluding oxides of nitrogen (NO_x) and particulate matter (PM) (Belkhode et al., 2021).

D.1.1 Brake Specific Fuel Consumption

The brake specific fuel consumption (BSFC) is best described as the quantity of fuel per unit of engine brake power generated (Yesilyurt and Aydin, 2020) and is expressed in g/kW-hr (Popa and Gheti, 2020). The BSFC exemplifies the efficiency of any engine and as such plays an important role in the selection criteria of a fuel's quality (Ramesh et al., 2019). It is highly dependent on the fuel properties (Ağbulut et al., 2021). It is directly reliant on the calorific value of the fuel (Rajak et al., 2020; Saravanan et al., 2020).

D.1.2 Brake Thermal Efficiency

The brake thermal efficiency can be described as the brake power (bp) of a diesel engine as a function of the thermal energy input obtained from fuel consumed in a unit time (Ramesh et al., 2019). It is essential for evaluating the fuels efficiency (Belkhode et al., 2021). BTE for unadulterated diesel fuel tends to increase with brake power (Prabhu and Venkata, 2020). Brake thermal efficiency shows the capacity of the internal combustion engine system to receive the fuel and provide a means of assessing how the energy in the fuel is efficiently converted to mechanical power (Sayin, 2010).

D.1.3 Cylinder Pressure

The measurement of engine cylinder pressure is important and generally used in laboratory and field applications to support diagnostic and monitoring applications (Antonopoulos et al., 2012; Payri et al., 2011). Diesel engine cylinder pressure measurement is believed to be a useful source of information at the time of engine development and calibration, as it offers significant data such as indicated mean effective pressure, pumping mean effective pressure, and peak pressure (Payri et al., 2011). Cylinder pressure analysis could be made use of in the determination of more complex applications, like noise control, emission control, heat transfer, air mass flow estimation, and in-line combustion detection (Payri et al., 2011). An engines cylinder pressure is dependent on the amount of fuel burned during the premixed phase and the fuel's ability to mix well with air, while the premixed phase is caused by the ignition delay period, and the mixture preparation during the ignition delay period (Shehata, 2013).

Cylinder pressure could also be affected by other factors. According to Kim et al. (2018) the addition of water to marine diesel oil (MDO) showed a rise in cylinder pressure and heat release rate compared to an engine run with marine diesel oil without water. A similar result was reported in a study carried out by Oh et al. (2019), the comparison of NO_x and smoke characteristics of water-in-oil emulsion and marine diesel oil in a 400-kw marine generator engine. Result revealed that as the water content is increased in the emulsion fuel the combustion pressure tends to increase. In their study to determine the effect of emulsified fuel on combustion in a four-stroke engine, Harbach and Agosta (1991), result revealed an increase in peak cylinder pressure for both water in diesel and hydrous ethanol/diesel fuel emulsion with maximum cylinder pressure increase for water in diesel at 27% water and 25.6% for hydrous ethanol/diesel. This is because of fuel atomisation and the improved mixing of air and fuel due to the micro-explosion and evaporation of the water contained in the emulsified marine diesel oil. High cylinder pressure could also be attributed to high levels of toluene. According to Ozer (2020) the addition of toluene to soyabean oil biodiesel, and diesel fuel oil results in shortened ignition delay; toluene reduces the flash, and ignition point of fuel. The addition of toluene is believed to start the burning in the first phase of the spray before the target point, possibly reducing the duration of the combustion (Şimşek and Çolak, 2019). Due to its very low boiling point, toluene is easily gasified, and mixed with the charged air at the end of compression, this could lead to a higher rate of combustion and higher cylinder pressure.

D.2 Emissions

The level of anthropogenic greenhouse gas (GHG) emissions in the environment is worsening the greenhouse effect, leading to human health risks and global warming (Harris et al., 2020). The reduction of GHG emissions has become an essential issue in the protection of the environment (Modak et al., 2018). According to Ahmed (2020) 83% of the world's energy supply is indirectly or directly fulfilled by the utilisation of fossil fuels. This has resulted in huge climate change coupled with environmental and health issues (Ahmed, 2020). The combustion of gasoline and diesel fuels for transport purposes is the second-largest source of CO_2 emission in the world (Geng et al., 2016). Also, Moreno- Gutiérrez, and Durán-Grados (2021) reported that the powering of land-based and maritime means of transport by the inefficient burning of diesel fuel oil, coal, and other fuels is a key contributor to climate change emissions and air pollution.

High amounts of sulphur oxide (SO_X), nitrogen oxide (NO_X), carbon monoxide (CO), particulate matter (PM) and greenhouse gases are produced during diesel fuel combustion (Lao et al. 2020). However, the severity of the emissions from diesel engine is dependent on the operating condition of the fuel and the engine used (Venkatesan et al. 2021).

D.2.1 NO_x Emissions

Nitrogen oxide (NO_x) is a key pollutant of diesel engine combustion (Jafarmadar, 2013) and is difficult to control (Emiroğlu and Sen, 2018). The formation of nitrogen oxide (NO_x) in diesel engine combustion is basically reliant on the oxygen level, the in-cylinder temperature, gas residence time taken for the reaction (Ning et al., 2020) and the spray characteristics (Maawa et al., 2020). NOx in diesel exhaust emissions is typically made up of >90% NO (Koebel et al., 2000).

Patil and Thipse (2015) and Rajak et al. (2020) describes nitrogen oxides as a group of compounds which represent a mixture of NO and NO_2. According to Gonca (2014) the formation of NO_x in internal combustion engine is greatly reliant on peak combustion. Cheung et al. (2008) reported that the concentration of nitrogen oxide increases as the engine load increases. N_2 and O_2 in the combustion chamber separate into their atomic states and take part in a series of reactions because of the high combustion (flame) temperature (Sayin, 2010). According to Saleh (2009) it is anticipated that during diesel engine combustion the fuel with the maximum in-cylinder temperature readings would have the highest NO_x. According to Zhang et al., (2021) oxide of nitrogen (NO_x) emission from diesel engine accounts for 70% of total vehicle emission, which makes vehicle emission a vital pollution source. The three key reactions producing NO_x during combustion of diesel fuel are described in the Zeldovich Mechanism (Sayin, 2010).

$$N_2 + O \rightarrow NO + N \qquad (1)$$

$$N + O_2 \rightarrow NO + O \qquad (2)$$

$$N + OH \rightarrow NO + H \qquad (3)$$

D.2.2 Carbon Monoxide

Carbon monoxide emission is toxic and must be controlled (Sayin and Canakci, 2009). It is an odourless and colourless gas produced in diesel engines as a result of incomplete burning of fuel (Ning et al., 2020). CO emission is highly poisonous to humans and has a density a little higher than atmospheric air (Yesilyurt, 2020). The major factors affecting the formation of carbon monoxide emissions during combustion are combustion chamber shape, injection pressure, fuel type, fuel atomization rate, timing, engine load and speed (Emiroğlu and Sen, 2018). Sayin and Canakci (2009) describe the formation of CO emission as an intermediate product of the combustion of hydrocarbon fuel which develops from a process of incomplete combustion. CO emission is significantly dependent on the air-fuel ratio relative to the stoichiometric ratio (Mani et al., 2009).

D.2.3 Carbon Dioxide

Carbon dioxide is a product of combustion that occurs naturally in the atmosphere (Sayin and Canakci, 2009). The carbon dioxide (CO_2) emission in diesel engines is connected to the fuel's complete combustion and is a product of fuels with carbon molecules in their structure (Yesilyurt, 2020; Maawa et al., 2020). The emission of CO_2 gases is dependent upon the atomization process, viscosity, engine speed, compression ratio and oxygen (Rajak et al., 2020).

D.2.4 Exhaust Gas Temperature

The exhaust gas temperature (EGT) is a major factor that influences the exhaust emissions in internal combustion engines (Yesilyurt and Aydin, 2020). It indicates the quantity of heat dissipated during the combustion process within the cylinders of internal combustion engines (Venu et al., 2020). However, the exhaust gas temperature is reduced because of several properties like viscosity, density, calorific value and cetane number (Rajak et al., 2020).