Journal of Science and Technology, Special Issue Vol. 1 No 1 (2024), pp 1 - 14

https://dx.doi.org/10.4314/just.v1i1.1s

# EVALUATING THE HEALTH AND ENVIRONMENTAL CONSEQUENCES OF SULPHUR-RELATED DIESEL EMISSIONS

**Kwao–Boateng, E.[1]*, Ankudey, E. G[1], Darkwah, L.[1], Danquah, K. O.[2], Kontoh, D. B.[3]**

[1] *Department of Chemical Engineering, College of Engineering, KNUST, Kumasi – Ghana*
[2] *Department of Clinical Pathology, Noguchi Memorial Institute for Medical Research, University of Ghana, Legon*
[3] *Kumasi Centre for Collaborative Research in Tropical Medicine, KNUST-Kumasi, Ghana*

***Corresponding: Email: ebosomtwi11@gmail.com**

## ABSTRACT

*Sulphur content is one of the most important fuel parameters affecting exhaust emissions from vehicles. Sulphur is a direct pollutant that can combine with other atmospheric elements to form compounds that contribute to global warming; hence minimising its quantity in fuels is essential. Standards have been set globally to regulate the sulphur content of diesel fuels. This research undertakes a comparative analysis of the sulphur content in fuel samples, randomly collected from five different fuel station brands. The sulphur content of diesel was analysed with sulphur analyser Hitachi LAB X-5000 following the ASTM D 4294-16 test method which is deemed simple. In the Kumasi Metropolis, the mean sulphur concentration in diesel was considerably elevated (ranging from 60 – 258 parts per million (ppm)) in comparison to the global standard of 50 ppm. From the analysis, the sulphur levels were in the order: Brand A< Brand C < Brand D < Brand E < Brand B. An assessment of the impact of sulphur emissions (from cradle to gate) on health, the ecosystem, and climate change was done using SimaPro software (v9.4.0.2). The results revealed the detrimental effects of the emissions, particularly when using fuels sourced from Brand B. Therefore, it is essential to enforce measures that ensure the imported and consumed diesel in the metropolis aligns with the stipulated regulations. This will mitigate potential health risks and environmental damage that may ensue from escalated sulphur emissions. Random checks on diesel quality at retail outlets are recommended to ensure compliance with set regulations.*

**Keywords:** Sulphur content, diesel fuel, fuel quality, crude oil, potential impact assessment

## INTRODUCTION

Abundant and cost-effective natural liquid fuels serve as the fundamental building blocks for modern industrial economies. These economies exhibit a significant dependence on generous provisions of affordable natural fuels, with the preeminent source being crude oil and its by-products. (Hyne, 2001; Kumar *et al*., 2011).

The transportation sector exhibits a substantial reliance on petroleum, accounting for over one-third of the worldwide primary energy supply and exceeding 95% of the energy requisites for transportation. Despite recent advancements in the scientific community regarding sustainable alternatives to petroleum, the transportation sector encounters considerable limitations about the feasibility of substitution alternatives (Miller and Sorrell, 2013) Moreover, the availability of light crude oil reserves, characteristically possessing low sulphur content, has markedly diminished owing to their extensive exploitation and preference, resulting in progressive depletion (Kilbane and Le Borgne, 2004; Le Borgne and Quintero, 2003; Shafi and Hutchings, 2000; Sousa *et al*., 2020). The largest reserves, primarily located in the Middle East, South America, and the Gulf of Mexico, consist of sour oil, which is characteristic of heavy crude oil (Kilbane and Le Borgne, 2004; Babalola and Susu, 2019; Sousa *et al.*, 2020). Kumar *et al* (2021) reiterated the negative impact of vehicular emissions on the health and environment and emphasised the need to reduce vehicular emissions despite the growing population.

Diesel is ubiquitously employed as a fundamental energy source across various industrial sectors, including production plants, transportation, and power generation. Nonetheless, the combustion of diesel results in emissions encompassing deleterious compounds, including particulate matter and sulphur oxides, thereby contributing to environmental pollution (Perera, 2018). During the combustion process, the combination of sulphur with oxygen leads to the formation of sulphur oxides (SOx), which have detrimental effects on air quality and pose risks to both the environment and human health (El Morabet, 2019; Thurston, 2016). Sulphur emissions are recognised as a significant contributor to a wide range of health issues, with respiratory illnesses being the most prevalent among them (Gokhale and Khare, 2004; Kelly and Fussell, 2015). The presence of sulphur in vehicular fuels also causes an increase in the release of other environmentally harmful compounds (Jain *et al*., 2015). High sulphur content affects the aggregate morphology and nanostructure of the diesel particulate matter (Tan and Wang, 2018). According to the authors, sulphur presence causes the particulate matter to have very small particle sizes, capable of penetrating the lungs and posing a health threat. Also, the sulphur oxides formed during the combustion of diesel fuels with high sulphur content reacts with the atmospheric water leading to the formation of acid rain which has been known to have a ruinous effect on ecological systems (Singh and Agrawal, 2008; Bhargava and Bhargava, 2013; Burns *et al*., 2016).

With the growing global population, there is a high demand for fuel consequently causing a significant increase in the emissions of particulate matter and sulphur oxides emissions and hence a deterioration of the ecosystem. This increase in emissions contributes to the degradation of the ecosystem and raises the likelihood of human exposure, leading to severe health conditions including respiratory tract diseases, heart diseases, and skin cancer. Therefore, it is imperative to prioritise the maintenance of high fuel quality to address these concerns (Manisalidis *et al*., 2020; Perera, 2018; World Health Organisation, 2021)The desire is to limit the sulphur content of fuels to 50 ppm in the West African sub-regional countries to fall in line with regulations for environmental protection (ECOWAS Commission, 2022). Ayetor *et al.* (2021), reported that no African country required vehicles to pass annual in-service emission test and only 25% of the vehicles they sampled passed emission tests in Ghana. This indicates that if fuel quality monitoring is not taken very seriously, then there would be a lot of emissions exposing people and the environment to harm. Peng *et al* (2020) also highlighted the negative effect of diesel emissions on health and environment and in their research, recommended the replacement of diesel with natural gas in marine vessel. Kwao-Boateng *et al* (2024) also outlined some key diesel fuel quality parameters in the research area which needed a critical relook and paramount among these parameters was sulphur content.

This research assesses the sulphur content of diesel fuel samples taken from selected retail outlets to ascertain the sulphur levels and evaluates the impact of the sulphur emissions on the health of inhabitants in the research area, Kumasi (Ghana- West Africa), the ecosystem as well as climate change. The Life Cycle Assessment of the diesel fuel from the crude oil refining to the point of combustion is performed using SimaPro (v9.4.0.2) software.

# MATERIALS AND METHODS

## Materials

The equipment used in this study were obtained from the Process Development Laboratory of the Department of Chemical Engineering at Kwame Nkrumah University of Science and Technology (KNUST) and the Quality Control Laboratory of Ghana Standards Authority. All chemicals used were of analytical grade and obtained from Ernest Chemist, Ghana and Sigma-Aldrich Solutions, Germany.

## Method

### Sampling

The fuel retail outlets in the research area were grouped under brand names which were coded as A, B, C, D, and E (which is a mixed brand). 1 Litre each of diesel fuels were taken at each sampling station. New HDPE bottles were used for the sampling. The bottles were first rinsed with a portion of the diesel fuel to be sampled and disposed of into the collection bottle that accompanied the sampling team. After rinsing the bottles, the bottles were filled with the respective samples for analysis. Subsequently, the bottles were appropriately labelled with details such as the name of the station, location, date, and time of sampling. The samples were then transported to the laboratory and stored under normal atmospheric conditions.

### Sulphur Analysis

The sulphur analyser Hitachi LAB X-5000 was used for the measurement following the ASTM D 4294-16 as the test method. The measurement procedure was broken down into three, the safety window preparation, the sample cup preparation and the measurement and disposal as outlined by the analyser manufacturer.

### Safety window preparation

The safety window comprised two components: the inner part and the outer part. The inner part featured a smooth, bevelled edge, which was positioned facing upwards on a clean, flat surface. Similarly, the outer part, marked internally, was also placed with the mark facing upwards adjacent to the inner part. The designated film was delicately pulled, and a portion was torn while holding the film at the edge to prevent any contamination. Subsequently, the film piece was placed over the inner part of the safety window, and the outer part of the safety window was carefully slid over the inner part, ensuring no contact with the film. The safety window assembly tool was utilised to fully insert the outer part into position. It was ensured that the film remained undamaged, free from contaminants, and devoid of any wrinkles.

**Sample cup preparation**

The O-ring of the sample cup was greased with high vacuum grease. The sample cup inner with its 'lips' was positioned at the bottom within the preparation ring. A layer of film was placed over the preparation ring. With the O-ring facing upwards, the sample cup's outer part was carefully stretched over the sample cup's inner section until it securely snapped into position. The Lab-X cup was then filled with the diesel sample, ensuring it reached the designated mark. To minimise evaporation and prevent any spills, a sample cup lid was utilised to cover the sample cup.

**Sample measurement and disposal**

The prepared safety window served as the platform for placing the sample in the analysis port, where the measurement was conducted. The results were presented on the screen and provided in printout form. Additionally, the results were also exported to a USB drive.

Following each measurement, the inner part, lid, and film of the sample cup were appropriately disposed of. This process of steps 2 and 3 was repeated for every diesel sample taken.

### Potential Impact Assessment

The SimaPro software (v9.4.0.2) was utilised to analyse the average sulphur content of each Brand. The objective was to assess the influence of diesel quality on human health, the ecosystem, and climate change. Specifically, the analysis focused on predicting the emissions associated with crude oil refinery to obtain the diesels with similar sulphur content as those obtained from retail outlets (cradle to gate). Simulation was employed to determine the emissions released into the environment during the production of diesel fuel with such quality. The environmental impact upon combustion can be inferred by examining the outcomes of producing these diesel fuels.

## RESULTS AND DISCUSSION

### Analysis of sulphur content

The average sulphur content for each of the brands is compared with the Ghana Standard Authority's standard (50 ppm maximum limit) as shown in Figure 1:

The data presented in Figure 1 reveals that all brands exceed the GSA standard of 50 ppm for sulphur levels. It is important to note that more than 90 percent of petroleum products used in Ghana are imported due to challenges faced in the local refining process. Various agencies are responsible for ensuring the quality of petroleum products entering Ghana through its borders. However, there have been multiple reports of illegal entry and unregulated fuels in the market, indicating fuel smuggling across the borders. Many of these fuels are found to be adulterated, as reported by the Chamber of Petroleum Consumers (2019), Gati (2022), and the National Petroleum Authority (2021).

The high sulphur content in purchased diesel fuels could be attributed to several factors. Firstly, oil marketing companies (OMCs) or their retail outlets may be adding sulphur-containing additives to the fuels without the knowledge or authorisation of the parent company (Boadu, 2019).

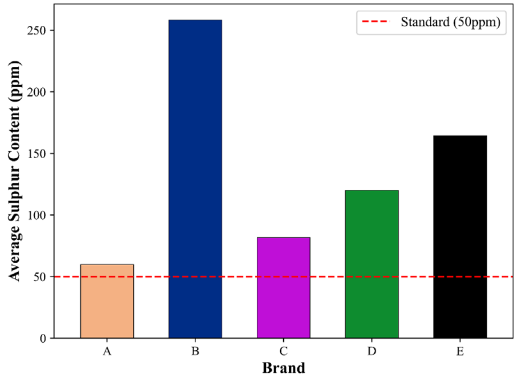


**Figure 1. Average sulphur levels (ppm) for fuel brands A to E**

Secondly, the contamination of underground storage tanks where the fuels are stored before being dispensed at petrol stations may contribute to the elevated sulphur content.

Regarding the same oil marketing companies, it is expected that stations operating under the same franchise would provide similar fuel quality across different stations. This research also aimed to compare the sulphur levels of diesel fuels within the same brand name. The graphs below depict the sulphur levels of these diesel fuels for each brand. A total of 75 retail outlets were included in the research area for this examination.

In Figure 2, a comparison is presented for 17 retail outlets belonging to Brand A. Out of these, twelve outlets were found to dispense diesel fuels that met the sulphur level requirement of 50 ppm, resulting in a compliance rate of approximately 70.6 percent. Similar comparisons were conducted for three other brands (Brands B, C and D).

In Figure 3, the results reveal that eight retail outlets under a specific brand demonstrated a compliance rate of 50 percent, while the remaining 50 percent did not meet the required sulphur levels. This finding raises concerns regarding the fuel quality of this particular brand.

The retail outlets may either have a peculiar problem that needs their managers to investigate, or the regulator needs to investigate the cause of such high sulphur levels.

Figure 4, on the other hand, presents a more favorable scenario in terms of sulphur compliance. Out of the samples taken from eleven retail outlets of Brand C (as shown in Figure 4), only one out of the eleven exceeded the 50-ppm sulphur threshold, accounting for 9% non-compliance. This particular brand demonstrates a strong performance in maintaining low sulphur content in their diesel fuels. The one outlier outlet may have specific challenges that require further investigation. It is possible that there were issues during the sampling or analysis process that resulted in the higher sulphur reading.

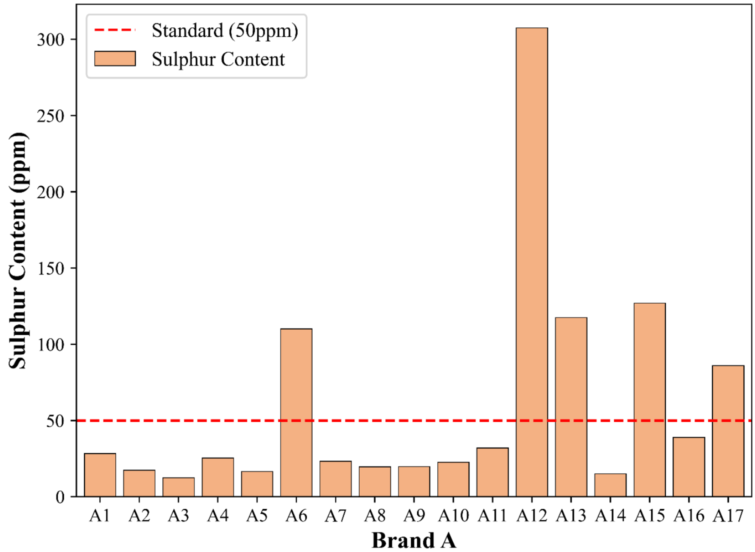


**Figure 2. Sulphur content of diesel samples from retail outlets under Brand A**

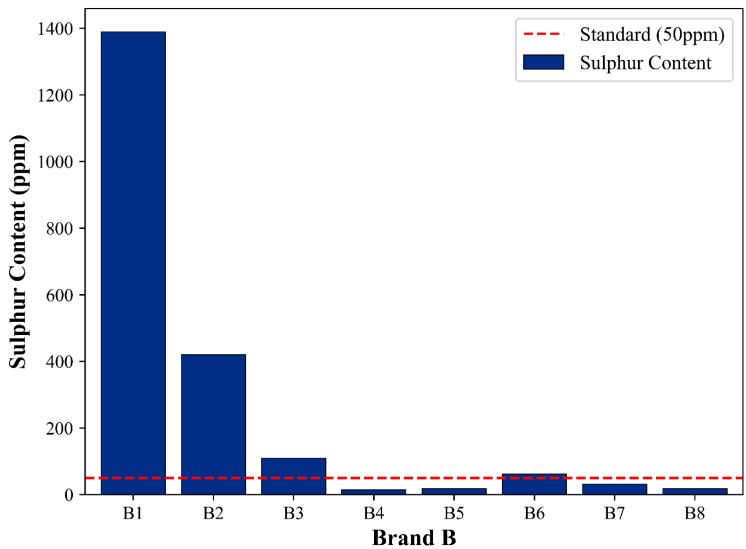


**Figure 3. Sulphur content of diesel samples from retail outlets under Brand B.**

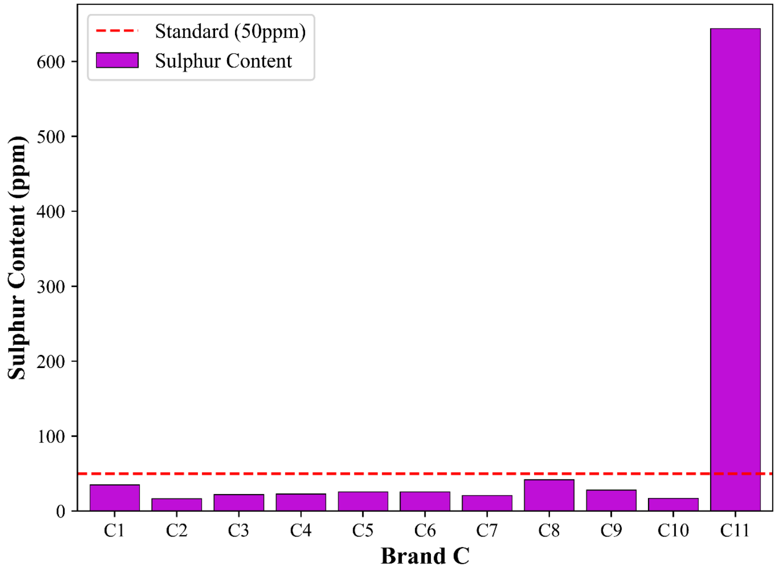


**Figure 4. Sulphur content of diesel samples from retail outlets under Brand C**

Another potential explanation could be the presence of unauthorised activities carried out by attendants or outlet managers, such as blending cheaper high sulphur diesel fuels with the fuel stored in tanks, which would compromise the overall sulphur content.

From the results in Figure 5, eleven out of the sixteen outlets had sulphur content up to the 50 ppm threshold.

Based on the findings presented in Figure 5 above, it is important to monitor the diesel sulphur content from the five outlets that had significantly higher sulphur levels than the permissible limit.

A total number of twenty-three (23) retail outlets under the mixed brand (Brand E) showed a relatively good trend since only seven (7) out of them had sulphur levels higher than the allowed 50 ppm threshold. The compliance level is approximately 70%. The other outlets needed a bit more monitoring to ascertain the main causes of these high sulphur levels.

The differences in the fuel quality can be attributed to the importation of fuels from different areas (countries) as well as the regulatory changes that may be done for example the waiver for local refineries to produce up to 1500 ppm sulphur level of fuels by NPA.

## Potential environmental impacts

To assess the potential environmental effects of producing 1 kg of diesel from crude oil, an environmental impact assessment was conducted. This analysis utilised SimaPro (v9.4.0.2) software, a commonly used tool for life cycle assessment that quantifies the environmental impacts of a process. Specifically, the study focused on the cradle-to-gate impacts of delivering 1 kg of average diesel from crude oil.

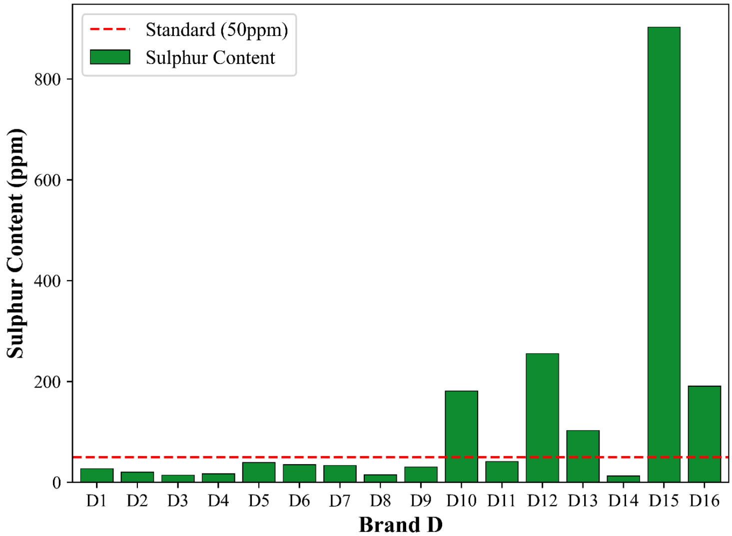


**Figure 5. Sulphur content of diesel samples from retail outlets under Brand D**

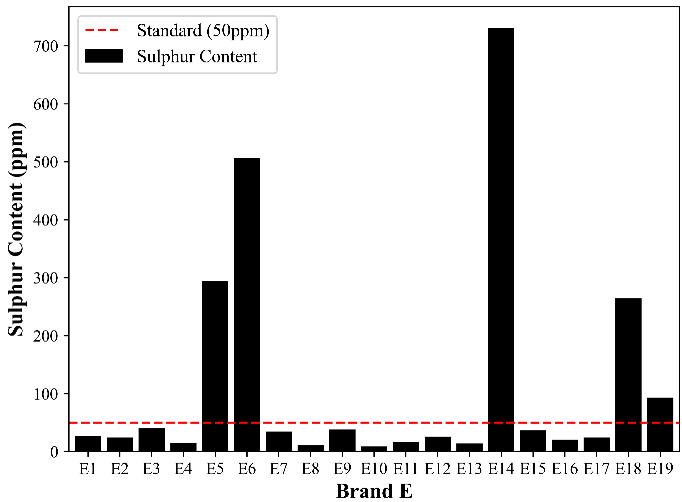


**Figure 6. Sulphur content of diesel samples from retail outlets under Brand E**

The assessment considered various emissions components, including carbon dioxide ($CO_2$), carbon monoxide (CO), methane ($CH_4$), non-methane volatile organic compounds (NMVOCs), sulphur oxides (SOx), and nitrogen oxides (NOx).

Table I provides an overview of the emissions associated with this process for well-known air emission components.

**Table I. Emissions associated with cradle-to-gate 1 kg of average diesel (~50 ppm sulphur content)**

| Component | Value (kg emission/kg diesel) |
|---|---|
| $CO_2$ | 4.88E-01 |
| CO | 9.10E-04 |
| $CH_4$ | 1.58E-03 |
| NMVOCs | 9.22E-04 |
| SOx | 3.91E-03 |
| NOx | 1.74E-03 |
| **Total** | **4.97E-01** |

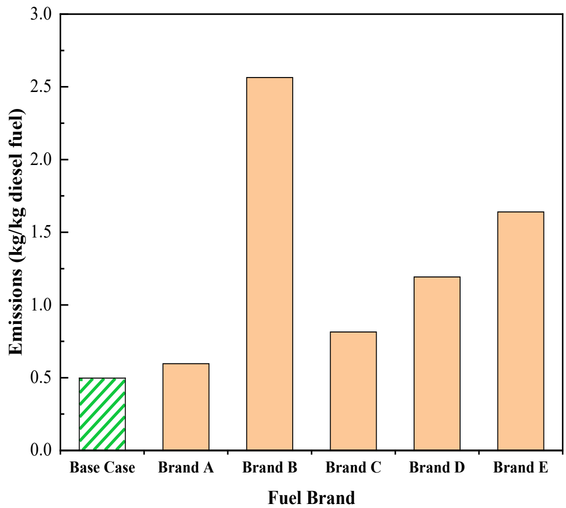


**Figure 7. Potential emissions associated with delivering 1 kg of diesel fuel to consumers for each fuel brand. (Base case in green stripes pattern)**

According to the data presented in Table I, carbon dioxide ($CO_2$) emissions make up a significant portion of the total emissions associated with delivering 1 kg of diesel to consumers, accounting for 98.18% of the overall emissions. Using Table 1 as a reference for analysis, a comparative assessment was conducted for each brand of diesel fuel. It was assumed that the emissions scale linearly with the sulphur content.

Figure 7 illustrates the results, indicating that Brand B exhibits the highest emissions with a potential percentage increase of 416% compared to the base case. Conversely, Brand A demonstrates the lowest emissions with a percentage increase of only 20%, primarily due to its low sulphur content.

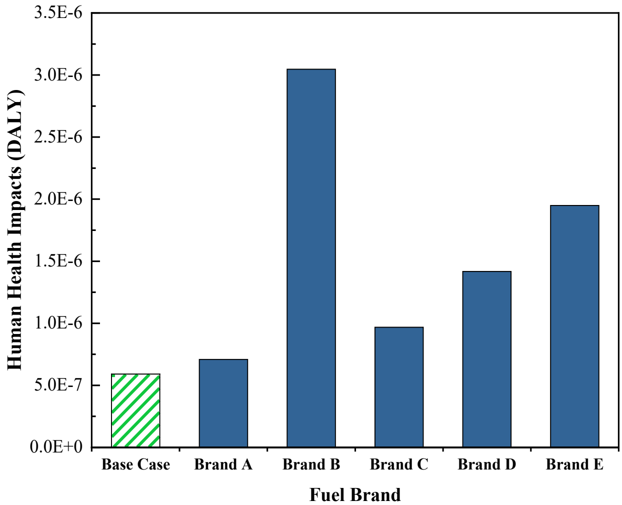


**Figure 8. Human health impacts of 1 kg of diesel fuel for the different fuel brands measured in Disability-Adjusted Life Years (DALY). [Base case in "striped" pattern]**

A comprehensive impact assessment was conducted to evaluate the long-term consequences of emissions on human health, ecosystem quality, and climate change. By conducting damage or long-term assessments, it becomes possible to consider the varying potential impacts of the different emissions. For instance, 1 kg of methane gas has a 24-times higher impact on heat trapping and atmospheric temperature increase compared to 1 kg of carbon dioxide ($CO_2$). Consequently, damage-oriented assessments enable the assessment of relative impacts of emissions. Figure 8 illustrates the impact on human health, measured in Disability-Adjusted Life Years (DALY), which represents the years of healthy life lost due to disability or premature death resulting from exposure to these emissions (Jolliet *et al*., 2002).

Lower DALY values indicate a lesser impact of the process or product on human health. Fuel Brand B exhibits a higher impact on human health, primarily attributed to its higher sulphur content. The same trend is observed for the impact on ecosystem quality and climate change, as depicted in Figure 9. Ecosystem quality quantifies the potential loss of species per square meter within a year due to the emissions.

Sulphur-related emissions have the tendency of causing acid rains with the effect of acidification of aquatic systems, increase in soil acidity, and damage to vegetation (Ramalingam and Fuad, 2017). The presence of sulphur also leads to corrosion and has the potential to affect the performance of advanced emission control technologies installed in vehicles (Zhang *et al*., 2010).

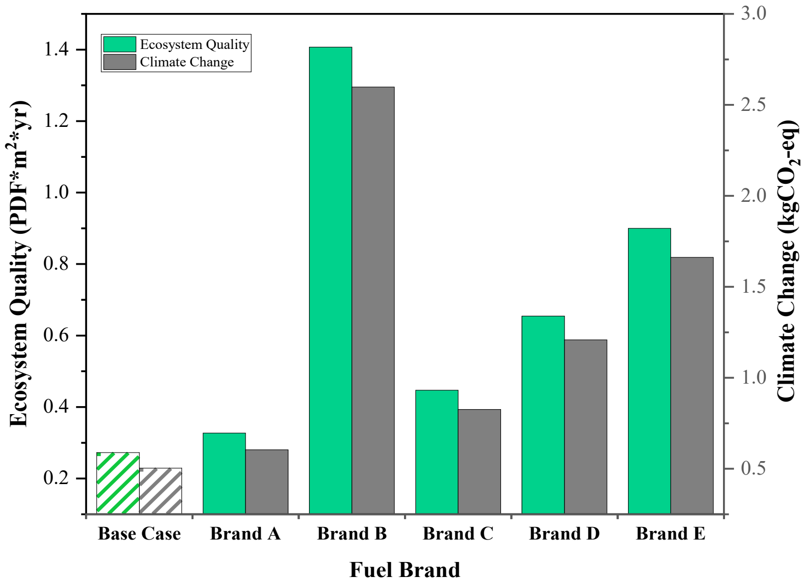


**Figure 9. Ecosystem and Climate Change impacts for the various fuel brands for 1 kg of diesel. Ecosystem quality, measured in Potential Disappeared Fraction (PDF) species found within a squared meter area in a year. Climate Change in kilogram of $CO_2$ equivalents [Base case in "striped" pattern].**

## CONCLUSION AND RECOMMENDATION

### Conclusion

Generally, sulphur when present in small quantities helps with lubrication within the engine. However, high average sulphur levels obtained from the study have shown negative effects on health, ecosystem and climate change as predicted by the employed SimaPro software. Approximately 13% (10 outlets) dispensed up to 15 ppm sulphur levels, 27% dispensed higher than 50 ppm and the rest between 15 and 50 ppm. Different outlets under the same brand name are observed not to have same quality which is of great concern and hence close monitoring of this companies to ensure compliance to their quality standards would be ideal.

### Recommendation

It is recommended to implement adequate measures to ensure compliance with the set regulations for the diesel fuels used within the metropolis. This implementation will help prevent any health and environmental implications resulting from high sulphur pollutants, as indicated by the potential impact assessment. The relevant authority should also continue its practice of conducting random assessments of fuel quality to ensure strict compliance and take necessary sanctions against companies found to be violating the regulations. The government should assist the various local refineries to ensure the supply of low sulphur fuels across the country.

## ACKNOWLEDGMENT

The following are being acknowledged for their immense support during the research work: the management of KNUST Engineering Education Project (KEEP), the management of West Coast Gas Ghana (WCGG) especially Mr. Emmanuel Amonoo Johnson, Mr. Courage Dey, MD of Elsco Company Limited, Mr. Derrick Kontoh Boateng, Dr. Mizpah A. D. Rockson, Adjei Domfeh, Emmanuel Aboagye Apau, Anthony Nana Prempeh Agyemang, Michael Kwadwo Fokuo, James Nana Gyamfi and Abena Owusuwaa Ansah for their immense support during all the research.

## REFERENCE

Ayetor, G.K., Mbonigaba, I., Ampofo, J. and Sunnu, A., (2021). Investigating the state of road vehicle emissions in Africa: A case study of Ghana and Rwanda. *Transportation Research Interdisciplinary Perspectives*,*11*, p.100409.

Babalola, F. U., and Susu, A. A. (2019). Pre-Treatment of Heavy Crude Oils for Refining. In *Processing of Heavy Crude Oils - Challenges and Opportunities (pp. 1–18)*. https://doi.org/10.5772/intechopen.89486

Bhargava, S., and Bhargava, S. (2013). Ecological consequences of The Acid rain. *IOSR Journal of Applied Chemistry 5, 19–24*. https://doi.org/10.9790/5736-0541924

Boadu, K.O. (2019). Effects of Adulteration on Diesel Oil with Kerosene Fuel in Ghana. *Journal of Applied Sciences and Environmental Management 23, 1195*. https://doi.org/10.4314/jasem.v23i7.1

Burns, D.A., Aherne, J., Gay, D.A., Lehmann, C.M.B. (2016). Acid rain and its environmental effects: Recent scientific advances. *Atmos Environ 146, 1–4*. https://doi.org/10.1016/j.atmosenv.2016.10.019

Chamber of Petroleum Consumers, 2019. COPEC alleges presence of adulterated diesel on market [WWW Document]. GhanaWeb. URL https://www.ghanaweb.com/GhanaHomePage/business/COPEC-alleges-presence-of-adulterated-diesel-on-market-803820 (accessed 11.30.22).

ECOWAS commission. (2022). Presentation on the status of implementation of ECOWAS directive on harmonized specifications for automotive fuels (gasoline and diesel). November.

El Morabet, R. (2019). Effects of outdoor air pollution on human health. In *Encyclopedia of Environmental Health* (2nd ed.). Elsevier Inc. https://doi.org/10.1016/B978-0-12-409548-9.11509-X

Gati, K., (2022). Ghana: NPA Impounds Smuggled Petroleum Products [WWW Document]. Ghanaian Times. URL https://allafrica.com/stories/202208250127.html (accessed 1.1.23).

Gokhale, S., and Khare, M. (2004). A review of deterministic, stochastic and hybrid vehicular exhaust emission models. *International Journal of Transport Management*, *2*(2), 59–74. https://doi.org/10.1016/j.ijtm.2004.09.001

Hyne, N. J. (2001). Nontechnical Guide to Petroleum Geology, Exploration, Drilling and Production. (2nd ed). Pennwell Corp.

Jain, R. K., Cui, Z., and Domen, J. K. (2015). Environmental Impact of Mining and Mineral Processing: Management, Monitoring, and Auditing Strategies. In *Environmental Impact of Mining and Mineral Processing: Management, Monitoring, and Auditing Strategies* (2005th ed.). Oxford, UK : Butterworth-Heinemann, [2016]. https://doi.org/10.1016/C2014-0-05174-X

Jolliet, O. ;, Margni, M., Charles , Raphael; Humbert, S. ;, Payet, J., Rebitzer, G., and

Rosenbaum, R. (2002). IMPACT 2002+: A New Life Cycle Impact Assessment Methodology. *Industrial Ecology and Life Cycle Systems Group*. https://doi.org/https://doi.org/10.1007/BF02978505

Kelly, F. J., and Fussell, J. C. (2015). Air pollution and public health: emerging hazards and improved understanding of risk. *Environmental Geochemistry and Health, 37(4), 631–649*. https://doi.org/10.1007/s10653-015-9720-1

Kilbane, J. J. I., and Le Borgne, S. (2004). Petroleum biorefining: the selective removal of sulfur, nitrogen, and metals. In R. ed. Vazquez-Duhalt, R. and QuinteroRamirez (Ed.), *Petroleum Biotechnology – Studies in Surface Science and Catalysis, (Vol. 151, pp. 29–66)*. Elsevier.

Kumar, A., Munjal, A. and Sawhney, R., (2011). Crude oil PAH constitution, degradation pathway and associated bioremediation microflora: an overview. International Journal of Environmental Sciences, 1(7), pp.1420-1439.

Kumar, P.G., Lekhana, P., Tejaswi, M. and Chandrakala, S.J.M.T.P. (2021). Effects of vehicular emissions on the urban environment-a state of the art. *Materials Today: Proceedings*, 45, pp.6314-6320.

Kwao-Boateng, E., Ankudey, E.G., Darkwah, L. and Danquah, K.O. (2024). Assessment of diesel fuel quality. *Heliyon*, *10*(2).

Le Borgne, S., and Quintero, R. (2003). Biotechnological processes for the refining of petroleum. In *Fuel Process Technology* (Vol. 81, Issue 2). Elsevier. https://doi.org/https://doi.org/10.1016/S0378-3820(03)00007-9.

Manisalidis, I., Stavropoulou, E., Stavropoulos, A., and Bezirtzoglou, E. (2020). Environmental and Health Impacts of Air Pollution: A Review. In *Frontiers in Public Health* (Vol. 8). https://doi.org/10.3389/fpubh.2020.00014

Miller, R., and Sorrell, S. (2013). Introduction: The future of oil supply. *Philosophical Transactions A: Mathematical, Physical and Engineering Sciences, 372(2006), 1–28*.

National Petroleum Authority (2021). NPA secures police support to stop illegal fuel trading in Upper East Region [WWW Document]. National Petroleum Authority. URL http://www.npa.gov.gh/latest-news/npa-secures-police-support-to-stop-illegal-fuel-trading-in-upper-east-region (accessed 12.30.22).

Peng, W., Yang, J., Corbin, J., Trivanovic, U., Lobo, P., Kirchen, P., Rogak, S., Gagné, S., Miller, J.W. and Cocker, D. (2020). Comprehensive analysis of the air quality impacts of switching a marine vessel from diesel fuel to natural gas. *Environmental Pollution*, 266, p.115404.

Perera, F. (2018). Pollution from fossil-fuel combustion is the leading environmental threat to global pediatric health and equity: Solutions exist. *International Journal of Environmental Research and Public Health*, *15*(1). https://doi.org/10.3390/ijerph15010016

Ramalingam, M., and Fuad, A.A. (2017). Short Communication: Sulphur Levels and Fuel Quality in Peninsular Malaysia. *ASEAN Journal on Science and Technology for Development 32, 52.* https://doi.org/10.29037/ajstd.11

Shafi, R., and Hutchings, G. J. (2000). Hydrodesulfurization of hindered dibenzothiophenes: An overview. (pp. 423–442).

Singh, A., and Agrawal, M. (2008). Acid rain and its ecological consequences. J Environ Biol 29, 15–24. https://doi.org/10.1016/S0140-6736(11)60180-3

Sousa, J. P. M., Ferreira, P., Neves, R. P. P., Ramos, M. J., and Fernandes, P. A. (2020). The bacterial 4S pathway-an economical alternative for crude oil desulphurization that r educes $CO_2$ emissions. *Green Chemistry, 22(22), 7604–7621*. https://doi.org/10.1039/d0gc02055a

Tan, P. Q., and Wang, D. Y. (2018). Effects of sulfur content and ash content in lubricating oil on the aggregate morphology and nanostructure of diesel particulate matter. *Energy and Fuels, 32(1), 713–724*. https://doi.org/10.1021/acs.energyfuels.7b03017

Thurston, G. D. (2016). Outdoor Air Pollution: Sources, Atmospheric Transport, and Human Health Effects. *In International Encyclopedia of Public Health (Second Edi, Vol. 5, Issue 69). Elsevier*. https://doi.org/10.1016/B978-0-12-803678-5.00320-9

World Health Organisation. (2021). *Ambient (Outdoor) Air Pollution Facts Sheet*. https://www.who.int/news-room/fact-sheets/detail/ambient-(outdoor)-air-quality-and-health

Zhang, K., Hu, J., Gao, S., Liu, Y., Huang, X., and Bao, X. (2010). Sulfur content of gasoline and diesel fuels in northern China. *Energy Policy 38, 2934–2940*. https://doi.org/10.1016/j.enpol.2010.01.030