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Research article

Assessment of diesel fuel quality

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ABSTRACT

Diesel is an essential energy source in the transportation and industrial sectors worldwide; hence, the quality of this commodity is crucial. This study compares various fuel samples to understand the quality of the fuels in terms of sulphur content, density, surface tension, viscosity, and calorific value. The properties of diesel fuel samples from eight (8) Filling Stations (Marketing Companies (MC)) were examined and compared with GSA 141:2022 and ISO 8217:2017 standards. Fuel from two companies, MC-A and MC-G had slightly lower densities than the standard, indicative of a possible contamination with lower-density fuels such as kerosene. The surface tension of all samples, except one was within the standard range. The only sample with the lower than the standard value also displayed high sulphur content. Although all the fuel samples met the minimum requirement for calorific value, the viscosities of the fuels from three companies were slightly higher than the specified standard value which can potentially result in higher emissions. In the case of sulphur content, fuel samples from only three companies were in compliance with the maximum 50 ppm standard. This means 62.5 % of the diesel fuel within the study area at the time contained more than the acceptable amount of sulphur. The findings in this research highlight the need to re-examine the quality of fuels along the distribution chain.

1. Introduction

Petroleum diesel is widely used in several industries, including transportation, power generation, and production plants. Modern refineries produce diesel fuel by blending various suitable streams, such as light cycle oil, hydrocracked gas oil, and straight-run products [1]. This liquid fuel's energy is extracted through combustion, which emits particulate matter and other pollutants, leading to environmental pollution and related health effects [2]. Therefore, it is crucial to ensure the quality of the fuels on the market as per the standards to reduce potential environmental pollutant levels, particularly due to the significant rise in fuel adulteration.

Several diesel properties such as density, viscosity, calorific value, flash point, cetane number, water and sediment content, corrosivity, lubricity, oxidation stability, particulate count/distribution, ash content, total sulphur, etc play a significant role in having a complete assessment of diesel fuel. According to Matijošius and Sokolovskij [3], fuel properties may be segmented into the operational properties of the fuel (which show durability and chemical stability of the fuel based on its chemical composition) which includes cetane number, cetane index, and heating value, the safety of fuels within transportation and storage such as the flashpoint and the properties related to environmental requirements with sulphur content being key. Selected and readily measurable parameters are

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presented in this study to ascertain the quality of diesel fuel in the chosen locality. Fuel performance is, however, best determined by an actual engine test [4].

Fuel viscosity plays a critical role in its application, as higher viscosity subjects the fuel pump of internal combustion engines to excessive drag, reducing the engine's net power output [5]. Fuel viscosity also affects atomisation and the fuel delivery rate, potentially causing damage to the engine or fuel system if it is too high or too low [6].

The presence of high quantities of sulphur in diesel fuel is one of the main problems that have an effect on the combustion and emission characteristics of the fuel. The combination of sulphur and water during combustion forms corrosives that can etch finished surfaces, accelerate engine wear, attack softer metals such as bearings, and deteriorate engine oil. Similar corrosion damage from sulphur is often found in the engine's exhaust system [7]. High sulphur content also affects the effectiveness and potentially damage emission-control systems [8,9]. The amount of sulphur in a fuel depends on the kind of crude from which it is obtained [8]. Crude oil naturally contains sulphur, and typical crude oils can have up to 5 wt percent sulphur [10]. Because diesel and sulphur impurities in crude have similar boiling characteristics, most of the sulphur ends up in the diesel fraction during the refining process [11]. Sulphur emissions are recognised as a significant contributor to a wide range of health issues, with respiratory illnesses being the most prevalent among them [12.13]. According to Tan and Wang [12], the presence of sulphur causes the particulate matter from diesel combustion to have tiny particle sizes, capable of penetrating the lungs and posing a health threat. Also, the sulphur oxides formed during the combustion of diesel fuels react with the atmospheric water leading to the formation of acid rain which has been known to have a ruinous effect on ecological systems [13].

Heating value (calorific value or heat of combustion) describes the energy content of the fuel produced in the form of heat when that fuel is combusted completely with oxygen or air [14] and can be expressed in two ways: higher heating value and lower heating value. The heating value or calorific value and density are directly proportional, keeping other factors constant, on volume basis [4,6] Water or moisture content also reduces the higher heating value of fuels [14]. The higher heating value, which often correlates with the API gravity, is roughly 11,000 kcal/kg for diesel fuel [14].

The surface tension of diesel fuel is also a crucial factor in combustion, affecting its initial stage, fuel atomisation, and spray characteristics. Improved atomisation and proper air-fuel mixing can achieve complete combustion, reduce pollutant emissions, and increase engine efficiency [15]. However, the high surface tension of the liquid fuel makes droplet formation more challenging and leads to inefficient atomisation [16]. Thus, achieving an optimum surface tension is necessary to promote effective utility, as the surface tension of diesel fuels exhibits a better potential than other methods in predicting the ignition quality.

Monroe [6] suggests that denser diesel fuel has a higher energy content, which results in higher power output or greater fuel economy in a diesel engine. In a diesel engine system, the fuel performs three critical functions to ensure efficient performance: converting chemical energy into mechanical energy, lubricating precision parts in the fuel system components, and cooling metal surfaces operating in friction conditions.

With the global increase in population, there is a high demand for fuel leading to a significant increase in particulate matter (PM) emissions and hence a deterioration of the ecosystem ([17,18]. These higher emissions increase the probability of human exposure, resulting in severe health conditions such as respiratory tract diseases, heart diseases, skin cancer, and many others; hence, the need to ensure high fuel quality [2,19,20,21,22]. According to the WHO key facts on 2019 ambient (outdoor), air pollution caused approximately 4.2 million premature deaths worldwide and sulphur-related emissions have been reported to have been the cause of respiratory diseases and mortality [23–25].

1.1. Diesel fuel adulteration

Diesel fuel accounts for roughly 47 % of all fuel consumed in road transportation in Ghana [23]. The number of diesel and petrol-powered vehicles in the country's cities is steadily increasing due to rapid population growth, industrialisation, and changes in lifestyle [23,24]. Adulteration is the (illegal) alteration of the original formulation of a product using another (adulterant) and this results in a compromised quality of the product. Adulteration of diesel fuel is normally done with low-cost products, used lubricants, and industrial solvents. However, the abuse of diesel and petrol adulteration with kerosene and other products is a significant issue worldwide [23–25]. Kerosene has been identified as the most common diesel adulterant worldwide and hence several researches have been on its detection in diesel and petrol [26–29]. Kerosene's chemical similarity to diesel and petrol, as well as its cheaper price, historically made it a popular adulterant for individuals seeking to make undue profits at the expense of consumers [24,25,30]. However, recent changes in pricing structures have made kerosene less attractive as an adulterant, as its prices have become closer to those of diesel and petrol at the pumps in Ghana.

To address the issue of adulteration and its associated environmental and health effects, various techniques to detect fuel adulteration levels and reduce the harmful effects of combustion on health and the environment have been explored [25,29–31].

This study seeks to understand the quality of diesel fuels in Ghana by analysing the 24 diesel samples obtained from eight fuel-filling stations located in Kumasi, Ghana. The study evaluated fuel quality based on sulphur content, density, surface tension, viscosity, and calorific value. The results from the study may serve as a useful guide for blenders at storage facilities to ensure their products meet regulatory standards. This will also help in identifying the possible contamination points in the distribution within the country since the products entering the ports are expected to meet standard specifications. This when achieved will limit the negative impact of fuel-related emissions on the health of inhabitants in the research area as well as the environment.

2. Materials and methods

2.1. Materials

The study utilised equipment from the Process Development Laboratory of the Department of Chemical Engineering and the Fluid Properties Laboratory of the Department of Petroleum Engineering at Kwame Nkrumah University of Science and Technology (KNUST). The chemicals used were of analytical grade and were sourced from Fisher Scientific and Sigma-Aldrich, while the sulphur content analyses were obtained from Tema Oil Refinery. The researchers collected 3 L of diesel fuel samples from eight fuel filling stations under review in the Kumasi Metropolis, Ghana.

2.2. Methods

This research analysed and compared the density, viscosity, calorific value, surface tension, and sulphur content. Diesel fuel samples were obtained from the filling stations using a new PET plastic bottle with lids. Prior to sampling, a small amount of the specific diesel was used to rinse the bottle to ensure that any possible contaminant in the bottle was washed off. This was done twice at every sampling point. The samples were then stored under room conditions in the laboratory for all the analyses. All experimental works were based on the American Standard for Testing and Materials (ASTM) and the values obtained were compared with the standards as set by Ghana Standard Authority (GSA), the authority mandated by the state to provide various standards in terms of fuel quality. GS 141:2022 is the requisite standard used for benchmarking.

2.2.1. Density

To determine the densities of the diesel fuel samples, the standard method, ASTM D4052-18a was followed. The method involves measuring the mass per unit volume of the sample at a temperature of 15 °C and 1 atm. The unit of measurement used is kg/m^3. The density of each sample was measured using a KRUSS DS 7800 density meter. A volume of 0.9 mL of each sample was carefully transferred into the sample compartment of the density meter using a syringe to avoid the formation of bubbles. The density of each sample was then determined automatically and displayed on the screen.

2.2.2. Viscosity

The viscosity was determined using the kinematic viscometer (Cannon-Fenske Viscometer by Eduteq Educational Training Equipment) and followed the ASTM standard for kinematic viscosity determination (ASTM D445-18).

The kinematic viscosity, υ was calculated from the measured flow time t and the instrument constant by means of Equation 1:

$$\upsilon = C(t - \vartheta) \tag{1}$$

Where:

υ = kinematic viscosity, *cSt.*
C = calibration constant, *cSt/s*
T = flow time, *s*
ϑ = Hagenbach correction factor, when $t < 400$ s, it should be corrected according to the manual. When $t > 400$ s, $\vartheta = 0$.

2.2.3. Sulphur content

The sulphur content of the diesel fuels was determined using XRF analyser SLFA-60. The process requires no pretreatment of samples before measurement. This was determined using the standard ASTM D4294-16e1 method. 4–10 mL of diesel samples were pipetted into disposable sample cups, lined with polyethylene plastic liners. The liners are the protective shields, made to protect the equipment from possible leakage. The analysis is automated with an average sulphur content computed and the results displayed in a printout.

2.2.4. Surface tension

The Du Noüy Ring tensiometer (Sigma 700/701 Force Tensiometer) was used for the surface tension determination according to the methods of Lunkenheimer and Wantke [32] and Mohameda et al. [33] as specified in ASTM D1331-14. The technique makes use of the contact of a platinum ring with the liquid's surface. By shifting the stage where the liquid container is situated, the ring was submerged below the interface. The stage was progressively lowered after immersion, and the ring pushed the liquid's meniscus up and the corresponding surface tension was recorded.

Table 1
Requirement and test methods for diesel fuel oils

Property	Set Limit (GS 141:2022)	Set Limit (ISO 8217:2017)	Test Method
Density at 15 °C (kg/m^3)	820–850	820–900	ASTM D 4052
Viscosity at 40 °C (mm^2/s)	2–4.5	2–4.5	ASTM D 445
Sulphur content (ppm)	50	50	ASTM D 5453
Calorific value (MJ/kg)	Not set	≥42.7	ASTM D 4868

2.2.5. *Calorific value*

The calorific value for each sample was determined by following the standard ASTM D5865-13 using the bomb calorimeter PARR 6400. In the bomb calorimeter, the diesel sample was loaded in the reaction chamber along with oxygen; this was submerged in water within an insulating container. Once the sample was ignited, a thermometer that was partially submerged in the water recorded the temperature change, ΔT, that occurred. The calorific value, q, was calculated as $q = C\Delta T$, where C is the heat capacity of the calorimeter.

All parameters analysed were compared with those of Ghana Standard Authority (GSA) standard GS 141:2022 and ISO 8217:2017) (Table 1) to ascertain the quality of diesel fuels.

3. Results and discussions

The results of the properties of diesel fuels measured are presented and discussed in the following sections.

3.1. *Density*

The density of diesel fuel is a significant quality indicator for usage in automobile engines because it controls the amount of fuel compressed and burned in the combustion chamber.

Fig. 1 displays the average densities of all diesel fuels. The average density values for each sample were within the regulated average range of density given by GS 141:2022 and ISO 8217:2017, except for fuel sold from MC-A and MC-G, which had slightly lower densities. The fuel market in Ghana is deregulated, and oil marketing companies source their supply from various sources, provided the standards are met. Lower diesel density is usually attributed to adulteration with lighter fractions, especially kerosene, which has similar properties to diesel and is much cheaper [23]. Price variations between diesel and kerosene were significant in times past, making diesel adulteration very possible [23]. The price incentive of kerosene is currently impossible due to regulations that have been placed in place to place the prices of diesel and kerosene so close, and such possible adulteration could be from other fuel types or hydrocarbons. Unintentional contamination is also a possibility, mainly during storage and transportation. According to the study by Lui et al. [34], the density of diesel fuel on heavy-duty engines had a very direct relationship with emissions and engine performance. The higher the density, the higher the emissions of nitrogen oxides (NO_x) and particulate matter (PM).

3.2. *Viscosity*

Fig. 2, which compares the average viscosities for the diesel samples from the OMCs with the GSA GS 141:2022 and ISO 8217:2017 standards, showed that all samples studied had their viscosities within the standard except for the few that had slightly higher viscosities. High viscosity in fuels tends to negatively affect the engines that run on them.

According to Krause and Labuda [5], the viscosity of the fuel affects the droplet size formed during atomisation, and the increase in the size of the droplets injected into the fuel combustion chamber may affect the quality of the fuel-air mixture, leading to increased fuel consumption, and increase the harmful exhaust constituents released into the environment.

High-viscosity diesel fuel can have negative effects on engine performance and emissions. A study published in the journal Fuel found that high-viscosity diesel fuel can lead to reduced engine power output, increased fuel consumption, and higher emissions of nitrogen oxides (NO_x) and particulate matter (PM) [35,36]. This is because high-viscosity diesel fuel has low cetane numbers and hence can cause incomplete combustion, leading to the formation of these harmful pollutants [35]. Regarding the environment, low-viscosity diesel can potentially reduce emissions of particulate matter and nitrogen oxides (NO_x) by improving combustion efficiency. However, it can also lead to increased fuel leakage and evaporative emissions, which can contribute to air pollution and

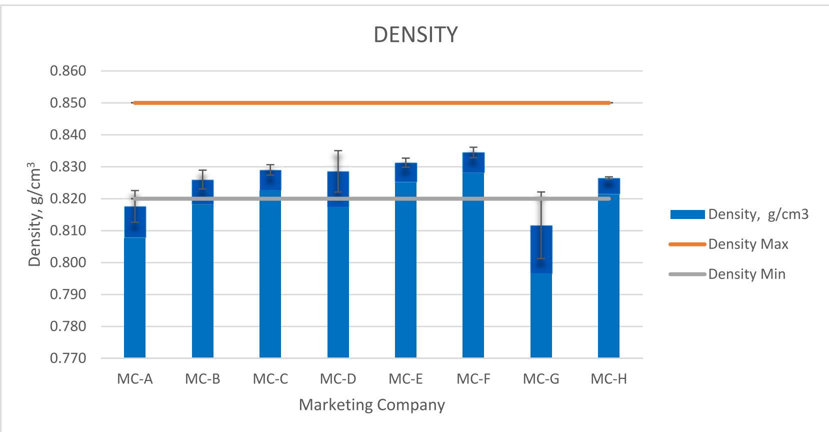

Fig. 1. A graph of the density of diesel fuels collected at different locations in Kumasi, Ghana.

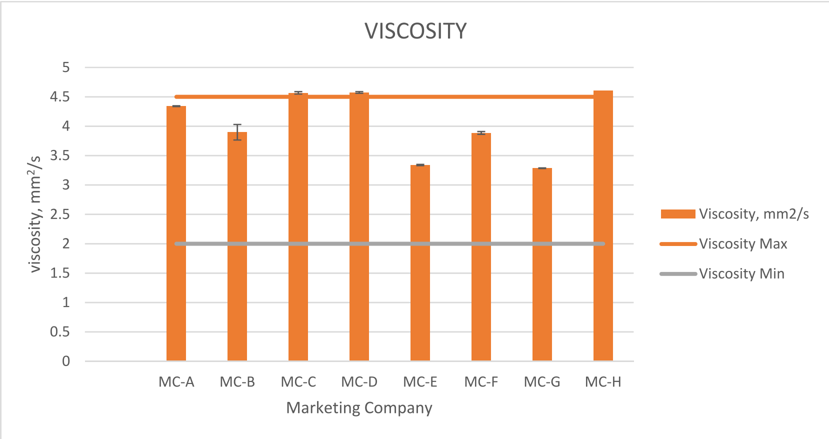

Fig. 2. A graph of the viscosity of diesel fuels collected at different locations in Kumasi, Ghana.

potentially harm human health.

3.3. Surface tension

The surface tension tells the force between the sample molecules, especially at the fluid surface. The surface tension of diesel fuel plays a vital role in the fuel's combustion characteristics, affecting its atomisation and spray characteristics [15,37,38].

The surface tension of diesel fuel is crucial for proper combustion as it affects fuel atomisation and spray characteristics, leading to enhanced atomisation and better air-fuel mixing, reduced pollutant emissions, and increased engine efficiency [15,16,39]. From Fig. 3 in this study, the surface tension of all diesel fuel samples met the standard for comparison, except for MC-C, which was slightly lower. According to the research outcome of Molea et al. [15], a higher amount of sulphur in the fuel tends to weaken covalent bonds, resulting in lower surface tension. This assertion is confirmed by the fact that MC-C, which had the lowest surface tension, also had the highest sulphur content. Even though the surface tension of diesel fuels is not limited by any standards, it is very key consideration due to the impact on engine performance and emissions. Generally, for diesel, the surface tension is expected to be in the range of 25.84–28.89 mN/m at 25 °C [16,38] even though it is not one of the very critical diesel fuel parameters.

3.4. Calorific value

Based on Fig. 4, all the average calorific values of the samples from the filling stations met the ISO 8217:2017 standard. The calorific value of the fuel is an indication of the energy content of the fuel and depends on the composition of the fuel [8]. A high proportion of heavier components will result in high calorific values. The average consumer is typically only concerned about how long the fuel lasts and the higher the calorific value, the lower the rate of fuel consumption [40].

The calorific value of the fuels is important as it signifies the energy content of the fuel. Once the calorific value is not below the

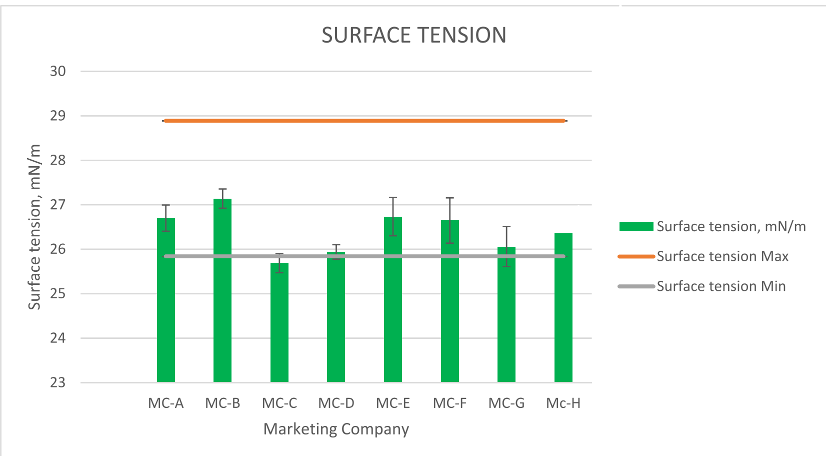

Fig. 3. A graph of surface tension of diesel fuels collected at different locations in Kumasi, Ghana.

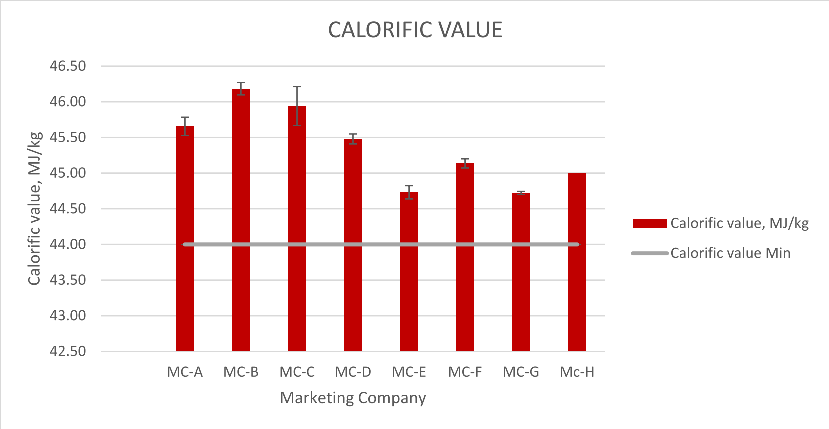

Fig. 4. A graph of calorific values of diesel fuels collected at different locations in Kumasi, Ghana.

lower standard limit, the fuel would be ideal for the market.

3.5. Sulphur content

The sulphur content of diesel fuels is an essential property to consider due to the high environmental and health consequences of their combustion [41–43]. Sulphur in diesel has been of great concern over the years, hence the effort to control its presence in fuels [44,45]. There has been a worldwide approach to reduce the amount of sulphur in diesel and there have been strict regulations to effectively achieve that [46,47]. Fig. 5 shows the average sulphur content of diesel fuels from the filling stations under consideration.

From Fig. 5, it can be observed that only three fuel filling stations out of the eight tested were dispensing diesel fuel within the GSA GS 141:2022 and ISO 8217:2017 set limits of 50 ppm of sulphur content. The sulphur content of the diesel fuels from these three stations was between 20 ppm and 30 ppm. The remaining five filling stations exceeded the set limit, with MC-E, MC-F, and MC-G having the highest sulphur levels. It is important to note that the National Petroleum Authority (NPA) has given a waiver to local refineries operating in the country to produce fuels with up to 1500 ppm sulphur content until the end of December 2024. However, this permit does not apply to imported fuels, which must adhere to a maximum of 50 ppm [48,49]. The high sulphur contents recorded could be due to the blending of these fuels during storage and distribution or the purchase of finished petroleum products from the local refineries that operate with the waiver. It is also possible that some of these fuels enter the market illegally and are not regulated, as there are reports of fuel smuggling across the borders, most of which turn out to be adulterated [50–52]. The sulphur content compliance for this study was found to be at 37.5 %, indicating that the majority of diesel samples exceeded the established limit. This raises concerns due to the detrimental effects of sulphur in fuels on both the environment and people's health.

Sulphur converts to different forms (oxides of sulphur) such as SO_2 during combustion, which has a negative effect on the environment and the health of the people living within this research area. The sulphur content compliance in this research is 37.5 %, indicative of the fact that most of the diesel samples exceeded the set limit; a cause for concern due to the negative effects of sulphur in fuels on the health of people as well as the environment.

Vehicles operated on high sulphur fuels are a source of pollution to the environment and its associated health implications. Intermittent power outages in Ghana have also compelled many businesses and individuals to use generators as a backup solution to ensure continuous processes both at business centers and in homes. These stationary generators also contribute hugely to environmental pollution when not operated on clean fuels. A study by Ahmed [53] revealed high concentrations of Particulate Matter (PM1, PM2.5, and PM10) released when high sulphur content diesel fuels are used in powering these generators. The effect of these is even more grievous since most of the generators are operated in close proximity to residential facilities. Sulphur-related emissions have the tendency to cause acid rains with the effect of acidification of aquatic systems, increase in soil acidity, and damage to vegetation [54]. The presence of sulphur also leads to corrosion and has the potential to affect the performance of advanced emission control technologies installed in vehicles [55].

Aside from the purchase of high sulphur diesel fuels from the local refineries, the most probable reason may be the adulteration of the fuels. This high sulphur may result from some adulterants that could have been introduced by either OMCs themselves or their retail outlets on the blind side of their mother company [23] after these petroleum products entered the country. The other possible reason may be the contamination from underground tanks that store these fuels before they are dispensed at the pumps. The contamination could result from overaged tanks which may be rusty and may introduce some sulphur compounds (composition of the steel tank) into the fuels they store [56]. Moreover, underground leakage of surrounding soil constituents into the content of the underground tanks could also be a contributing factor since soil sulphur can easily leach out of the soil [57]. Sulphur reduction methods can also be employed in minimising the high sulphur content of petroleum products such as biodesulphurisation. Also, proper storage and handling to avoid possible sulphur contamination could be looked at.

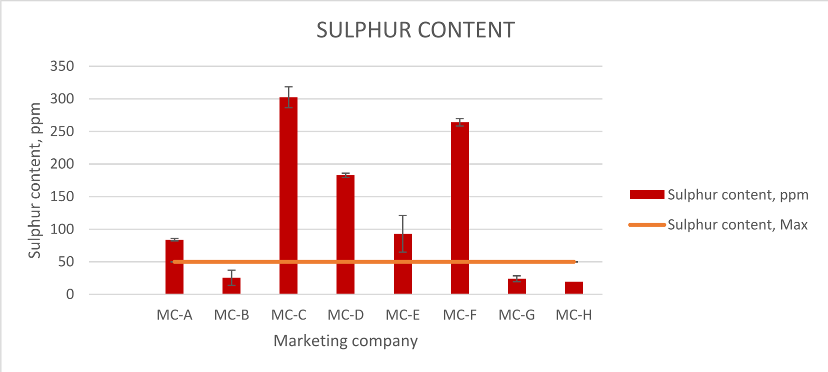

Fig. 5. A graph of sulphur content of diesel fuels collected at different locations in Kumasi, Ghana.

4. Conclusion and recommendation

The study has shown that the fuel quality for most of the fuels adheres to the standard limits specified in the two reference standards used. The density of the fuels in 6 out of the 8 fuel filling stations was within the set limit with the remaining two having a comparatively lower density. This could be a result of contamination with other lighter fractions and this translates to 75 % compliance with the standard. In terms of the viscosity, 3 out of the 8 fuel filling stations dispensed high-viscosity fuels and this generally affects fuel engine performance thereby having a negative impact on the emissions of NO_x and PM. This indicates only 62.5 % compliance with the set standard. All the filling stations had diesel fuels with standard calorific values. Sulphur content is very key in fuel standards since the presence of sulphur has a very negative effect on both human health and the environment. The level of compliance to sulphur content in diesel fuels in the study area was found to be 37.5 % since only 3 fuel filling stations had sulphur up to 50 ppm. Even though there is no strict regulation for surface tension for diesel fuels, it gives an indication of some contaminants such as sulphur. The higher the sulphur content, the lower the surface tension and this is confirmed by the results of this research. The variations in the various properties could also be a result of the source of the fuel products and possible contamination along the distribution chain.

It is thereby recommended that the regulator, the National Petroleum Authority (NPA), develops a system to continuously monitor the quality of fuels at the Filling Stations and along the distribution chain. This, in addition to their oversight responsibility of ensuring the quality of fuel that enters the country through the ports, the country can attain the clean fuels (SDG 7) and climate change (SDG 13) goals.

Data availability statement

Has data associated with your study been deposited into a publicly available repository? NO. All the data used and needed for reproducibility of this study have been included fully in the manuscript.

CRediT authorship contribution statement

Emmanuela Kwao-Boateng: Writing – review & editing, Writing – original draft, Validation, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Emmanuel G. Ankudey:** Writing – review & editing, Validation, Supervision, Methodology, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Lawrence Darkwah:** Writing – review & editing, Validation, Supervision, Methodology, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Kwabena O. Danquah:** Writing – review & editing, Validation, Supervision, Methodology, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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