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Diesel's Share of Pollutants and Greenhouse Gas Emissions among All Energy Sources in Iran from 2000 to 2017

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ABSTRACT

The annual pattern of diesel pollutant emissions is a significant environmental concern, with key pollutants such as suspended particulate matter, nitrous oxide, sulfur trioxide, sulfur dioxide, and nitrogen oxides impacting human health and the environment. A literature review focused on diesel-emitted pollutants was conducted using online databases. Data on diesel-related air pollution in Iran were collected, examining emissions of various pollutants from 2000 to 2017. Data distribution was analyzed using the Kolmogorov-Smirnov test. Descriptive and correlation analyses were performed using SPSS v27 to explore relationships among greenhouse gases and air pollutant emissions. The study examines the impact of diesel on pollutants and greenhouse gas emissions in Iran from 2000 to 2017. It shows a small decline in diesel's share of NO_x emissions, attributed to better combustion efficiency and emission control systems. In contrast, diesel's share of SO_2 emissions has risen, likely due to increased diesel use despite a shift to natural gas and renewable energy. CO emissions have remained stable due to improved technologies, and CH_4 emissions have significantly dropped due to reduced methane slip and bio-based diesel adoption. The study also indicates a decrease in diesel's contribution to SPM, linked to better fuels and particulate filters. The correlation analysis reveals significant inverse relationships between CO_2 and N_2O emissions and suggests that reducing one type of pollution may affect another.

Introduction

Diesel fuel is produced through the refining of crude oil, where it undergoes heating to create mixtures suitable for combustion. Important characteristics of diesel include high energy density, low volatility, and the appropriate viscosity for injection. Diesel is categorized based on its sulfur content, with high-sulfur fuels being phased out due to environmental concerns [1]. Ultra-low sulfur diesel (ULSD) is specifically designed to reduce

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sulfur emissions and meet regulatory standards [2].

Diesel is crucial for compression-ignition engines commonly found in heavy vehicles and machinery. Its composition supports optimal combustion in these engines. The cetane number measures the speed at which diesel ignites after injection; higher cetane numbers result in faster ignition and improved efficiency, especially during cold starts [3]. The cetane number is influenced by branched hydrocarbons and carbon chain length, with longer paraffins generally leading to higher numbers than aromatics [4].

The higher density of diesel compared to gasoline allows for better fuel economy by providing more energy per volume. Maintaining this density is essential for fuel delivery and engine performance, as fluctuations can negatively impact emissions. High-quality diesel reduces engine wear and contains fewer impurities, preventing deposits and corrosion [5]. A balanced hydrocarbon mix enhances lubricity, reducing friction. The viscosity of diesel fuel is crucial for proper atomization during injection; incorrect viscosity can result in incomplete combustion or damage to the fuel system [6]. Additives are used to maintain viscosity and improve cold flow properties to prevent gelling at low temperatures, ultimately enhancing diesel quality and protecting engine parts [3].

The composition of diesel includes long-chain alkanes and aromatic compounds that vary during the refining process. Additives are included to improve stability and performance. While diesel fuel is effective for heavy-duty vehicles, it poses health risks due to the pollutants in its exhaust [7]. Cleaner technologies are being developed to address these issues. Diesel is also used in other industries such as oil drilling, with ongoing research into biodiesel to minimize environmental impacts. The chemical composition of diesel fuel also impacts its emissions, with aromatics contributing to harmful emissions such as particulate matter (PM) and polycyclic aromatic hydrocarbons (PAHs), which are carcinogenic. Additionally, polar compounds containing nitrogen and sulfur can interfere with engine parts. Lowering sulfur compounds in diesel is crucial for reducing nitrogen oxides (NO_x) and sulfur oxides (SO_x) emissions, which are linked to severe environmental and health issues [8]. Desulfurization processes such as hydrodesulfurization (HDS) eliminate sulfur while maintaining fuel performance, although achieving deep removal without negative impacts can be challenging. New methods, such as oxidative desulfurization using graphene show promise for more efficient sulfur content reduction [9-12].

Increased industrial activity, energy consumption, and the growing number of diesel vehicles are often associated with economic development and urbanization, leading to increased emissions from transportation and industrial sectors [10-12]. Modern diesel engines utilize various emission control technologies, such as diesel particulate filters (DPFs) and selective catalytic reduction (SCR) systems, to reduce PM and NO_x emissions. The quality of diesel fuel is crucial for the effectiveness of these systems, with ultra-low sulfur diesel (ULSD) being essential for SCR systems to prevent sulfuric acid formation that can damage catalysts [10-13]. The introduction of emission control technologies, such as catalytic converters, can play a significant role in reducing emissions, particularly NO_x, but may have less impact on CH_4 emissions due to their distinct origins. The shift to ultra-low-sulfur diesel (ULSD) has significantly influenced observed trends by reducing sulfur content in diesel fuel, leading to decreased formation of sulfur oxides and SPM during combustion [10-14].

The previous study showed a strong correlation between the study year and the annual production of air pollutants from diesel fuel in Iran. These pollutants include nitrogen oxides (NO_x), sulfur dioxide (SO_2), carbon monoxide (CO), carbon dioxide (CO_2), and suspended particulate matter (SPM). Some factors such as industrial activity, energy use, and the growth of diesel vehicles likely influence these pollutants, all of which are related to economic development and urbanization [10-12].

The annual pattern of diesel pollutant emissions concerning total fuel consumption is a significant environmental concern. Key pollutants include suspended particulate matter (SPM), nitrous oxide (N_2O), sulfur trioxide (SO_3), sulfur dioxide (SO_2), and nitrogen oxides (NO_x). These substances have a substantial effect on human health and the environment. Understanding the sources and impacts of these emissions, as well as potential solutions, is crucial for addressing this issue [10-15].

Materials and Methods

Literature review

A comprehensive review of keywords related to diesel-emitted pollutants was conducted, focusing on pollutants such as NO_x, SO_2, CO_2, SO_3, CO, CH_4, and SPM. This analysis involved searching online databases such as Google Scholar and Scopus to explore relevant scientific literature and resources on air pollution.

Data collection

Initially, data on diesel-related air pollution metrics were collected, with a specific focus on the diesel share in pollutants and greenhouse gas emissions in Iran. This dataset included the emissions share of diesel sources by the percentage of pollutants such as NO_x, SO_2, CO_2, SO_3, CO, CH_4, SPM, and N_2O among all emitted pollutants from fuels in Iran from 2000 to 2017. The data were sourced from the Statistical Center of Iran's database, which is accessible at https://amar.org.ir. All data from the Statistical Center are based on statistics provided by the Ministry of Energy of the Islamic Republic of Iran. The calculation method is based on the Energy Balance Sheet from the Ministry of Energy, Deputy of Electricity and Energy Affairs. To calculate diesel's share of pollutants and greenhouse gas emissions, emission factors for greenhouse gas inventories and the amount of fuel consumption (diesel) can be utilized. The EPA (2014) Inventory of U.S. Greenhouse Gas Emissions and Sinks paper can be referenced [10-12].

Three types of distillate fuel oils are examined: No. 1, No. 2, and No. 4, all of which are petroleum-based. No. 1 Fuel Oil is a light distillate used in stoves and heaters; No. 2 Fuel Oil is a medium distillate used for heating and as diesel fuel; and No. 4 Fuel Oil can be a mix of distillate and residual fuels. The provided emissions data include measurements of CO_2, CH_4, and N_2O per gallon for diesel and its alternatives. The emissions per gallon of diesel are calculated, resulting in 10.29 kg of CO_2, 0.41 g of CH_4, and 0.08 g of N_2O. In comparison, Distillate Fuel Oil No. 1 emits 10.18 kg of CO_2 per gallon, No. 2 emits 10.21 kg of CO_2 per gallon, and No. 4 emits 10.96 kg of CO_2 per gallon. For CH_4 emissions, diesel emits 0.41 g; No. 1 emits 0.42 g; No. 2 remains the same as diesel; and No. 4 emits 0.44 g. N_2O emissions are consistent at 0.08 g for all distillate fuels. Other pollution calculation factors are possible from the EPA (2014) Inventory of U.S. Greenhouse Gas Emissions and Sinks paper. The accuracy of the evaluation depends on the precision of emission factors and consumption data (Table 1) [10-12].

Data distribution analysis

The normal distribution of the data was evaluated using the one-sample Kolmogorov-Smirnov test. This analysis focused on diesel's share in pollutants and greenhouse gas emissions (percentage), specifically looking at air pollutants such as NO_x, SO_2, CO_2, SO_3, CO, CH_4, and SPM [16].

Descriptive and analytical statistics study

A comprehensive descriptive and correlation analysis of diesel's share in pollutants and greenhouse gas emissions (percentage) from 2000 to 2017 was conducted using SPSS v27 software. The study examined the relationships among study year, various greenhouse, and air pollutant gas emissions by applying Pearson and Spearman correlation tests [16].

Table 1: The emission factors used for calculating the annual contribution of air pollutants and greenhouse gases

	Crude Oil	Distillate Fuel Oil No. 1	Distillate Fuel Oil No. 2	Distillate Fuel Oil No. 4	Vehicle Type	Diesel Ships and Boats	Diesel Locomotives	Diesel Agricultural Equip.	Diesel Construction Equip.
kg CO_2 per gallon	10.29	10.18	10.21	10.96	CH_4 Factor (g / gallon)	0.06	0.8	1.44	0.57
g CH_4 per gallon	0.41	0.42	0.41	0.44	N_2O Factor (g / gallon)	0.45	0.26	0.26	0.26
g N_2O per gallon	0.08	0.08	0.08	0.09					
Unit	Gallon	Gallon	Gallon	Gallon					

Results and Discussion

Diesel's share in pollutants and greenhouse gas emissions among all fuels as energy sources

The share of diesel in pollutants and greenhouse gas emissions has been fluctuating and decreasing for certain pollutants over the analyzed period from 1997 to 2017 (Figure 1, Table 2). The share of diesel in NO_x emissions exhibits a slight downward trend, indicating that either the combustion processes for diesel have become more efficient or that there has been a shift toward other energy sources with lower NO_x emissions. The introduction of stringent emission control technologies such as selective catalytic reduction (SCR) systems in diesel engines could have contributed to this decrease. Moreover, the use of alternative fuels with lower nitrogen content or the implementation of cleaner combustion methods may also play a role [10-12,17]. The increase in diesel's share of SO_2 emissions from 35.10% in 2000 to 57.97% in 2017 can be attributed to an increase in diesel consumption. Additionally, the shift toward natural gas and renewable energy sources with minimal sulfur emissions may have contributed to the increase in the share of diesel in SO_2 emissions, as it is the primary source of SO_2 and SO_3 emissions. Finally, this indicates that total SO_2 and SO_3 emissions were decreased in Iran [10-12,18]. The fluctuating trend in CO_2 emissions from diesel, with a slight overall decrease, suggests that while diesel's absolute emissions may have decreased due to increased efficiency or a shift toward natural gas, its relative share in the total emissions mix may have been influenced by changes in energy consumption patterns and the growth of other energy sources. Economic factors, such as the rise of renewables due to their declining costs, could also explain the observed trend [10-12,19]. Diesel's share of CO emissions remains low and stable, which is consistent with the expectations for a fuel that is less carbon-rich compared to coal or biomass. Modern combustion technologies and engine designs are typically optimized to minimize CO emissions may contribute to this consistent trend [10-12,20].

The substantial decrease in diesel's share of CH_4 emissions from 25.70% in 2000 to 6.5% in 2017 likely reflects efforts to reduce methane slip during combustion, improvements in diesel quality, or a shift toward natural gas which is often marketed as a cleaner alternative. Diesel has a lower methane content and a lower share of methane emissions [10-12,21].

The data for SO_3 emissions can be inferred from the trends in SO_2 emissions. As diesel's sulfur content increases, a proportional increase in SO_3 emissions can be expected as well, assuming similar oxidation rates of SO_2 to SO_3 [10-12].

The decrease in diesel's contribution to SPM emissions from 81.30% in 2000 to 72.22% in 2017 may be due to the introduction of particulate filters in diesel engines and the trend toward the use of low-sulfur fuels, which reduce the formation of particulate matter. Additionally, the phasing out of older, dirtier vehicles and the adoption of cleaner road transportation technologies could also contribute to this trend [10-12,22].

Emission control in diesel's share of N_2O emissions from 66.31% in 2000 to 59.46% in 2017 could be a result of improved combustion efficiency and emission control technologies that reduce the formation of nitrous oxide. The observed trends could be influenced by several factors, including changes in fuel quality, advancements in emission control technologies, shifts in the energy mix, and the implementation of environmental regulations [10-12,23].

Table 2: Diesel's share in pollutants and greenhouse gas emissions among all fuels as energy sources (percentage)

Year	NO_x	SO_2	CO_2	SO_3	CO	CH_4	SPM	N_2O
2000	48.00	35.10	21.90	30.00	2.00	25.70	81.30	-
2001	48.00	35.10	22.00	30.10	1.90	24.90	81.20	-
2002	47.20	36.40	20.90	31.60	1.80	24.00	80.90	-
2003	47.30	38.80	21.00	33.80	1.70	23.10	81.30	-
2004	44.40	60.60	19.60	59.10	1.60	21.40	77.10	-
2005	44.10	61.20	19.90	59.90	1.50	20.70	76.60	-
2006	42.70	61.50	19.80	60.40	1.40	19.50	75.10	-
2007	44.05	37.62	18.82	42.18	1.72	10.42	76.12	66.31
2008	38.50	33.30	18.40	41.00	1.70	10.00	76.20	66.70
2009	38.60	31.80	18.00	38.70	1.80	9.20	75.80	67.30
2010	40.90	39.00	18.60	48.50	2.00	9.10	46.30	68.70
2011	43.10	37.40	19.20	54.20	2.00	9.30	76.80	67.20
2012	41.64	34.18	18.13	51.20	1.90	8.42	76.25	65.75
2013	44.43	35.31	19.46	55.43	1.81	4.04	76.02	64.72
2014	40.60	36.30	17.20	48.70	1.80	8.10	75.10	63.70
2015	35.80	38.60	15.00	38.60	1.50	6.90	72.10	62.50
2016	35.24	51.63	14.72	66.67	1.43	6.71	76.62	60.98
2017	34.31	57.97	14.37	73.89	1.39	6.50	72.22	59.46

Source: Energy Balance Sheet, Ministry of Energy, Deputy of Electricity and Energy Affairs. "-": Years with a "-" line indicate that no information is available for them.

Results and discussion of the descriptive study

Suspended particulate matter (SPM) consists of tiny particles and droplets in the air, emitted from diesel engines due to incomplete fuel combustion. High levels of SPM can lead to serious health problems such as respiratory diseases and heart conditions. Diesel combustion contributes 74.8% of the SPM emissions, indicating its major role in air pollution [8,13,14]. Nitrous Oxide (N_2O) is a powerful greenhouse gas, contributing to global warming even though it may not be directly harmful to health in low concentrations. Its high diesel emission proportion of 64.3% points to diesel engines being a significant source of N_2O [10-12,23]. Sulfur trioxide (SO_3) and sulfur dioxide (SO_2) are gases released from burning diesel and other sulfur-containing fuels. They contribute to acid rain and can worsen respiratory diseases. Diesel contributes 47.6%

to total SO_3 and 41.94% to SO_2 emissions, highlighting the need for lower sulfur content in diesel fuel [10-12]. To reduce the environmental impact of diesel emissions, several strategies can be employed. Improving fuel quality by enforcing strict regulations on sulfur levels would decrease SO_3 and SO_2 emissions. Emission control technologies, such as diesel particulate filters (DPF) and selective catalytic reduction (SCR) systems, can reduce SPM and NO_x emissions [1,2,9,15,18].

Nitrogen oxides (NO_x) include gases that cause ground-level ozone formation, which can lead to smog and respiratory issues. Diesel's contribution of 41.79% to total NO_x emissions indicates that diesel vehicles significantly impact air quality [10,12,15,17]. Implementing stringent vehicle standards can lead to cleaner engines, while encouraging alternative fuels such as biodiesel and electric vehicles can lower reliance on diesel. Infrastructure improvements, such as better public transportation and support for non-motorized transport, can also help reduce diesel emissions. Taxation on high-emission fuels and incentives for low-emission vehicles can promote greener choices (Table 3) [10-12].

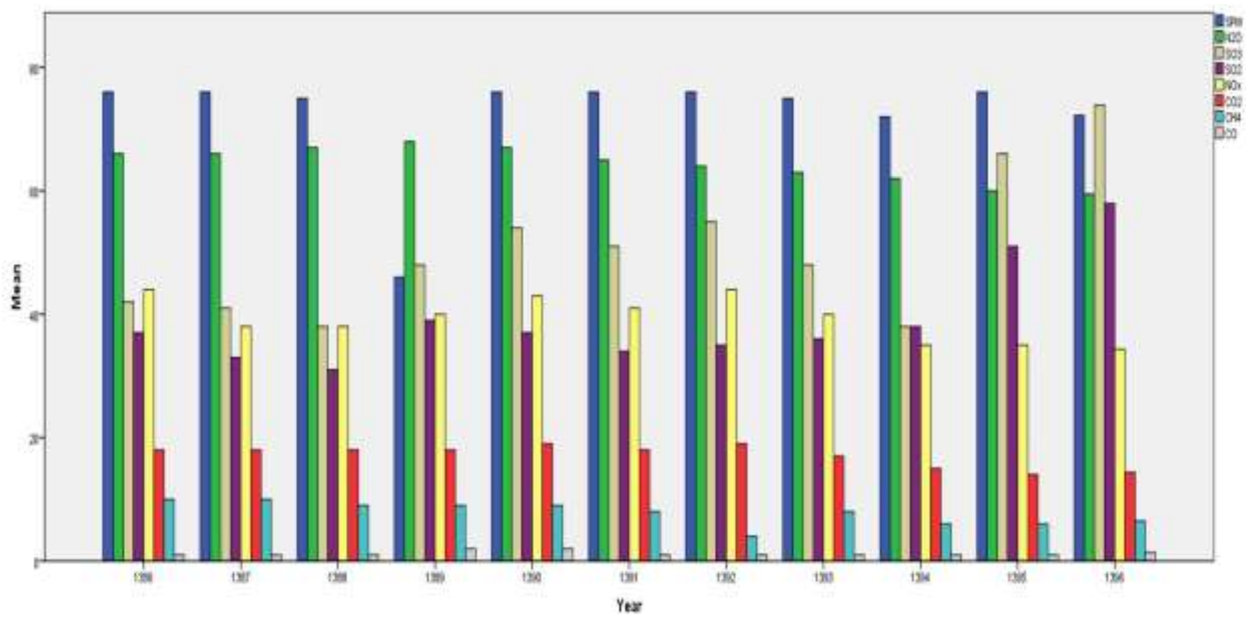

Figure 1: Diesel's share in pollutants and greenhouse gas emissions (percentage)

Data distribution analysis

The variables for SO_2, CO, and SPM emissions percentages from diesel do not follow a normal distribution, while the other variables do. For future studies involving the SO_2, CO, and SPM emission percentage variables, nonparametric statistical tests should be utilized. Parametric statistical tests are suitable for the other variables (Table 4) [6].

Table 3: A descriptive overview of the share of air pollutants emitted by diesel fuel, expressed in percentages

Variables	N	Mean	Std. Deviation	Minimum	Maximum
NO_x	18	41.7950	4.44826	34.31	48.00
SO_2	18	41.9428	10.73198	31.00	61.00
CO_2	18	18.2983	2.17708	14.00	22.00
SO_3	18	47.6050	13.10250	30.00	73.89
CO	18	1.1883	.38453	1.00	2.00
CH_4	18	13.4167	7.55032	4.00	25.00
SPM	18	74.8456	7.67463	46.00	81.00
N_2O	11	64.3145	2.89004	59.46	68.00

Table 4: One-sample Kolmogorov-Smirnov test of studied variables (diesel's share in pollutant and greenhouse gas emissions among all fuels as energy sources (percentage))

Variables	Year	NO_x	SO_2	CO_2	SO_3	CO	CH_4	SPM	N_2O
N	18	18	18	18	18	18	18	18	11
Kolmogorov-Smirnov Z	0.332	0.570	1.401	0.947	0.467	1.976	1.212	1.448	0.579
Asymp. Sig. (2-tailed)	1.000	0.901	0.039	0.331	0.981	0.001	0.106	0.030	0.890

An Asymp. Sig. (2-tailed) value greater than 0.05 indicates that the data distribution is normal.

The correlation test was conducted among the studied variables, specifically the share of air pollutants emitted by diesel fuel from all fuels, expressed as a percentage:

The highly significant inverse correlation (r = -0.884) suggests a strong relationship between decreasing N_2O emissions from diesel fuel and the passage of time. This could be a result of advancements in diesel technology, such as the introduction of selective catalytic reduction (SCR) systems, which reduce nitrous oxide (NO_x) emissions and consequently N_2O. Additionally, regulatory measures that mandate lower nitrogen oxide emissions could indirectly lead to reduced N_2O emissions. However, it is important to note that correlation does not imply causation, and further analysis is required to confirm the underlying reasons for this trend [10-13].

The strong inverse correlation (r = -0.930) indicates a consistent decrease in CH_4 emissions from diesel fuel over time. This trend may be due to improvements in engine technology that reduce methane slip, which is the unburned methane that escapes from engines into the atmosphere. Moreover, there could be changes in fuel quality or a shift toward bio-based diesel fuels, which may have lower methane content. However, without additional data on specific technologies, fuel types, and regional policies, it is difficult to pinpoint the exact cause of this trend [24].

There is a statistically significant direct correlation between the percentage of SO_3 emitted by diesel fuel and time. This suggests that as time progresses, the proportion of SO_3 emitted by diesel fuel increases. However, the previous study also indicates a reduction in total SO_2 and SO_3 emissions in Iran [10-12].

The highly significant inverse correlation (r = -0.882) suggests that carbon dioxide emissions from diesel fuel are decreasing over time. This is likely a result of increased efficiency in diesel engines, the introduction of alternative fuels with lower carbon content, and potentially a shift toward electric vehicles and other non-fossil fuel transportation options. Moreover, the correlation may reflect the overall trend in reducing greenhouse gas emissions driven by international agreements and environmental policies [23-25].

The inverse correlation (r = -0.853) with a significance level of 0.000 indicates a strong relationship between decreasing NOx emissions from diesel fuel and the passage of time. This is likely due to the implementation of stricter emission standards, such as Euro standards in Europe and Tier standards in the United States, which have led to technological advancements in diesel engines including exhaust gas recirculation (EGR) and SCR systems. These measures aim to reduce nitrogen oxide emissions, a major contributor to air pollution and the formation of ground-level ozone [10-13].

There is a high direct correlation between NO_x and CH_4 emissions, with an r of 0.780, significant (p = 0.000). Nitrogen oxides (NO_x) are a group of gases primarily consisting of nitric oxide (NO) and nitrogen dioxide (NO_2), produced during the combustion of fossil fuels such as diesel at high temperatures in the presence of nitrogen and oxygen. Methane (CH_4) is a potent greenhouse gas and the primary component of natural gas. While both are emitted during combustion processes, they are typically emitted in different proportions and under different conditions. The correlation may be due to similar combustion conditions or other confounding factors [12,26].

A very strong direct correlation between CO_2 and NO_x emissions, with an r of 0.936, significant at the 0.01 level (p=0.000), suggests that as diesel fuel emits more CO_2, it also emits significantly higher amounts of nitrogen oxides. This is generally true, as both CO_2 and NO_x are byproducts of the combustion process in internal combustion engines. In fact, the correlation is expected to be strong and direct because both are products of the oxidation of carbon and nitrogen in diesel fuel. Increased CO_2 emissions usually indicate higher fuel consumption, which can also lead to higher emissions of nitrogen oxides if the combustion process is not optimized to reduce their formation [12,27].

An inverse correlation coefficient of -0.520 indicates a moderate to strong inverse relationship between nitrogen oxides (NO_x) emissions and sulfur trioxide (SO_3) emissions from diesel fuel. However, there is a discrepancy in the chemicals being discussed. NO_x refers to nitric oxide (NO) and nitrogen dioxide (NO_2), which are produced during the burning of diesel fuel. In contrast, SO_3 is not typically emitted from diesel combustion; instead, sulfur dioxide (SO_2) is the common sulfur compound released when sulfur in diesel fuel is oxidized [12]. The inverse correlation suggests that as one type of emission decreases, the other may increase, or vice versa. Diesel engines are often regulated for both NO_x and sulfur oxides (SO_x) emissions, meaning that a reduction in one does not necessarily lead to an equal increase in the other, due to different control strategies. Efforts to lower one pollutant can have indirect effects on the other. For instance, reducing sulfur in diesel fuel primarily not only aims to lower SO_2 emissions, but it may also alter NO_x emissions due to changes in combustion. Additionally, exhaust after treatment systems, such as selective catalytic reduction (SCR) for NO_x and diesel particulate filters (DPF), play a role in influencing emissions, with their efficiency dependent on vehicle conditions and fuel type [28]. The data indicate a moderate to strong direct correlation, with a coefficient of 0.643, between nitrogen oxides (NO_x) emissions and nitrous oxide (N_2O) emissions during diesel fuel use. This correlation is crucial for understanding air pollution and the environmental impacts of diesel combustion. NO_x is a group of gases, including nitric oxide (NO) and nitrogen dioxide (NO_2), formed when nitrogen and oxygen react under high temperatures in diesel engines. Nitrous oxide (N_2O), a potent greenhouse gas, is also produced during combustion, especially in high-temperature engines [12]. The direct correlation suggests that as NO_x emissions increase, N_2O emissions also tend to rise. Both gases are produced from burning diesel fuel, primarily resulting from reactions between atmospheric nitrogen (N_2) and oxygen (O_2) during combustion. Excess oxygen can lead to more nitric oxide being formed, a key component of NOx. Other reactions at varying temperatures and pressures can produce nitrogen dioxide and N_2O [12].

The correlation may be influenced by the effectiveness of diesel engine emission control systems, such as selective catalytic reduction (SCR) and exhaust gas recirculation (EGR), which help reduce NO_x emissions. Engine conditions, such as load, speed, and temperature, can also impact emissions. To reduce air pollution, strategies should address both NO_x and N_2O emissions together. Policymakers could use this information to create regulations targeting both types of emissions to better combat diesel-related air pollution [29]. A strong inverse correlation between CO_2 and N_2O emissions with an r value of -0.870 is significant at the 0.01 level. This means that as diesel fuel emits more CO_2, it tends to produce less nitrous oxide (N_2O), a potent greenhouse gas. Although N_2O can be emitted during combustion, diesel engines generally do not release much of it. Some modern diesel engines have selective catalytic reduction (SCR) systems that convert nitrogen oxides (NO_x) into nitrogen and water, which may explain the inverse correlation. High CO_2 levels might indicate better combustion efficiency, leading to lower N_2O formation. This effect may vary according to different operational conditions [12,30]. The text describes a significant inverse correlation between sulfur trioxide (SO_3) emissions and nitric oxide (N_2O) emissions from diesel fuel. The correlation coefficient of -0.645 indicates that as SO_3 emissions increase, N_2O emissions decrease, and vice versa, but this does not imply causation. Diesel fuel contains sulfur, which converts to sulfur oxide, including SO_3, during combustion. N_2O mainly forms when nitrogen reacts with oxygen in the air during combustion. Modern diesel engines utilize emission control systems such as selective catalytic reduction (SCR) and exhaust gas recirculation (EGR) to reduce both SO_3 and N_2O emissions. The reduction of sulfur content in diesel fuel due to environmental regulations has decreased sulfur oxides emissions. This reduction might alter the relationship with N_2O emissions if fuel quality is a significant factor. The combustion of diesel produces various pollutants, with factors such as temperature and pressure influencing the formation of SO_3 and N_2O. Stricter diesel emission regulations have led to improved fuels and engines, suggesting that reducing sulfur emissions may also reduce nitric oxide emissions, although the connection is not direct. The observed correlation may vary by location and regulations on diesel fuel [12,31].

There is a moderate inverse correlation between CO_2 and SO_3 emissions, with an r of -0.602, significant at the 0.05 level (p=0.008). This suggests that as diesel fuel emits more carbon dioxide, it tends to emit fewer SO_3 emissions [12,32]. Diesel fuels with lower sulfur content, designed to reduce SO_3 (and SO_2) emissions, may have a higher carbon content or be derived from sources that inherently emit more CO_2 due to better combustion of diesel fuel [12]. The correlation between CH_4 and N_2O emissions is significant at the 0.05 level (p=0.022), with an r of -0.679. The inverse correlation between CH_4 and N_2O emissions likely arises from differences in their formation pathways during combustion and the influence of various combustion conditions and fuel types (Table 5) [12,32].

A strong inverse correlation has been found between Suspended Particulate Matter (SPM) emissions and the year, with a correlation coefficient of -0.734 ($p < 0.001$), indicating a significant trend of decreasing SPM emissions from diesel fuels over time.

This decline is due to strict regulations aimed at reducing air pollution from vehicles, such as the EU's Euro standards and the EPA standards in the United States, which have established lower limits for diesel engine emissions.

To comply with these regulations, the automotive industry has developed technologies to lower emissions, such as ultra-low sulfur diesel (ULSD) and biofuels. ULSD has reduced sulfur content in diesel fuel, which helps decrease particulate matter formation. Biodiesel can change how diesel fuel burns, leading to less soot production [33].

Table 5: The results of the Pearson correlation test for the studied variables, specifically the contribution of diesel fuel to emitted air pollutants as a percentage of the total pollutants

Variables		N_2O	CH_4	SO_3	CO_2	NO_x
Year	Pearson Correlation	-0.884**	-0.930**	0.603**	-0.882**	-0.853**
	Sig. (2-tailed)	0.000	0.000	0.008	0.000	0.000
	N	11	18	18	18	18
NO_x	Pearson Correlation	0.643*	0.780**	-0.520*	0.936**	
	Sig. (2-tailed)	0.033	0.000	0.027	0.000	
	N	11	18	18	18	
CO_2	Pearson Correlation	0.870**	0.771**	-0.602**		
	Sig. (2-tailed)	0.000	0.000	0.008		
	N	11	18	18		
SO_3	Pearson Correlation	-0.645*	-0.451			
	Sig. (2-tailed)	0.032	0.060			
	N	11	18			
CH_4	Pearson Correlation	0.679*				
	Sig. (2-tailed)	0.022				
	N	11				

***. Correlation is significant at the 0.01 level (2-tailed).*
**. Correlation is significant at the 0.05 level (2-tailed).*

Technological improvements in engine design, such as common rail injection systems, have enhanced diesel engine efficiency, resulting in fewer unburned hydrocarbons and less particulate matter. The use of after-treatment systems, such as diesel particulate filters (DPF) and selective catalytic reduction (SCR) systems, has also played a key role in capturing and converting particulate matter, making modern diesel vehicles cleaner [30,31].

Additionally, the rise of alternative fuels and electric vehicles has reduced reliance on fossil fuels, further decreasing SPM emissions. Better lubricants and proper vehicle maintenance can also lower emissions, such as through regular engine tune-ups and using the right diesel fuel [10,12]. The weak direct correlation with a coefficient (r) of 0.06 and a high p-value of 0.814 indicates that there is no statistically significant relationship between the percentage of CO emissions and the year. This suggests that CO emissions from diesel fuels have not exhibited a clear trend of increase or decrease over the observed period. The lack of a significant trend may be due to the effectiveness of existing emission control technologies that manage CO emissions, or it could be a result of other factors not included in the analysis that are influencing the data [12].

The very weak correlation coefficient (r) of 0.085 and a high p-value of 0.737 for the relationship between SO_2 emissions and the year implies that there is no statistically significant trend in SO_2 emissions from diesel fuels over time. The data do not provide evidence of a consistent reduction or increase in SO_2 emissions as the year progresses. This could be due to several factors such as the effectiveness of sulfur content regulations in diesel fuel, the use of diesel particulate filters that also reduce SO_2 emissions, or other environmental and technological factors that have not significantly altered SO_2 emissions in the time frame studied [12].

The data highlight a strong direct relationship between the percentage of suspended particulate matter (SPM) and nitrogen oxides (NO_x) emissions, with a correlation coefficient of 0.820 and a significance level of 0.000. This correlation is significant due to combustion processes which are major sources of both pollutants. Combustion, especially involving fossil fuels, releases various pollutants including SPM and NO_x [12,34]. Suspended particulate matter consists of tiny particles in the air, while nitrogen oxides are gases formed when nitrogen combines with oxygen during high-temperature combustion. The generation of these pollutants is connected to the presence of nitrogen in fuel and air. During combustion, nitrogen reacts with oxygen to create different nitrogen oxides, mainly nitric oxide (NO) and nitrogen dioxide (NO_2), which are collectively called NO_x. At the same time, fine particles and aerosols produced contribute to SPM [34]. Understanding the relationship between SPM and NO_x is crucial for pollution control, as reducing one type of emission can help lower the other. Policies aimed at decreasing emissions, such as stricter industrial standards or cleaner vehicle fuels, can improve air quality and lessen health and environmental impacts [34]. There is a strong direct relationship ($r = 0.763$, $p < 0.01$) between suspended particulate matter (SPM) and carbon dioxide (CO_2) emissions, meaning that as SPM increases, CO_2 emissions also tend to rise. This could be caused by factors such as changes in fuel composition, higher fuel usage, or better measurement methods. However, the connection between SPM and CO_2 is not very strong, indicating that while CO_2 emissions generally rise, their direct link to SPM is weaker [35]. CO_2 is a greenhouse gas released during fossil fuel burning, particularly diesel, contributing to climate change and global warming. The relationship suggests that burning diesel creates harmful particles and significantly contributes to CO_2 emissions. Diesel combustion is complex and produces both gases and particles, including CO_2 and SPM. Emission levels can be influenced by combustion efficiency, fuel quality, and engine design. Older or poorly maintained diesel engines often emit more SPM and CO_2 than newer engines equipped with better emission control technologies [35]. From relationship involves combustion chemistry. The reaction during diesel burning produces CO_2, water vapor, heat, and other emissions. Factors such as incomplete combustion and contaminants affect SPM formation. The strong correlation implies that efforts to reduce SPM could also lower CO_2 emissions. This insight is important for environmental policy, as policies aimed at reducing one type of pollution may also benefit another, such as enforcing stricter diesel emission standards or promoting alternative fuel use to improve air quality and combat climate change [35]. There is a strong direct correlation between Suspended Particulate Matter (SPM) and Methane (CH_4) emissions from diesel fuel, with a correlation coefficient of 0.693 and a significance level of $p < 0.01$. This means that as SPM increases, CH_4 emissions also tend to rise. This relationship is influenced by the combustion process in diesel engines and the chemical makeup of diesel fuel. The quality of diesel fuel affects emissions; fuels with higher sulfur content can increase SPM, while those with higher aromatic content can raise CH_4 emissions. After-treatment devices may reduce SPM but may not effectively lower CH_4. Higher combustion temperatures can reduce both emissions, but excessive heat may create thermal NO_x. Heavy loads and aggressive driving can lead to incomplete combustion, increasing SPM and CH_4 emissions (Table 6) [35].

Table 6: Spearman's rho test of studied variables (air pollutants emitted by diesel fuel among all fuels in percentage)

Variables		**SPM**	**CO**	**SO_2**
Year	Correlation Coefficient	-0.734**	0.06	0.085
	Sig. (2-tailed)	0.001	0.814	0.737
	N	18	18	18
NO_x	Correlation Coefficient	0.820**	-0.033	-0.111
	Sig. (2-tailed)	0.000	0.897	0.662
	N	18	18	18
SO_2	Correlation Coefficient	-0.228	0.091	
	Sig. (2-tailed)	0.362	0.720	
	N	18	18	
CO_2	Correlation Coefficient	0.763**	0.03	
	Sig. (2-tailed)	0.000	0.907	
	N	18	18	
SO_3	Correlation Coefficient	-0.434	0.033	
	Sig. (2-tailed)	0.072	0.897	
	N	18	18	
CO	Correlation Coefficient	-0.157		
	Sig. (2-tailed)	0.533		
	N	18		
CH_4	Correlation Coefficient	0.693**		
	Sig. (2-tailed)	0.001		

Conclusion

The analysis of diesel's impact on pollutant and greenhouse gas emissions reveals significant trends. There has been a slight decrease in diesel's contribution to nitrogen oxides (NOx) emissions, indicating improvements in combustion and emission technologies. However, diesel's share of sulfur dioxide (SO_2) emissions has increased, likely due to higher diesel usage, despite overall emissions possibly decreasing due to a shift toward natural gas and renewable sources. Diesel emits low levels of carbon monoxide (CO) due to modern technologies and its lower carbon content compared to coal and biomass.

There has been a notable reduction in diesel's methane (CH_4) emissions, attributed to efforts to minimize methane leakage and a transition to bio-based diesel. A strong correlation between carbon dioxide (CO_2) and nitrous oxide (N_2O) emissions suggests that advancements in diesel technologies and regulations have helped decrease these emissions. In contrast, the direct relationship between CO_2 and NO_x emissions highlights the complexity of combustion and the necessity for effective emission controls.

Policymakers should enforce stricter emission standards for diesel vehicles and power plants, aligning with international standards or enhancing local regulations. Investing in public transportation and alternative fuels, particularly electric vehicles, is vital to reduce diesel usage and emissions. Encouraging renewable energy sources and improving diesel fuel quality through lower sulfur content and advanced technologies is also crucial. Offering financial incentives for enhanced emission control systems and ensuring regular vehicle maintenance can help minimize pollution.

Establishing low emission zones (LEZs) in urban areas to restrict high-emission vehicles, alongside public education efforts to raise awareness about diesel pollution and cleaner alternatives, is essential. The energy sector should transition to renewables to decrease dependence on diesel energy. For sectors still reliant on diesel, implementing advanced technologies and after-treatment devices can aid in emission reduction. Increasing the use of biodiesel and fostering collaborative research efforts can lead to solutions for diesel pollution.

Future research should encompass long-term studies on policy impacts, the health effects of diesel pollutants on vulnerable populations, and life cycle analyses of diesel. Real-world emission testing is critical, as is the evaluation of the cost-effectiveness of strategies to lower diesel emissions.

Conflict of Interest

The authors declared no conflicts of interest in this study.

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