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Review

Overview of Biodiesel Combustion in Mitigating the Adverse Impacts of Engine Emissions on the Sustainable Human–Environment Scenario

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Abstract: Air pollution is a precursor to many health issues such as difficulty breathing, asthma, lung and heart diseases, and cancer. This study presents a concise view of biodiesel combustion in mitigating pollutant emissions which are generated by the combustion of fossil fuels, thereby eliminating the negative effects on human health and the environment. Gaseous pollutants such as carbon monoxide, unburned hydrocarbons, nitrogen oxides, particulate matter, and carbon dioxide are found to be major exhaust emissions from vehicles running on fossil fuels. Excessive exposure to these pollutants was found to be a precursor to reductions in life expectancy via health complications in humans. Greenhouse gas emissions from the transport sector were found to be 24% of total annual emissions, 74.5% of which came from the combustion of fossil fuel in road vehicles. Biodiesel combustion in vehicular engines is established to be a control technology in reducing gaseous pollutants toward building a sustainable and healthy human–environment scenario. The emissions reduction index from the United States National Biodiesel Board showed that the combustion of biodiesel wholly as a transportation fuel decreased total hydrocarbons, polycyclic aromatic hydrocarbons, carbon, and sulfur emissions by 67%, 80%, 48%, and 100%, respectively. Evaluation of emission results from topical literature strongly suggests that the use of biodiesel is effective in the reduction in pollutants, which is beneficial to human and environmental sustainability.

Keywords: air pollution; biodiesel; gaseous pollutants; greenhouse emissions; environmental sustainability

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1. Introduction

Air is an important component of the environment which aids various life processes and our subsistence on earth [1]. Air pollution is described as the introduction of pollutants, contaminated materials, chemicals, or particulate matter into the atmosphere which can cause damage to human health, other organisms, or to the environment [1,2]. According to the WHO [3], about seven million deaths are recorded yearly worldwide from excessive exposure to outdoor air pollution. These estimated deaths occur from excessive exposure to pollutant emissions which have adverse impacts on human health. Common gaseous and particulate pollutants, which are very dangerous to human health at high exposure, include carbon monoxide, ammonia, ethyl benzene, hydrogen sulfide, lead, methyl chloride, nitric acid, nitrogen dioxide, sulfur dioxide, ozone, welding fumes, and particulate matter. Common serious air pollution-related diseases and health issues suffered by humans include acute respiratory problems, cancer, birth defects, long-term lung injury, neurological and optical damage, risk of stroke, cardiovascular disease, premature death, and morbidity [4,5]. Recent studies on air pollution impacts have confirmed that there is a linear relationship between infection and death rates of patients suffering respiratory-related diseases in highly polluted environments [6–11].

The dependency on fossil fuels is currently high, even though their combustion is detrimental to the environment through the release of harmful emissions into the atmosphere [12]. Pollutant emissions from the combustion of fossil fuels have placed billions of lives at risk as a result of the increasing global warming phenomenon, which is caused by the damaging effect of emissions on the ozone layer, which protects the earth from the direct impact of sunlight radiation [13]. Air pollution from human-related activities have led to the formation of poor air quality, especially in urban areas. According to the World Health Organization (WHO) 2014 report, approximately seven million urban people globally lost their lives in 2012 as a result of air pollution [14]. High concentrations of particles in the air are threats to human health because of the associated negative effects such as heart disease, lung cancer, and lung malfunctions [15].

The human–environment scenario is becoming vulnerable to pollution hazards from the accumulation of large concentrations of gaseous pollutants in the atmosphere. For instance, greenhouse emissions are reported to have expansive negative effects on human health and the surrounding environment [16,17]. Consequently, the climate is changing, atmospheric temperatures are rising due to trapped heat from accumulated gases, the glaciers are melting and causing sea levels to rise at greater rates, and particulate matter and gaseous pollutants contribute to fatal respiratory diseases and health complications [18,19]. Relative to this, obnoxious and poisonous emissions from the combustion of fossil fuel products cannot be left to pollute our environment and make people susceptible to severe acute respiratory syndromes [20,21]. However, the use of natural resources in generating energy offers remarkable solutions in achieving the eradication of pollution and achieving a sustainable environment. Green technology is fast advancing by several energy-generation techniques which favor the protection of the natural environment [22,23].

Biofuel production and its utilization, particularly in the transportation industry, is one of the efficient ways to conserve nature and the environment [24]. Many scientific reports on the generation and application of renewable energy have shown that alternative energy sources can efficiently replace fossil fuel based on their renewability and eco-friendliness. A high level of global transition to clean energy has been witnessed over the years as the world continues to record huge production and trade-off rates of biofuels, with many innovative research studies offering progressive solutions [24]. Based on the increasing explorations of biofuels in vehicular engines, current studies are focused on developing novel feedstock and techniques to achieve considerable success in cutting down obnoxious engine emissions from the combustion of fossil fuels [25–28]. The recent trend of development and applications of biofuels in internal combustion (IC) engines is evident of increased global adoption and commercial availability to keep fossil fuels out of use. Between 2015 and 2019, biodiesel industries have increased their production by 15% compared to previous years [29].

Taking into consideration literature which captures the merits of biodiesel combustion and the relevance to air pollution reduction and environmental sustainability, there is no single inclusive study which connects the positive impacts of biodiesel combustion with reductions in harmful emissions in connection with a sustainable and healthy human–environment scenario, which can be achieved through clean air. The aim of this study is to present an overview of biodiesel combustion relative to air pollution reduction and environmental sustainability. This study was carried out to show the colossal destructive effects which gaseous pollutants from the combustion of fossil fuel resources have on the earth and living organisms on its surface. This is a systematic literature review which is both informative and knowledgeable on the much-needed positive impacts of biodiesel combustion in creating a sustainable environment. The collation of references was performed using Elsevier's reference management software Mendeley. The research literature was selected from journals indexed in Scopus, Web of Science, and verified international scientific reports. The chosen studies were peer-reviewed articles which have contributed significantly to the research area. Several keywords, such as biodiesel, air pollution, gaseous pollutants, green energy, sustainable development goals, global warming, and plant oil feedstock, were used for sourcing information.

In the Introduction, conservation of the environment via the sustainable use of biofuel was presented. Section 2 captures a narrative of pollutant emissions from fossil fuel combustion in ignition compression (IC) engines. Section 3 covers a discussion on the negative impacts of pollutant emissions on human quality of life. The abatement of pollutant emissions via biodiesel combustion was explored in Section 4. Road transportation as a contributor of harmful air pollutants and the nexus between fuel combustion in IC engines and sustainable environmental development are discussed further. The metrics which are expected of a sustainable biofuel, relative to positive human–environmental impacts, are highlighted for a better understanding of the long-term sustainability of biodiesel.

2. Pollutant Emissions from Fossil Fuel Combustion in IC Engines

Diesel engines are extensively used because of their energy efficiency, high durability, and reliability. Consequently, they have become the power source of commercial and heavy industrial vehicles [30]. However, their impacts on environmental pollution and human health cannot be underestimated. Exhaust gases from diesel engines majorly comprise pollutant emissions, CO_2, and minor traces of H_2O, O_2, and N_2. The pollutant emissions are generally made up of carbon monoxide (CO), unburned hydrocarbons (HC), nitrogen oxides (NO_x), and particulate matter [30]. Novotná et al. found that diesel emissions are more genotoxic than the emissions from biodiesel (B100) combustion [31]. Similarly, a toxicological risk assessment of fossil diesel and biodiesel fuels showed that high levels of poisonous particulate emissions were released from the combustion of diesel, while lower concentrations were released from biodiesel [32]. For the relevance of the discussion in this paper, the four major pollutant emissions and carbon dioxide are discussed in this section. The adverse environmental and health impacts of carbon dioxide are colossal owing to its greenhouse gas properties and contributions to global warming. Their negative footprints on environmental sustainability and human health are discussed in the following sections.

2.1. Carbon Monoxide Emissions

Carbon monoxide (CO) is a colorless, odorless gas that can cause illness and death when inhaled in large concentrations [33]. Carbon monoxide is a product of incomplete combustion where there is incomplete oxidation of the fuel. Most of the CO in the atmosphere comes from vehicle exhausts. This concentration is primarily determined by the air/fuel mixture and is highest where the excess air coefficient is less than 1.0, which is classified as rich mixture [34]. In internal combustion engines running on fossil fuels, CO is produced at both ignition and instantaneous acceleration stages of the engine, where an excessive proportion of fuel is needed for combustion. A rich mixture of fuel contains too much fuel and not enough air. Due to air deficiency, the combustion process leads to the formation of CO as a result of incomplete oxidation of all the carbon molecules into CO_2. When CO is inhaled by humans, adsorption into the gas exchange region of the respiratory tract occurs where it reacts with hemoglobin (Hb) to displace oxygen and form carboxyhemoglobin (COHb), a poisonous compound which inhibits the flow of oxygen to the tissues and organs of the body [35]. If the concentration of CO is too much in the human airways (440% blood saturation), cardiovascular collapse, seizures, coma, and death may occur [36]. Compared to the emissions from fossil diesel, the exhaust emissions of carbon monoxide were found to be 48% lower on average for biodiesel [37].

2.2. Unburned Hydrocarbons Emissions

Unburned hydrocarbon emissions are basically caused by the incomplete combustion of fuel as a result of insufficient temperature near the cylinder wall, which could be brought about by unfavorable engine design, low fuel quality, or failure in the control system [38]. Unburned hydrocarbons can be formed in both spark and compression ignition engines, but compounds from the latter are heavy owing to a higher molecular weight of the diesel fuel [39]. Hydrocarbon emissions have damaging effects on human health and the environment [30]. When inhaled in large concentrations, they have the potential to trigger irritation of the respiratory tract and cause cancer [37]. It is reported that vehicular emissions account for about 50% of unburned hydrocarbons, which react with other pollutant emissions to form ground-level smog [40]. Compared to the emissions from fossil diesel, the exhaust emissions of total hydrocarbons were found to be 67% lower on average for biodiesel [37].

2.3. Nitrogen Oxide Emissions

Nitrogen oxides (NO_x) are odorless, colorless gases which comprises nitrogen monoxide (NO), nitrous oxides (N_2O) and nitrogen dioxide (NO_2) [41,42]. Nitrogen oxide emissions are formed in IC engines as a result of higher in-cylinder temperature [43]. NO_x emissions are mostly formed in the early phase of combustion process, when the flame temperature is at the highest [44]. It is established more in some scientific studies that increase in combustion temperature increases NO_x emissions concentrations [43,45,46]. Nitrogen oxides from motor vehicle exhaust are responsible for many environmental and health hazards [47]. Tropospheric NO_x emissions, accumulating from fossil fuel combustion, have increased globally at 1–2% per decade since 1900. The consequent environmental hazards occasioned by this increase include acid rain, ozone, and smog formation [48]. Nitrous oxides, for instance, are gases whose greenhouse effect is 300-fold greater than that of CO_2 on a molecular basis. Prolonged exposure and inhalation of elevated NO_x emissions can cause respiratory diseases such as bronchitis and emphysema, and can also trigger heart diseases in humans [42]. NO_x emissions, from several research studies, were found to increase or decrease for biodiesel fuel depending on the engine type and testing procedures. NO_x emissions were found to increase by 10% on average from pure biodiesel (B100) [37].

2.4. Particulate Matter Emissions

Particulate matter, also known as suspended particulate matter (SPM), comprises fine solid particles which are generated from the combustion of fossil fuels [49]. Particulate matter emissions are small enough (varying from <2.5 µm ($PM_{2.5}$) and <10 µm (PM_{10}) in diameter) to enter human lungs and cause health complications [50]. Particulate matter is caused by a collection of very small particles from incomplete combustion of the hydrocarbons in fossil fuels [51]. Particulate matter comprises reactive gases, ions, metals, organic compounds, and particle carbon core. These fine particles are more hazardous than the coarser ones in terms of respiratory and cardiovascular effects in humans [52]. Research has shown that the inhalation of PM into human lungs can trigger complicated health problems such as asthma, lung cancer, aggravate asthma, reduced lung functionality, irritation in airways, coughing, difficult breathing, premature mortality in patients suffering from lung or heart disease, and other cardiovascular issues [52]. Several scientific studies indicate that short-term exposure to PM can bring about acute cardiovascular problems, while long term-term exposure can cause permanent heart failure [53]. On average, the primary PM emissions from biodiesel were found to be 47% lower than PM emissions from fossil diesel [37].

2.5. Carbon Dioxide Emissions

The carbon emissions from fossil fuel combustion have drastically increased over the years since 1900. Combustion of fossil fuels is one of the major processes responsible for air pollution through the release of high concentrations of carbon dioxide more than the stipulated standard [12]. Between the years 1970 and 2011, carbon dioxide emissions from fossil fuel combustion and industrial processes have contributed 78% of the total greenhouse gas. The increases in carbon dioxide emissions are associated with a number of factors, ranging from population growth to the utilization of fossil energy resources. The major sources of these carbon emissions include transportation, electricity generation (coal burning), industrial activities, commercial activities, and agriculture. The global distribution of carbon dioxide (CO_2) by continent and some major countries from 1750 to 2019 is shown in Figure 1. Carbon dioxide was found to have increased from 2 billion tons in 1900 to over 36 billion tons 115 years later (2015) [54]. The annual emissions of carbon dioxide are indicated to be high for China, followed by the United States of America in the diagram.

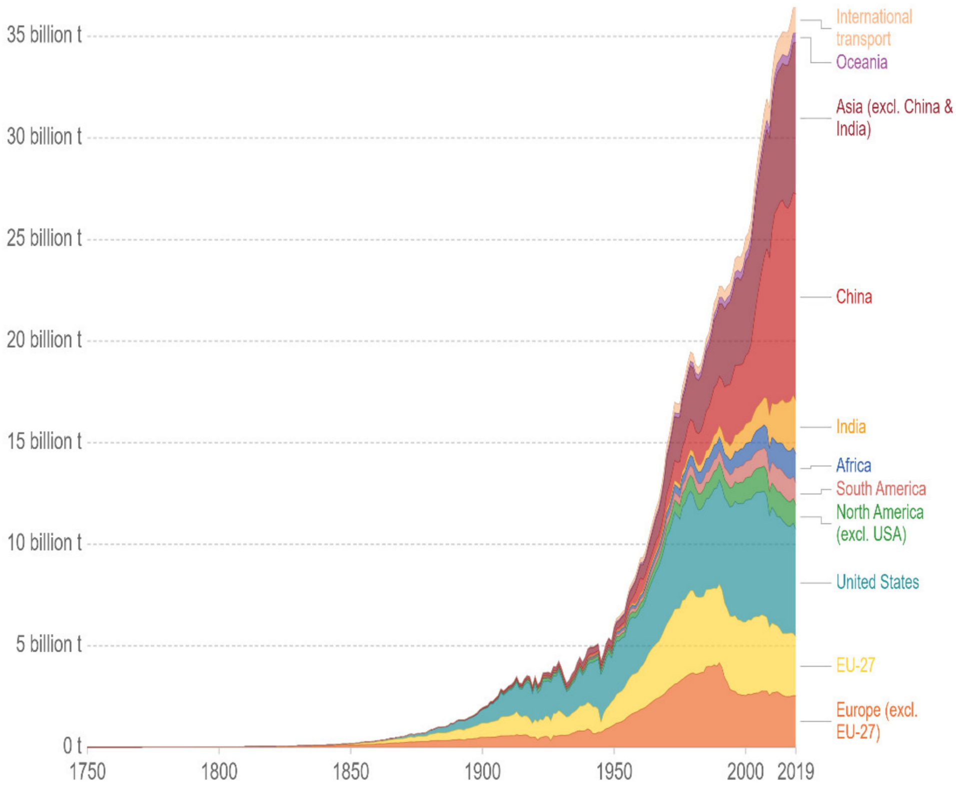

Figure 1. Annual total CO_2 emissions by world region, 1750 to 2019. Source: Global Carbon Project. Reprinted from Global Carbon Project [54].

Carbon dioxide is reported to constitute the largest emission concentrations contributing to global warming, a phenomenon caused by the increasing rates of atmospheric greenhouse gases (GHGs) [55]. This nexus between GHGs and global temperatures is a recurring phenomenon, which has been scientifically proven in the history of Earth's climate change [56]. The increased warming of the Earth's surface has brought about environmental and health impacts, including extreme weather conditions (such as heat waves, storms and floods), adverse changes in crop's growth, and increased ill human health [57]. A synergetic relationship between the averaged global temperature and carbon dioxide is depicted in Figure 2.

The six largest contributors of GHG emissions consist of the United States, China, India, the Russian Federation, Japan, and the European Union (EU-28). As a result of the existing occurrence of air pollution, countries such as China and the United States are threatened with health challenges. For China, an annual increase of 9% in pollution level is reported to occur as the emission levels advance towards their peak by the year 2030 [55]. This value will likely skyrocket with increasing industrial and locomotive activities which involve the considerable combustion of fossil fuel.

Out of the world's largest emitters (Figure 3), the GHG emissions from four of them have continued to increase, except for Japan and the EU, which recorded decreases of 1.2% and 1.5%, respectively. According to reports, the increasing global warming trend is directly linked to human emissions of GHGs. For instance, January 2020 was the hottest January on record globally. For the top emitters, the historical and projected GHG emissions from fuel combustion are shown in Figure 4. China was found to be the only country with a continuous increase in GHG emissions, which are caused by rapid industrialization unfolding in the country. Since 2014, GHG emissions from the EU-28 transport industry has kept increasing. As of 2016, about 72% of total GHG emissions were estimated to come from transport (44% came from passenger cars) [58].

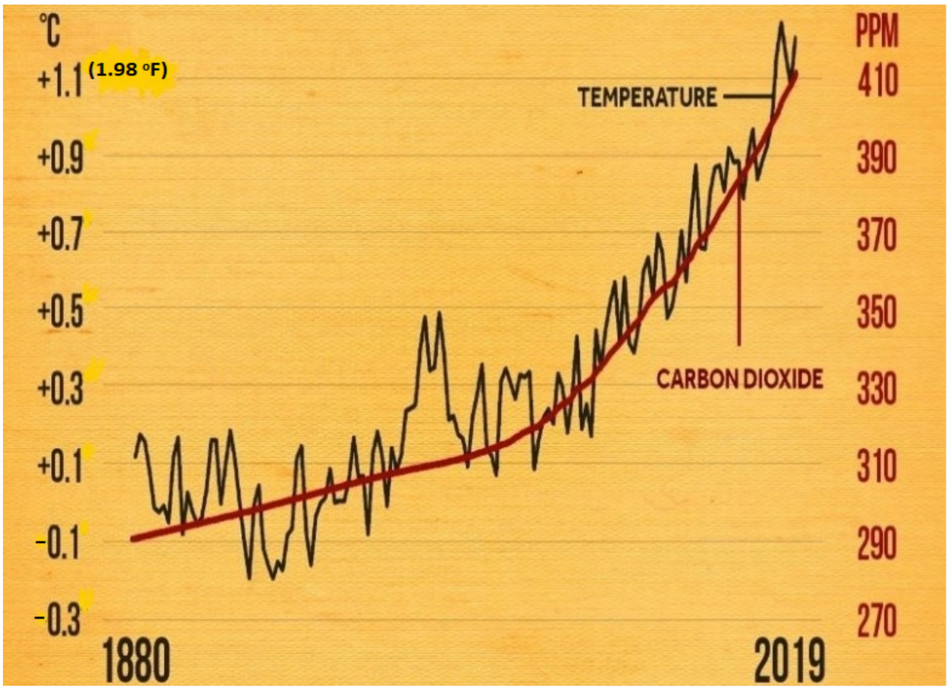

Figure 2. Relationship between global temperature and carbon dioxide. Reprinted from USEPA [59].

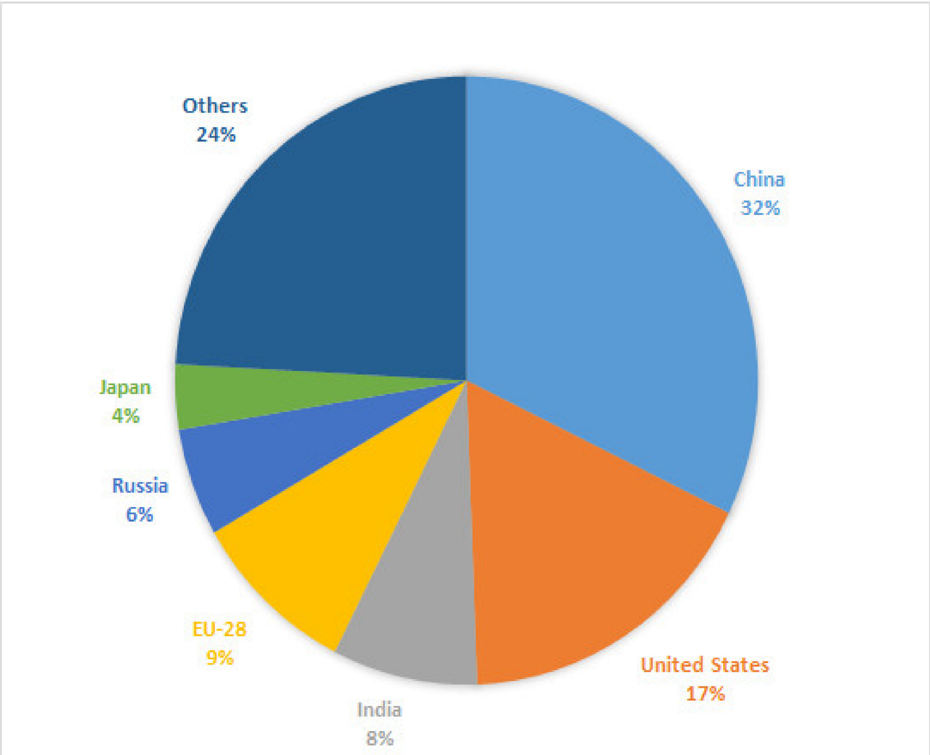

Figure 3. World largest GHG emitters. Adapted from Ghosh [60].

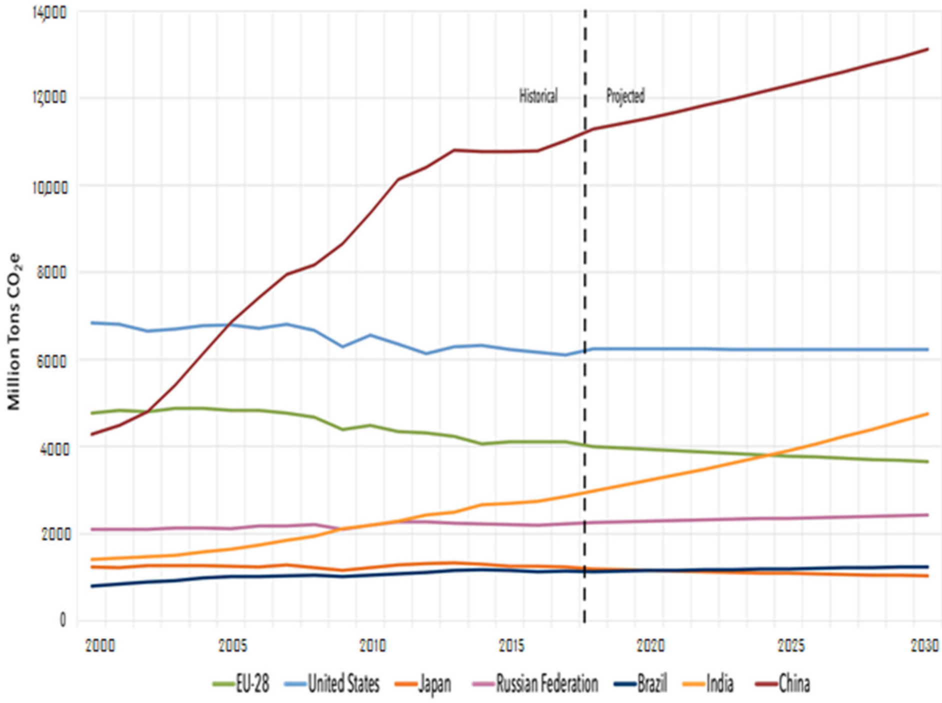

Figure 4. Historical and projected GHG emissions from fuel combustion for major economies, 1990–2030. Reprinted from International Energy Agency [61].

The global emissions, particularly carbon emissions, are expected to rise in the coming decades owing to rapid urbanization and population increases. By the year 2007, the car ownership rate had increased by 60% [62]. As long as these cars continue to run on fossil fuels, colossal increases in carbon emissions should be anticipated. The global annual transport emission concentrations from various modes are presented in Figure 5. From the chart, road transport contributes three-quarters of transport emissions. If the transport sector is responsible for 21% of global CO_2 emissions [63], road transport accounts for 15% of global CO_2 emissions. Beyond 2020, the global emissions need to decrease in order to achieve the global clean air act [64]. From the year 2040, renewable biofuels, such as biodiesel, are projected to have been adopted in many economies for the purpose of eradicating or decreasing carbon emissions from fossil fuel combustion by 70%.

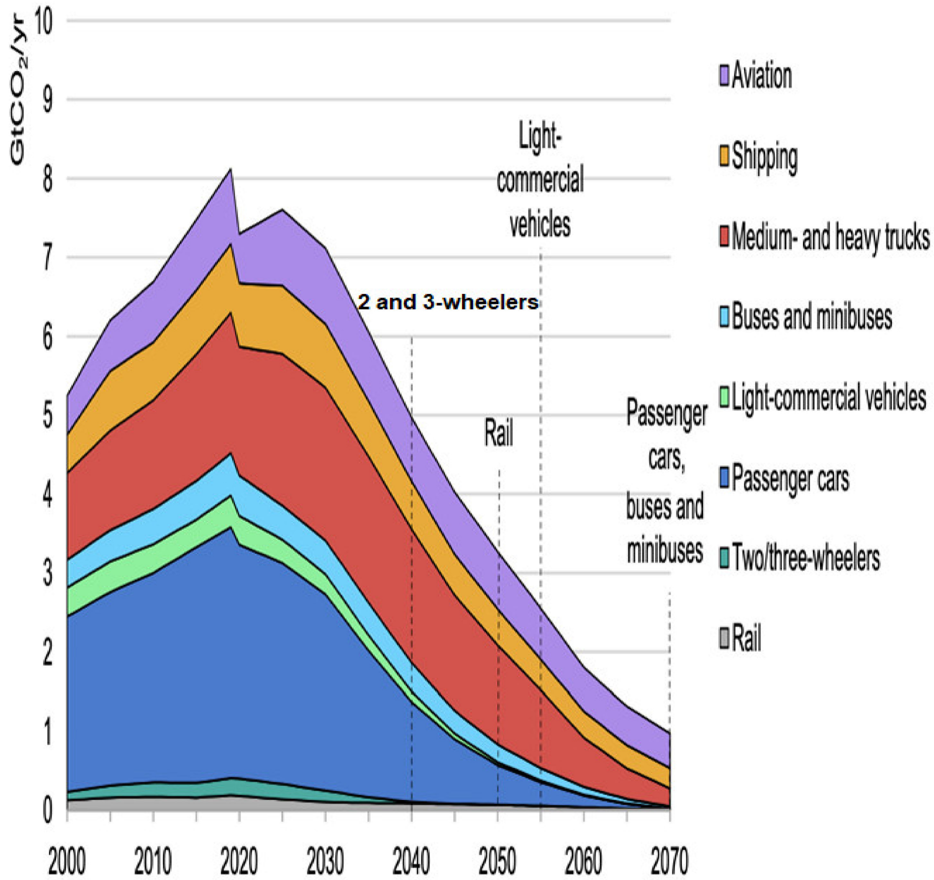

Figure 5. Current and projected global CO_2 emission from various modes of transport (Sustainable Development Scenario, 2000–2070) Reprinted from IEA Key World Energy Statistics 2020 [62]. Note: dotted lines indicate the year in which all transport modes are expected to have largely stopped running on fossil fuels.

3. Negative Impacts of Pollutant Emissions on Human Life Quality

A recent report entitled the "Air Quality Life Index" from the University of Chicago stated that air pollution is the world's top killer [65]. This publication revealed that pollutant emissions exceeding WHO guidelines reduce the life expectancy of every person by an average of 1.8 years. With the current world population distribution, an average of 12.8 billion years of life will be lost if the concentrations of air pollutants continue to increase. From Figure 6, particulate pollution was found to have the greatest reduction rate on average life expectancy per person, amongst several other causes. The "State of Global Air" study conducted by the Health Effects Institute revealed that the life expectancy reduction is attributed to existing levels of particulate matter (PM)—2.5 microns exposure [66]. The report detailed the top ten countries that are affected most by life expectancy cuts as a result of air pollution. The most affected countries by life expectancy reduction are shown in Figure 7. According to the infographics, six countries in Asia have some of the most harmful polluted air in the world. Coincidentally, these are some of the most populous countries in the world that are characterized by high human and industrial activities involving fossil fuel combustion.

Figure 6. Global average life expectancy reduction owing to different causes. Reprinted from Greenstone and Fan [65].

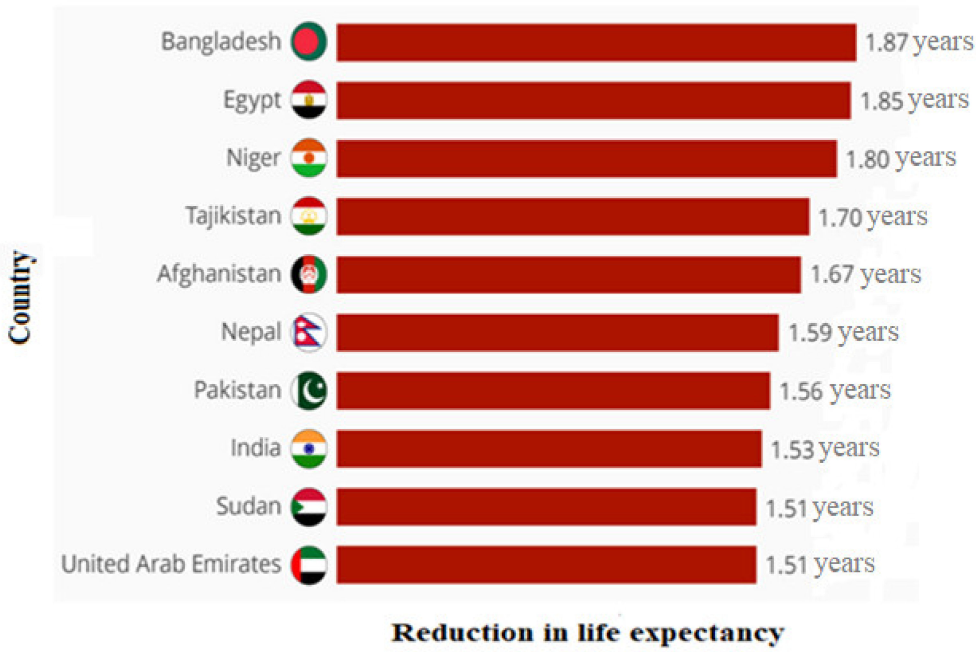

Figure 7. Most affected countries by life expectancy reduction. Reprinted from Health Effects Institute: State of Global Air [66].

Gaseous pollutants can accumulate to form haze or smog during unpleasant weather conditions. When inhaled, they can settle deep in the human lungs and cause acute respiratory malfunctions [67,68]. It is reported that certain pollutant emissions can lead to Alzheimer's, Parkinson's, and respiratory health problems such as asthma and lung cancers [69–71]. These gaseous pollutants and particulate matter can also combine to form some other types of air pollutants. Hydrocarbons and nitrogen oxides can combine in the presence of sunlight to form ozone. Even though ozone is meant to protect the earth's surface from the sun's ultraviolet rays, any damage to the layer by greenhouse gases will release ozone to the earth's surface, which further initiates the formation of smog and development of respiratory problems in humans [72,73]. A summary of the adverse impacts of harmful pollutant emissions on human health is presented in Table 1.

Table 1. Outdoor air pollutants and adverse impacts on human health. Adapted from Ritchie and Roser [5]; Ghorani-Azam et al. [74]; and Riojas-Rodríguez et al. [75].

Pollutant	Source of Emission	Adverse Impacts on Human Health
Carbon monoxide (CO)	Fossil fuel combustion, burning coal, oil industrial activities, oil and wood, smoke	Hypoxia (oxygen deprivation by displacing oxygen in bonding with hemoglobin. Common side effects include cardiovascular and coronary problems, risk of stroke, impaired learning ability, dexterity, and sleep).
Carbon dioxide (CO_2)	Fossil fuel combustion, burning coal, oil industrial activities, oil and wood, smoke	Inflammation, reduction in cognitive abilities, kidney calcification, bone demineralization, heart dysfunction.
Sulfur dioxide (SO_2)	Burning coal, fossil fuel combustion	Adverse effects on respiratory and central nervous systems, eye irritation.
Particulate matter (PM) (often estimated for 10 and 2.5 microns)	Fossil fuel combustion, industrial activities, smokes	Permanent deterioration of respiratory function, dysfunction of central nervous and reproductive systems, cardiovascular diseases, and cancer.
Lead (Pb)	Lead smelting, industrial activities, leaded petrol	Heart disease, premature death, and behavioral and development problems in children.
Nitrogen dioxide (NO_2)	Vehicular exhaust, fossil fuel combustion	Damaged lung tissue, liver, spleen, and impaired respiratory functions.
Polycyclic aromatic hydrocarbons (PAHs)	Fuel combustion, wood fires, motor engines	Damage to respiratory and central nervous systems, cancer.
Ozone (O_3)	Vehicular exhaust, industrial activities	Impaired respiratory function (short-term exposure), cardiovascular dysfunctions, and eye irritation.
Volatile organic compounds (VOCs)	Fossil fuel production and combustion, use of heavy chemicals (paints and coatings), biomass combustion	Irritation of eyes, nose, throat, and mucosal membranes, cancer.

The pediatric impact of pollution from fossil fuel usage is another issue that confronts human and environmental sustainability. A study showed that combustion of fossil fuel does not only pose a threat to the wellness of adults, children are also found to be negatively impacted in various degrees of disorderliness and impairment in their growth and behavioral development [19]. The authors reported that children show respiratory issues and other severe diseases as they develop [19]. Developing fetus are greatly affected when exposed to polluted environment. Air pollution greatly inhibits proper development of the tissues and organs solely because children are characterized by an immature or weak immune system, which serves as a line of defense against disease-causing organisms or substances [12].

4. Abatement of Pollutant Emissions Via Biodiesel Combustion in IC Engines

Biodiesel is the first alternative fuel that has perfectly accomplished the health effects assessment preconditions of the Clean Air Act of the United States. The Tier 1 and Tier 2 testing of biodiesel can be obtained from USEPA [74]. Owing to the clean burning nature of biodiesel, its adoption as an engine fuel has been established as an air pollution control technology. From its combustion, gaseous pollutants such as CO, SO_2, NO_x, HCs, etc., which are produced from the incomplete combustion of fossil fuels can be minimized. The green energy contained in biodiesel is a suitable alternative to petroleum diesel, and its combustion in internal combustion (IC) engines has minimal impact on the net gaseous emissions via reductions in CO_2, CO, SO_2, and HC [75]. The lifecycle assessment of biodiesel from the photosynthetic process to combustion in diesel engines is in favor of pollutant emissions reduction owing to the fact that more of the CO_2 released during engine combustion can be reabsorbed into biomass cultivation. Hence, when compared with the use of petroleum diesel, biodiesel combustion can more beneficially mitigate CO_2

emission, maintain ecological balance, and protect the natural environment [75]. It has been estimated that soy biodiesel reduces carbon dioxide by 78% on a life cycle basis [76,77]. The combustion of biodiesel in diesel engines has been established as an alternative fuel to reduce major transportation pollutant emissions CO, PM, NO_x and VOCs, all of which contribute to smog formation and poor air quality [78].

Emission reduction data from the National Biodiesel Board of USEPA [78,79] showed that the combustion of B100 as a transportation fuel decreased total HC, polycyclic aromatic hydrocarbon (PAH), carbon, and sulfur emissions by 67%, 80%, 48%, and 100%, respectively, in the year 2018 [29]. Higher reductions in PAH and sulfur emissions can be explained by the absence of aromatic compounds and sulfur. However, a 10% increase was reported for the same blend of biodiesel. As a result of the biological nature of biodiesel, its use in conventional diesel engines will generally reduce emissions related to hydrocarbons (HCs). Additionally, CO and particulate matter will be less discharged because ester compounds in biodiesel are rich in oxygen, which has the capacity to enhance the complete combustion of fuel and also promote clean burning. Additionally, the process of biodiesel combustion is meant to produce lower SO_2 emissions because biofuel is produced from bio-oil, which has a lower sulfur content than fossil diesel oil. The use of biodiesel as an alternative fuel will effectively reduce acid rain. The presence of sulfur and nitrogen oxides in atmospheric gaseous emissions is involved in the formation of acid rain [80]. The level of acidity of rain can be increased when these oxides mix with atmospheric moisture and form sulfuric acid or nitric acid, whose concentrations are more dangerous than carbonic acid [81]. Continuous formation and precipitation of acid rain to the earth poses a serious threat to human existence and the environment because it eventually increases the acidity of soil surface water and groundwater, causes damage to forest and vegetation, and inhibits aquatic life development [81].

The increasing usage of biodiesel in IC engines of passenger cars, light and heavy duty vehicles, marine ships, and municipal buses have been studied to evaluate the impacts of the blended fuel wholly or partially on the performance and exhaust emissions of these engines [82–88]. Aside from the benefits which biodiesel offer, there is a controversial increase in poisonous nitrogen oxides. Even though efforts have been made to reduce them by adding fuel and initiate ignition delays, the problem has not been totally solved. With reference to publication records on this negative impact of biodiesel combustion in transportation industry, the long-term focus of chemical science on biofuel production should be towards developing quality biofuels and achieving zero pollution levels from their combustion in IC engines.

In contrast to the use of fossil fuels, a good number of research studies on the combustion of renewable biodiesel in IC engines have shown that it is effective in terms of engine performance improvement and reduction in harmful emissions [29]. The impact of the reduction levels in gaseous pollutants have been established in many scientific studies. A statistical report on the effect of biodiesel on engine emissions was reported by Xue et al. [89], in order to promote understanding of successful research on the use of biodiesel in diesel engines. Most of the studies consulted were preferentially selected between the years 2000 and 2010. Records of significant reductions in CO_2, CO, and HC emissions and increases in NO_x were analyzed based on the selected available literature. An extracted summary of data from the statistical evaluation is presented in Table 2. The authors concluded that the utilization of biodiesel in diesel engines was successful with no major modification to the engines, and that it can help in controlling air pollution by cutting down the carbon footprints in atmospheric air as opposed to the increments recorded from the use of fossil diesel. Similarly, a few recent studies on biodiesel combustion in IC engines were sourced from high-impact journals to analyze their emissions rates as compared to petrol diesel. A summary is presented in Table 3.

Table 2. Statistical results of pure biodiesel on engine performances and emissions. Adapted from Xue et al. [90].

Emissions	Increase in Emission		Decrease in Emission	
	Number of Studies	%	Number of Studies	%
CO_2	6	46.2	5	38.5
CO	7	10.6	57	84.4
THC	3	5.3	51	89.5
NO_x	45	65.2	20	29.0

Table 3. Recent research on emissions release rate from biodiesel combustion compared to fossil diesel. Adapted from Ogunkunle and Ahmed [29].

Reference	Feedstock	Fuel Blends	Engine Condition	Emissions Reduction Compared to Fossil Diesel (%)			
				CO_2	CO	HC	NO_x
[45]	*Parinari polyandra*	B10, B20, B30	1700 to 2000 rpm	−21.7 to −53.8	−53.4 to −81.7	−7.8 to −13.8	24.8 to 51.1
[46]	*Chlorella vulgaris*	B10, B20		−3.4 to −5.4	−41.8 to −47.4	−44.3 to −51.1	1.9 to 5.1
[91]	Jatropha	B100	1500 and 2000 rpm	–	−20 to −25	−17 to −23	−0.3 to −4.5
[91]	Soybean	B5, B20, B50, B85	9.6 to 35.7 kW	−0.89 to 1.48	28 to 48	−9 to 18	-
[92]	*Eruca sativa*	B10	5.88 kW at 2600 rpm	160	−30	-	108
[93]	Waste oil	B5, B10	0.12 to 0.48 MPa, 2200 rpm	3.3 to 5	−11.8 to −51	−2 to −29	6.4 to 8.7
[94]	Jatropha	B10, B20, B30, B50	Full load, 1500 to 2400 rpm	13.08	− 16.3	− 7.4	27.25
[95]	*Chlorella protothecoides*	B20, B50, B100	1700 to 2900 rpm	−0.7 to −4.2	−12.3 to −28	–	−2.4 to −7.4
[96]	Sunflower and soybean oil	B30, B50, B70	5 HP; 7 kW at 1500 rpm	−6.06 to −14.17	−15.02 to −30.73	−1.83 to −4.18	4.28 to 11.9
[97]	Fish oil	B5	1200 rpm, 25% to full load	−25	−8	−8	35

The italicized indicate the scientific names of the feedstock.

All these values were measured on the tank-to-wheel basis. The common observation about the selected publications was that they reported on these gaseous emissions (CO_2, CO, THC, and NO_x). Highest average increases and reductions in emissions were found to have taken place concerning NO_x and CO. The carbon emission levels, on average, were found to have reduced significantly. The concentrations of measured CO [26,98–101], CO_2 [89,98,102], THC [103–106], and PM [107–110] were found to be lower than that of fossil diesel in the literature. This is one major environmental positive impact which guarantees the sustainable use of biodiesel in diesel engines in the long-term consideration of alternative clean fuel by consumers. More discussion on the emission reductions can be found in studies which have robustly reviewed the combustion of biodiesel in IC engines [29,111–113]

An analysis of the exhaust emissions and performance evaluation of *Parinari polyandra* biodiesel was performed by Ogunkunle and Ahmed [45]. They reported that the blending of *Parinari polyandra* biodiesel with fossil diesel was a viable alternative fuel for a reduction in carbon emissions into the atmosphere. All other measured emissions, THC, CO_2, CO, and SO_2, were found to be lower than that of fossil diesel, except NO_x. While using biodiesel–diesel blends of B10 (Biodiesel—10%, Fossil diesel—90%), B20 (Biodiesel—20%, Fossil diesel—80%), and B30 (Biodiesel—30%, Fossil diesel—70%) on volume bases, the percentage difference in emission values, compared to fossil diesel, is shown in Figure 8. Larger percentage reductions in CO_2, CO, and SO_2 emissions were recorded, while a noticeable increase in the NO_x emissions was brought about by combustion between the atmospheric nitrogen and oxygen at the exhaust–air interface. The increase in NO_x emissions was found to be similar to recent engine performance studies on IC engines which were operated with biodiesel–diesel fuel blends. More research studies on fuel treatment are being considered for the operation of IC engines running on blended biodiesel fuel to enhance quality combustion and eradicate NO_x emissions from the exhaust. Sarvi et al. [114] detected that reductions in the burning flame temperature resulted in a corresponding reduction in the NO_x. In the same vein, the ignition pressure was reported to have a reducing effect on the NO_x emissions [115].

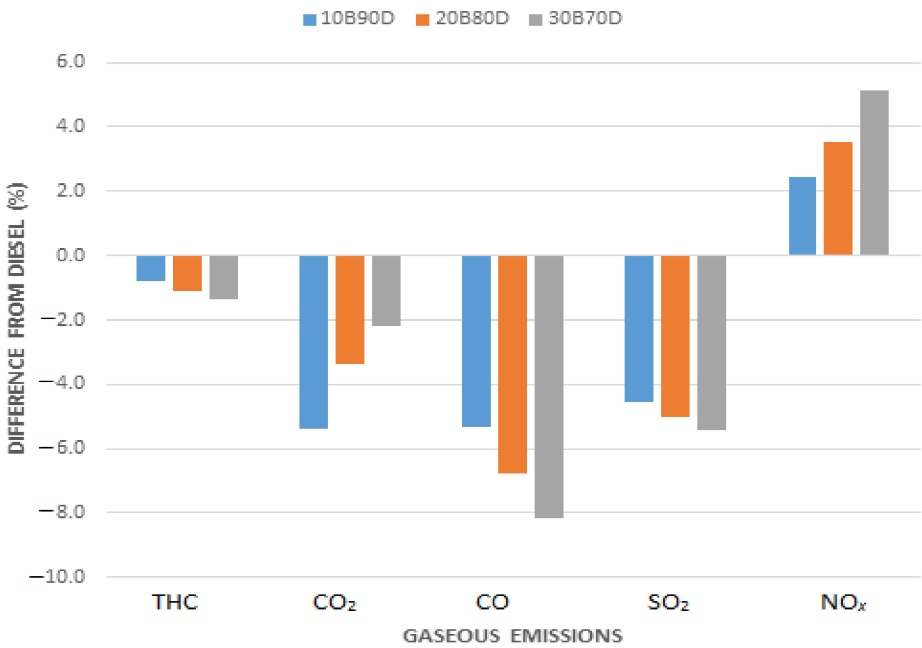

Figure 8. Average exhaust emissions of biodiesel blends compared with diesel. Adapted from Ogunkunle and Ahmed [45].

Similarly, the effect of engine speed on exhaust emissions was investigated by Tayari et al. [46]. The effects on emissions were found to reduce CO, HC, and NO_x, but not CO_2. The emission trend is shown in Figure 9. The effect of three different biodiesel blends on exhaust was studied as well, and the results showed that fuel blends prepared from biodiesel synthesized from waste cooking oil and Microalgae *Chlorella vulgaris* had more of an effect on reducing the average emissions from the combustion process. Considerable reductions in CO_2, CO, THC and NO_x emissions were recorded from the combustion of all fuel blends except for a few increments in CO_2 and NO_x. The differences in average exhaust emissions of biodiesel compared with diesel are presented in Figure 10.

An assessment of biodiesel combustion impacts on transportation fleets in the Houston metropolis, USA, in 2018, showed that biodiesel is more beneficial for passenger cars than heavy duty diesel trucks (HDDTs) per km [116]. A life cycle assessment under three pathways, Well-to-Pump, Pump-to-Wheel, and Well-to-Wheel, showed that the combustion of biodiesel blends in both passenger cars and long-haul HDDTs is environmentally friendly, although is also dependent on the vehicle types. Evaluation of the combustion of six different blends of diesel–biodiesel blends, B0, B5, B20, B50, B80, and B100, showed that the reductions in GHG emissions were significant at the Well-to-Pump stage, and all the emissions, except GHGs and NO_x, were reduced at the Pump-to-Wheel stage. A hypothetical scenario forecast showed that the daily GHG emissions would be reduced by 2.0 and 712.1 CO_2-equivalent tons in 2025, if half of the metropolis passenger cars and HDDTs were to be run on B20. The 2021 reports of International Energy Agency on CO_2 emissions showed that 31,500 CO_2eq tons of CO_2 were released globally in 2020 [117]. The Well-to-Wheel percentage reduction in emissions and energy use for passenger cars and HDDTs is shown in Figure 11.

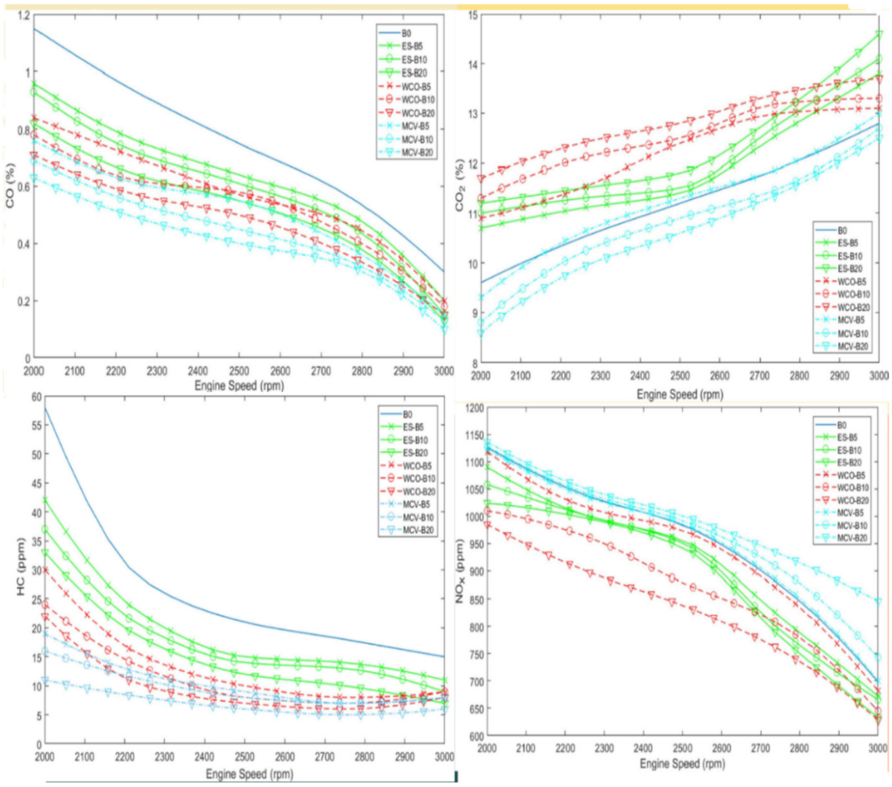

Figure 9. Effect of engine speed on exhaust emissions. Reprinted from Tayari et al. [46].

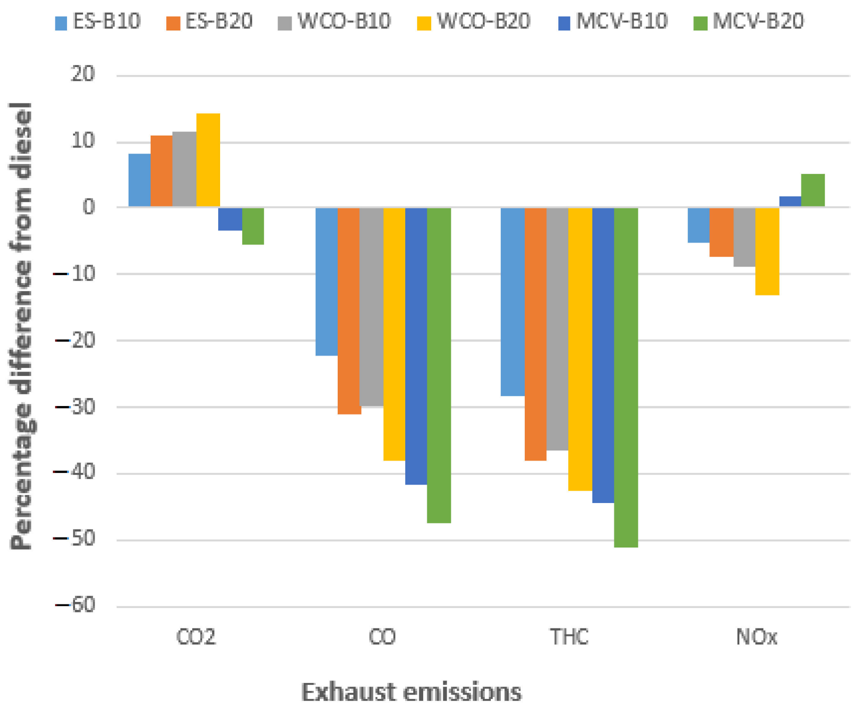

Figure 10. Percentage difference of emissions from biodiesel compared with diesel. Reprinted from Tayari et al. [46]. ES—*Eruca sativa*; WCO—Waste cooking oil; MCV—Microalgae *Chlorella vulgaris*.

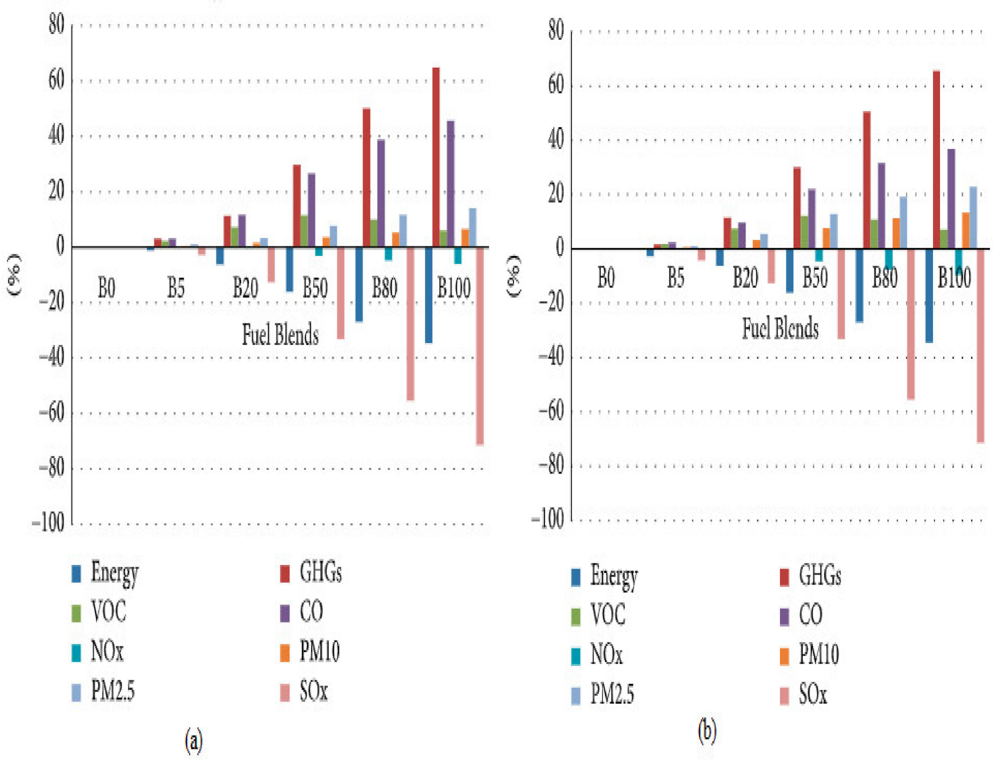

Figure 11. Well-to-Wheel percentage reduction in emissions and energy use for: (**a**) passenger cars and (**b**) HDDTs during the hypothetical scenario in 2025. Reprinted from Du et al. [116].

The combustion of diesel–biodiesel fuel blends in vehicular engines has proven to be a sustainable measure for reducing engine pollutant emissions. Air pollution due to fossil fuel usage can be drastically reduced by exploring other fuel sources such as environmentally friendly biodiesel, which has quality engine performance and relatively low pollutant emissions. Ogunkunle and Ahmed [29] reported that the use of biodiesel as an alternative fuel in diesel engines has brought about very large reductions in atmospheric pollutant emissions. With the growing global concerns of mitigating air pollutants and improving air quality, more of the reduction can be expected as biodiesel production and adoption continue to spread across all developed and developing nations. The continuous increase in global warming, induced by the use of fossil fuels, has been a major issue of discussion, leading to the development of biofuel as an alternative fuel. The reduction in pollutant emissions continues to stand as a global policy, supporting the adoption of biodiesel in whole or partial forms [29]. According to the fifth assessment report of the Intergovernmental Panel on Climate Change [55], pollutant emissions need to be reduced by 50–85% by 2050 in order to stabilize the concentration of GHGs in the atmosphere and mitigate climate change [118,119]. One of the viable means which has gained popularity for the reduction in atmospheric pollutants is the use of biodiesel in cutting down carbon and other pollutant emissions which are released by transportation vehicles [120]. The use of biodiesel wholly as a vehicular fuel is expected to increase in the coming years, with the sole purpose of mitigating GHGs that continue to increase global warming through depletion of the atmospheric protective ozone layer. The current form of deploying biodiesel in vehicles is by blending with varying amount of fossil diesel, even though efforts are being made to achieve 100% biodiesel use. The combustion of these blended fuels has the tendency to reduce pollutant emissions and cut down the carbon footprints which may have negative impacts on the environment.

Several researchers have reported the effects of different plant oil biodiesels on engine performance and exhaust emissions [88,121–124]. Most of the studies were carried out in existing diesel engines using blends of biodiesel–diesel fuel with little or no modification to the engines. However, the reduction or increase in exhaust emissions from fuel combustion is either related to the blending ratio of the fuel or the engine operating parameters. Mohsin et al. (2014) reported that combustion in a diesel engine was closer to complete combustion when a 20% biodiesel fuel blend was used to operate the engine. As a result, the UHC, CO, and CO_2 emissions were lower than the concentrations released when fossil diesel fuel was used to run the engine [125]. The THC, CO and CO_2 were significantly reduced in biodiesel blends than for ordinary diesel. Increases in biodiesel content of the blended fuel cause the oxygen composition to increase, which automatically improves the combustion quality and lowers the emissions [126]. At every engine operating conditions, it was found that the HC emissions were lower in the combustion of biodiesel–diesel fuel blends compared to fossil diesel [127]. Sayin et al. [128] found that the NO_x emissions increased while CO and HC decreased when the percentage of biodiesel content increased in the fuel blends. Likewise, it was found that smoke, HC and CO decreased when biodiesel content in tested fuel blends increased [129,130]. This was supported by the improved combustion properties of biodiesel blends as a result of the oxygen content in it.

Some scientific reports on engine performance and exhaust emissions [88,90,126,131,132], while running different types of diesel engines on biodiesel–diesel blends, have shown that certain engine operating parameters, such as compression ratio (CR), ignition pressure (IP), and ignition timing (IT), have varying effects on gaseous compositions of exhaust emissions [133,134]. Jinda et al. [135] concluded that the combined effect of compression ratio and injection pressure reduce emissions from the combustion of jatropha biodiesel in a variable compression ratio engine. The emission levels of biodiesel blends compared to diesel at different CRs are shown in Figure 12, while the effects of CR on engine emissions are presented in Figure 13. The smoke opacity, hydrocarbons, and carbon monoxide were found to decrease more as the compression ratio increased, while the NO_x emissions increased as the compression ratio increased. Ashrafur et al. [136] reported that increases in IT and IP leads to decreases in CO, HC, CO_2, and NO_x emissions. Sayin et al. [137] reported that increases in HC and CO emissions decreased when the IT and IP were increased for all the various fuel blends tested. They concluded that the fuel–oxygen link is improved when IT and IP are enhanced. Venkanna et al. [138] found that emissions were lower when a 30% pongamia biodiesel blend was used to run a diesel engine.

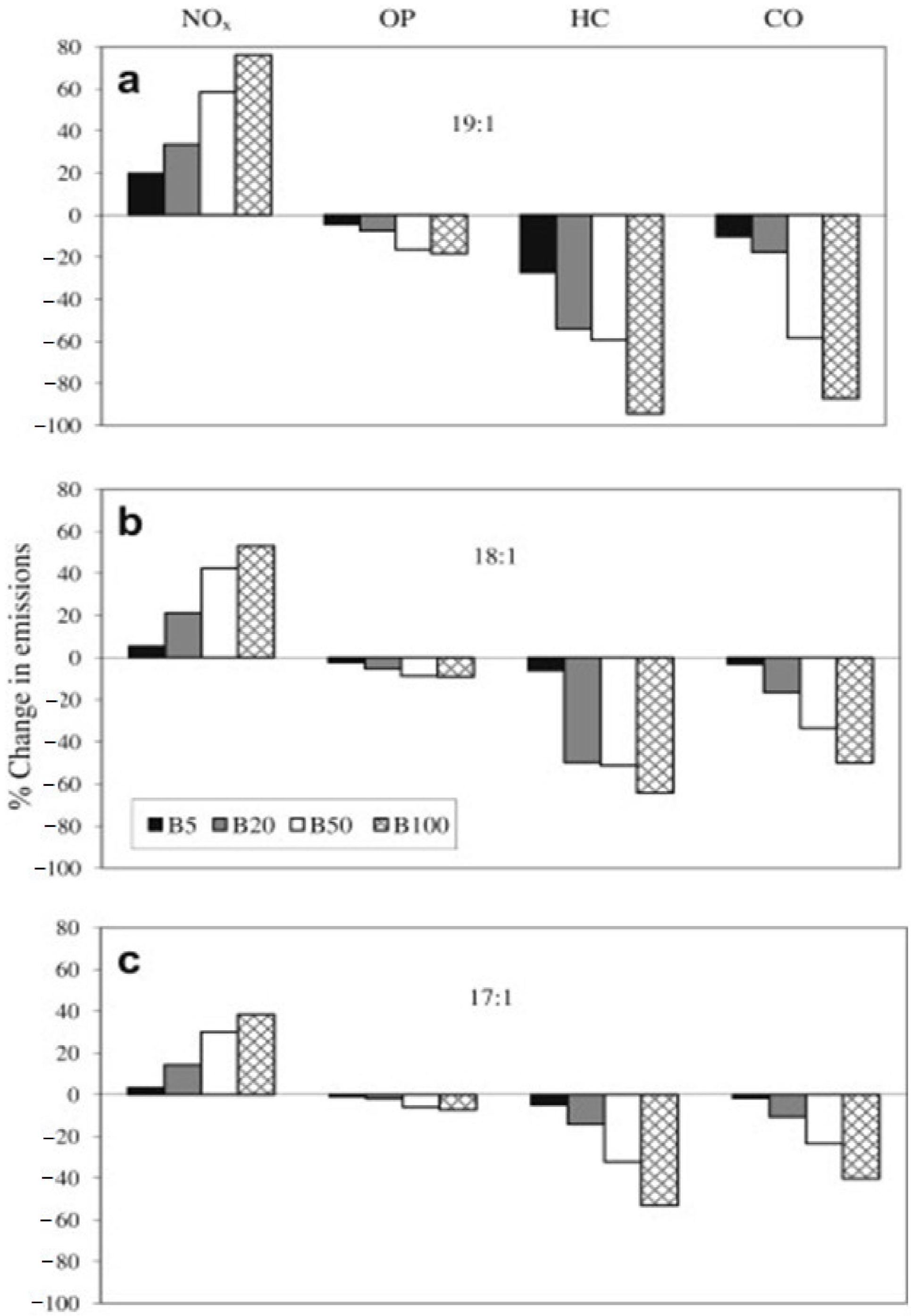

Figure 12. (**a**) Percentage change in emission levels at compression ratio of 19:1; (**b**) Percentage change in emission levels at compression ratio of 18:1; (**c**) Percentage change in emission levels at compression ratio of 17:1. Reprinted from Sayin and Gumus [128].

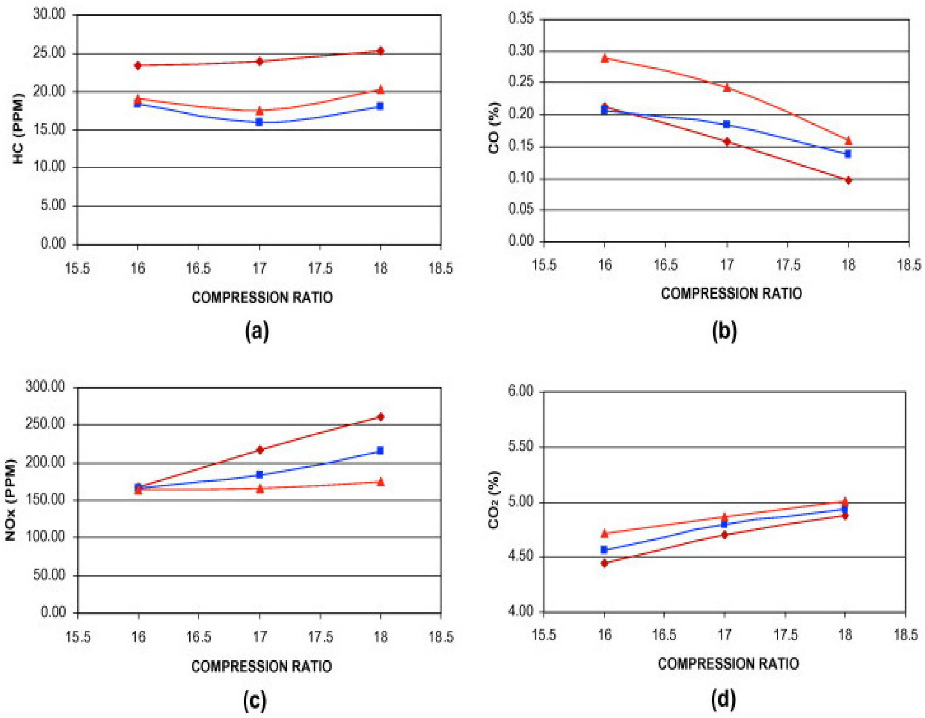

Figure 13. (**a**) Effect of compression ratio on HC emissions; (**b**) Effect of compression ratio on CO emissions; (**c**) Effect of compression ratio on NO_x emissions; (**d**) Effect of compression ratio on CO_2 emissions. Reprinted from Jindal et al. [135].

4.1. Road Transportation as a Contributor of Harmful Air Pollutants

The contribution of transport to air pollution, and the subsequent negative impacts on the atmosphere and climate change, are matters of concern. Right from the development of IC engines, hazardous emissions from the combustion of fossil fuels have become responsible for most of the GHGs in the atmosphere, which are measured in CO_2 equivalent (CO_2eq) [139,140]. Over the years, road transport has been recognized as the largest contributor of traditional gaseous pollutants, such as nitrogen oxides (NO_x), volatile organic compounds (VOCs), hydrocarbons (HCs), SO_2, CO, CO_2, and PM [141,142]. More than twenty years after this study, emissions from transportation still remain one of the major contributors to air pollution [143,144].

Five primary pollutant emissions (CO, CO_2, HCs, NO_x and PM), which contribute immensely to air pollution, were found to be considerably emitted from the combustion of fossil fuel in car engines [145]. According to the United States Environmental Protection Agency (USEPA), 75% of carbon monoxide in the United States is emitted by motor vehicles (a collection of cars, big trucks, bulldozers, and trains). Transportation currently contributes largely to the release of GHG emissions in the United States. These emissions are formed from the combustion of fossil fuel in IC engines. It is believed that emissions from cars increase the concentrations of carbon dioxide and other greenhouse gases in the atmosphere [146]. Recent estimates of emissions from road transport reflect an increasing trend (Figure 14) in related CO_2 emissions. As a result of the universal growing population and the subsequent increase in the number of passenger vehicles, carbon emissions increased by half a gigaton between 2010 and 2018, surpassing about a 50% increase [146].

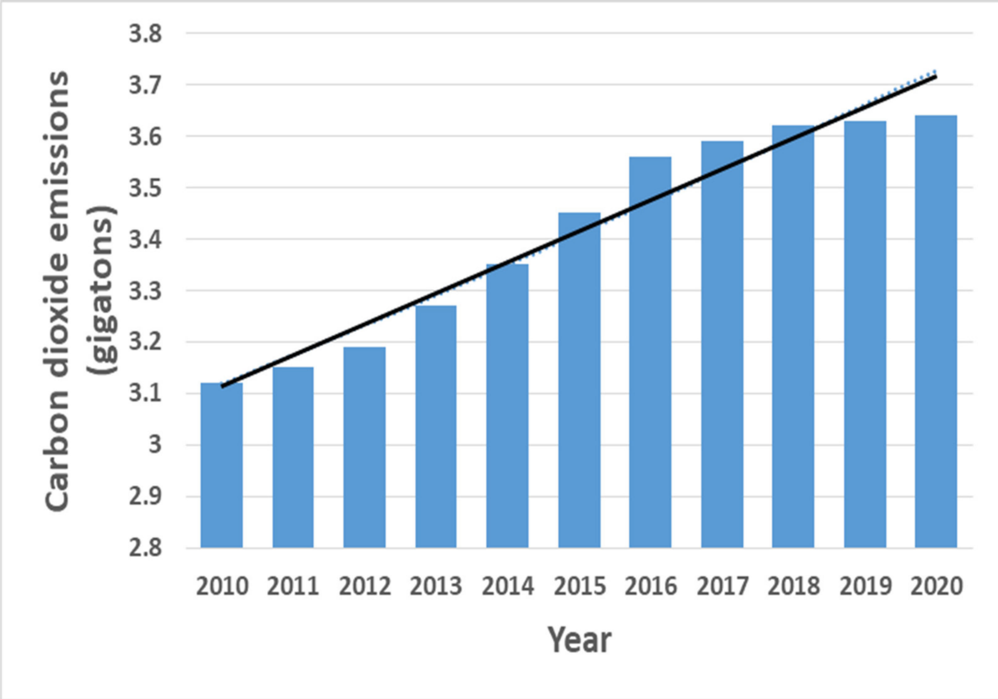

Figure 14. Global carbon dioxide emissions from passenger road transport (2010–2020). Adapted from Wagner [146].

Greenhouse gas emissions from the transportation industry come from the combustion of fossil fuels, with gasoline and diesel making up about 95% of the liquid fuels [79]. According to the statistical reports by International Energy Agency (IEA) [62], approximately one-fifth (24%) of global CO_2 emissions (about eight billion tons of CO_2 in 2018) come from transportation, while 74.5% of the emissions come from road vehicles. Despite the next industrial revolution across Europe and United States regarding the electrification of cars, global emissions continue to increase. Against the 1.9% annual increase since 2000, global transport emissions increased by less than 0.5% in 2019 [147]. The decrease was more attributed to the global adoption of biofuels in vehicular engines wholly or partially across major developed countries [29], coupled with the use of electric cars.

4.2. Nexus Between Engine Fuel Combustion and Sustainable Environmental Development

As a reference point, the production and usage of biofuels has gained global popularity amongst the various types of green energy [29]. Just as the demand for fuel, especially in vehicular engines, is expected to rise as the global population increases, the usage and inclusion of biodiesel in engine fuels are needed to prevent environmental exposure to pollution. Whether biodiesel has achieved complete greenness considering production and combustion lies in appraising its net performance in terms of energy delivery and emission rates. The reliability of biofuels in achieving SDG number seven (affordable and clean energy) has been questioned over time, just as scientific research contributions constantly emerge reporting the fuel quality of numerous plant oil-derived biodiesel and their performance efficiency as an engine fuel. Apart from the potential of reducing unpleasant pollutants in the atmosphere, one other critical component that is research-driven is the tendency of biodiesel to effectively deliver stored energy during combustion, by matching it up with corresponding forms of energy which are released from the combustion of the same volume of fossil diesel [133,148]. According to the IEA's report [62], in corroboration with Davis et al. [149], emissions from transport will continue to be the largest contributor to energy-related emissions by 2070. To achieve the SDGs of net-zero emissions by 2070, bioenergy systems which capture and store carbon have to be encouraged and adopted.

The environmental sustainability aspects of biodiesel can be analyzed by the overall positive and negative impacts on the environment. The main positive impact of biodiesel on the environment can be summarized as the net reduction in atmospheric pollutant emissions [150], while environmental pollution, caused by the release of NO_x emissions from biodiesel combustion, is critical in considering its unintentional negative impacts on environmental sustainability. In the reports of Kamil et al. [151], higher concentrations of NO_x were discovered in the exhaust emissions when different blends (B5, B10, B15, and B20) of waste spent coffee biodiesel were used to run a compression ignition (CI) engine. Even though the detected concentrations of NO_x emissions were very small, they concluded that this issue needs to be addressed because this gaseous emission is hazardous to human health. There is a huge biodiversity in biodiesel feedstock and varying production practices employed for oil extraction and transesterification. The net gaseous emissions cannot be of the same effect and magnitude, because the feedstocks are different in compositions. However, research efforts should be directed towards a harmonized bio-chemical scientific approach to maintain a sustainable LCA and GHG balance on the environment.

Access to sustainable energy is one of the important targets of Sustainable Development Goals (SDGs), and as such must be addressed as energy resources are extensively explored for sustainable environmental development. The SDGs are a collection of 17 global goals representing the plan to accomplish a better and more sustainable future for our planet [152]. The goals, which were regulated in 2015 by the United Nations General Assembly, are part of the commitment to be achieved by the year 2030 [153]. Each of the 17 SDGs has a list of targets which are measured by certain indexes. Much as these goals are extensively deployed, a few of them are interconnected in such a way that the progressive effects of one could be a positive response on the track towards achieving another. Out of the total seventeen SDGs, five of them are interwoven to support sustainable life and the environment. An evaluation of their mission goals and future targets suggests that numbers 6, 7, 13, 14, and 15 are geared toward the conservation, restoration, and sustainable use of natural resources in such a way that the environment is well preserved for perfect and healthy life for all organisms.

The beneficial advantages of biodiesel encompass the goals and targets of the detailed sustainable goals [29], and could certainly ensure the protection, conservation, and sustainable management of the earth's resources for maximum positive benefits. In connection to these SDGs, the use of biodiesel as a clean fuel can reduce pollution, ensure access to clean energy, mitigate climate change, and protect lives on the earth's surface and below water. The reduction in environmental pollution and global warming are two serious challenges that biodiesel combustion has the potential to address based on the clean burning and minimal carbon emissions. The seventh sustainable development goal is primarily focused on ensuring access to affordable, reliable, sustainable, and green energy. As many global communities continue to make progress toward perfectly achieving the seventh goal, sustainable energy is becoming more available in different forms. Renewable energy, generated from solar, wind, hydro, and biomass, has created efficient means of providing sustainable energy to rural communities, especially in developing countries [154]. However, there is a need to focus on improving the forms of energy available to achieve easy access and renewability of energy.

In order to achieve a sustainable environment with good air quality, joint global efforts are required to attain rapid reductions in GHG emissions in the air. The release of carbon emissions, hydrocarbons, nitrogen oxides, and particulate matter into the atmosphere must be cut down to net-zero emissions. A recent corroboration of the Yaron Ogen reports [65] by Jenny Bates, a popular air pollution campaigner with Friends of the Earth, opined that it is highly pertinent to keep traffic and pollution levels down by ensuring that only clean-burning vehicles are allowed on the road in our bid to build a sustainable world [155]. This is much-needed, because a larger percentage of the global air pollution index is contributed by transportation vehicles. There is urgent need to start focusing on the energy and agriculture sectors in order to accomplish sustainable progress in reducing these emissions. The transition to low-carbon alternatives around the globe has brought about the use of renewable and nuclear energy, which emit low or no emissions per unit of energy produced. The use of biodiesel as an engine fuel continues to gain global recognition, which is motivated by the concerns to reduce GHG emissions and their negative effect on climate change.

5. Discussion

An overview of negative impacts of air pollution upon human health and the environment, and merits of biodiesel as an alternative fuel, have been discussed in relation to the mitigation of negative environmental and health impacts induced by the use of fossil fuels in engines. Pollutant emissions, such as carbon monoxide (CO), unburned hydrocarbons (UBCs), nitrogen oxides (NO_x), particulate matter (PM), and carbon dioxide (CO_2) are found to be released primarily from the combustion of fossil fuels.

Generally, some acute health diseases and complications were found to be linked to air pollution. Many death cases were found to have occurred in places which have experienced poor air quality over a period of time. At the same time, pollution from fossil fuel combustion is found to be the principal cause of global climate change. This has brought about adverse environmental conditions which subsequently affect the ecosystems and human health.

Over the years, scientific research has shown biodiesel as a viable source of environmentally friendly energy which can be utilized in existing diesel engines without any major modification. Experimental tests, involving performance and emission analyses of biodiesel combustion in IC engines, were found to substantially reduce emissions of pollutants such as CO, UHC, and PM.

Based on the findings on the nexus between fossil fuel combustion and air pollution, and the relative advantages biodiesel offer in reducing air pollutants, possible improvements can be made in order to further develop biodiesel production and adoption in IC engines. These can be taken for future studies by researchers who are interested in promoting good air quality through the production and use of clean fuel in engine combustion. These include:

i. The development of novel methods for obtaining pure feedstock for quality biodiesel production engine applications. This is required to foster research efforts on certain groups of feedstocks which have the appropriate oil yields and high fuel qualities that may promote global adoption of biodiesel combustion toward a sustainable world;
ii. Long-term stabilization and biodiesel quality improvement to ensure stable combustion and improved engine performance without contributing to environmental pollution;
iii. Putting systems in place to harness and convert carbon emissions from fossil fuels into useable chemical products may contribute to the elimination of air pollution. Research is on-going to convert carbon dioxide into useful alternative energy sources such as combustible methane.

6. Conclusions

From the studies reviewed, the following conclusions can be drawn:

i. Gaseous pollutants and particulate matter, which largely constitute outdoor air pollution, have very common causes, particularly human activities which involve combustion processes;
ii. Gaseous pollutants such as carbon monoxide, unburned hydrocarbons, nitrogen oxides, particulate matter, and carbon dioxide are the major emissions from vehicle exhausts running on fossil fuels;
iii. Gaseous and particulate pollutants have negative impacts on human health and the environment;

iv. Greenhouse gas emissions from the transportation industry come from the combustion of fossil fuels, with gasoline and diesel making up about 95% of the liquid fuels;
v. Five of the total seventeen SDGs are interwoven to support sustainable life and the environment. A critical evaluation of their mission goals and future targets suggest that they are geared toward the conservation, restoration, and sustainable use of natural resources, in such a way that the environment is well preserved for perfect and healthy life for all organisms. The use of biodiesel as a clean fuel can reduce pollution, ensure access to clean energy, mitigate climate change, and protect lives on the earth's surface and below water;
vi. The reduction in or cessation of fossil fuel combustion can reduce or eliminate the risks of respiratory problems and related deaths caused by air pollution. There is a need for increasing the development and adoption of quality biofuels which are environmentally friendly, green, and sustainable;
vii. The use of biodiesel in internal combustion engines, either in whole or part, reduces environmental pollution and the health risks associated with the combustion of fossil diesel;
viii. Emission reduction facts from the National Biodiesel Board of the United States showed that the combustion of B100 as a transportation fuel decreased total HC, PAH, carbon, and sulfur emissions by 67%, 80%, 48%, and 100%, respectively. A hypothetical scenario forecast showed that the daily GHG emissions would be reduced by 712.1 CO_2-equivalent tons in 2025, if half of metropolis passenger cars and HDDTs were to be run on B20.

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