# Chapter 1 Introduction

## 1.1 World Energy Scenario:

Any civilization's level of economic growth and living standards can be measured by its energy consumption. One of the most crucial resources that contribute to the well-being of Earth's humans is energy. Readily available and affordable energy is the lifeline of modern civilization. Energy availability is important for a country's socioeconomic development and sense of sovereignty. Furthermore the country's GDP and per capita income, the country's per capita energy consumption required to determine its level of prosperity[1]. The generation of energy plays a significant role in the economic growth of the nation. The world's escalating modernization and industrialization have increased the need of petroleum products dramatically. The energy demand has significantly increased as a result of economic growth in developing countries.

The world's energy consumption has grown significantly over the years due to the industrial revolution. The U.S. Energy Information Administration (EIA)[2] research projected that global energy consumption will rise from 601.5 quadrillion British thermal units (Btu) in 2020 to 705.2 quadrillion Btu by 2030, 795.4 quadrillion Btu by 2040, and 886.3 quadrillion Btu by 2050. As a result, the world will require around 30% more energy in 2050 than in 2020. The majority of the world's primary energy is produced using conventional sources of energy.

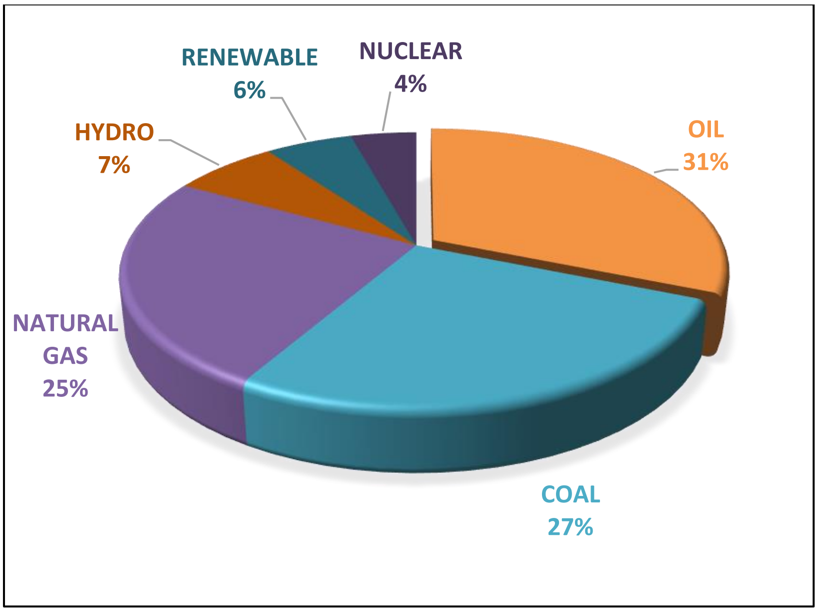



Figure 1-1: Global primary energy production in 2022.

Oil, coal, and gas continue to contribute 83.1% of the world's energy, as shown in Figure 1-1[3], while hydropower, nuclear power, and other renewable energy sources account for 6.9%, 4.3%, and 5.7% of the world's total primary energy production respectively[3].

After the industrial sector, the transport sector—which includes cars, trains, planes, and other moving objects—consumes the most energy globally. As mentioned in Figure 1-2[2].

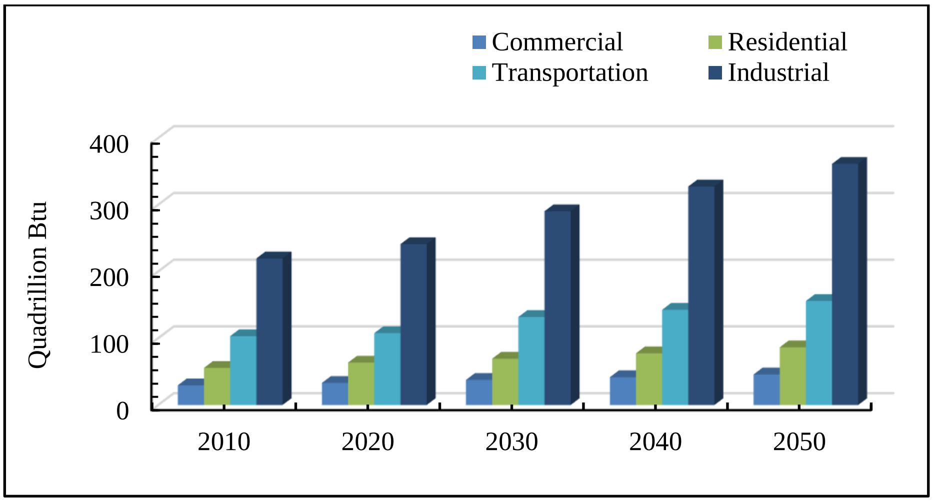



Figure 1-2:Global primary energy consumption by sector

The Transportation sector accounts for 25% of global energy consumption of which 80% of the energy is utilized for road transportation[2]. Now accounting for almost 60% of global oil demand, the transportation sector will also have the fastest rate of energy growth over the next few years. This industry uses 97.6% of the energy from oil and a minimal percentage from natural gas for conventional fuels[4]. Even though, the demand for oil for transportation is declining due to considerable fuel efficiency improvements and an enhancement in the usage of non-oil fuels like electricity, biofuels, coal, and natural gas.

### 1.1.1 Indian Energy Scenario

In India, energy is the fundamental input for all economic activities, including those related to domestic, commercial, industrial, and domestic agriculture. Since India's independence, enormous amounts of energy have been required to carry out its economic development. As a result, energy consumption is increasing gradually across the country. Oil and gas are necessary for economic expansion, which increases economic growth sustainably and raises the possibility of an energy supply crisis. In India, the demand for energy for products with a petroleum foundation has been increasing rapidly. As an example, India, the third-largest oil consumer in the world consumed 201.69 million metric tonnes of petroleum products from April 2021 to March 2022[5] (Source: Petroleum Planning & Analysis cell, India). In India over the past ten years, it saw the second-highest growth in transportation fuel use. Because of the economic reforms, it is anticipated that there will be an increase in the production of road vehicles, which would result in higher fossil fuel demand. Hence, it required to determine the ways to encounter India's growing need for fossil fuels. Because there are more and more vehicles with internal combustion engines, energy demand is increasing. Energy is required for economic development, and financial growth is important for developing nations. Compared to developed nations, India exhibits a remarkably low level of energy consumption per person.

The energy demand is rising in India at a 6.5% annual rate. By 2021, Almost 87% of India's entire oil needs must be supplied through imports. All countries are cognizant that non-renewable petroleum is becoming scarce and is being consumed very quickly. According to the Inter-Governmental Panel on Climate Change (IPCC), between 1990 and 2100, global warming is expected to cause a rise in global surface temperatures ranging from 1.1°C to 6.4°C. The gradual depletion of fossil fuels and increasing energy demand resulted in an energy crisis. Oil and coal are the primary energy sources used by industries and automobiles. A conventional and rapidly depleting energy source is petroleum. The oil crisis in 1973 already focused attention on this issue. Petroleum prices are always fluctuating and increasing across the board in the majority of countries. The predicted annual increase in global energy consumption, which currently stands at 147 trillion kWh, is expected to continue. Details of India's import and export of crude oil are shown in Table 1-1[6]. Over the last few years, there was a significant rise in the importation of crude oil.

Table 1-1: Crude Oil Import and Export Detail

| Year | Production (Million Tonne) | Import (Million Tonne) | Total (Million Tonne) | Import (%) |
|---|---|---|---|---|
| 2011-12 | 38.09 | 171.73 | 209.82 | 81.85 |
| 2012-13 | 37.86 | 184.8 | 222.66 | 83.00 |
| 2013-14 | 37.79 | 189.24 | 227.03 | 83.35 |
| 2014-15 | 37.46 | 189.43 | 226.89 | 83.49 |
| 2015-16 | 36.94 | 202.85 | 239.79 | 84.59 |
| 2016-17 | 36.01 | 213.93 | 249.94 | 85.59 |
| 2017-18 | 35.68 | 220.43 | 256.11 | 86.07 |
| 2018-19 | 34.2 | 226.5 | 260.7 | 86.88 |
| 2019-20 | 32.17 | 226.95 | 259.12 | 87.58 |
| 2020-21 | 30.49 | 198.11 | 228.6 | 86.66 |

**(Source: Petroleum and Natural Gas ministry, India)**

## 1.2 Need for Alternative Fuel

During the World Exhibition in Paris in 1900, Rudolf Diesel ran the first diesel engine on peanut oil[7]. Sadly, he passed away before his vision of diesel engines powered solely by vegetable oil came true, and the engines were soon modified to use fuel made from crude petroleum. The usage of petroleum oil contributes to the main issues of the twenty-first century, including the rapid depletion of fossil fuels, growing pollution concerns, global warming, and climate change, all of which contribute to devastating floods, heavy rainfalls, and storms[8]. The consumption of mineral fuels is increasing more quickly than their production despite the market's increased demand for them and their higher prices, particularly for diesel fuel. In 2021, India import about 87% of its petroleum consumption. Now it is the time to support Sir Rudolf Diesel's idea of using renewable vegetable oil as a diesel engine substitute some serious thought. Renewable and unconventional fuels, such as biofuel, biogas, and biodiesel, can be employed as substitute energy sources in this situation. To reduce our dependency on fossil fuels, it becomes important to concentrate on generating suitable biofuels.

## 1.3 Biodiesel as Diesel Engine Fuel

Biofuels, which are mostly made from biological resources, are available for use in transportation in both liquid and gaseous forms. A variety of fuels, including liquid fuels like bioethanol, bio-methanol, and biodiesel, as well as gaseous fuels like synergy gas and biogas, can be created from bioresources. Among all of these fuels, biodiesel is among the most dependable choices for replacing diesel as the main fuel. It is extremely biodegradable and has a low sulphate, low aromatic, and low toxicity content[9]. Biodiesel is safer than diesel fuel since it has a higher cetane number and flash point[10]. It typically has 10–11% weight-based oxygen, which increases combustion efficiency and reduces CO and unburned hydrocarbon (UBHC) emissions. If the tree's entire life cycle is taken into account, it produces no net carbon dioxide and emits less smoke and particulate matter[4] As a result, internal combustion engines may run on biodiesel-diesel blending without any engine modifications.

Many countries, including the United States of America, Brazil, Germany, Argentina, France, Thailand, and other European nations, export biodiesel commercially[11]. The amount of biodiesel produced in several of the top-producing countries in 2021 is shown in Figure 1-3, The Indonesia produces the highest biodiesel (8.09 billion liters) of any country. From 31 billion liters in 2016 to 35.12 billion liters in 2021, the yearly global production of biodiesel grew. The production of biodiesel increased at a rate of about 13.5% over the previous five years. Therefore, the potential for biodiesel to contribute as a sustainable energy source is enormous.

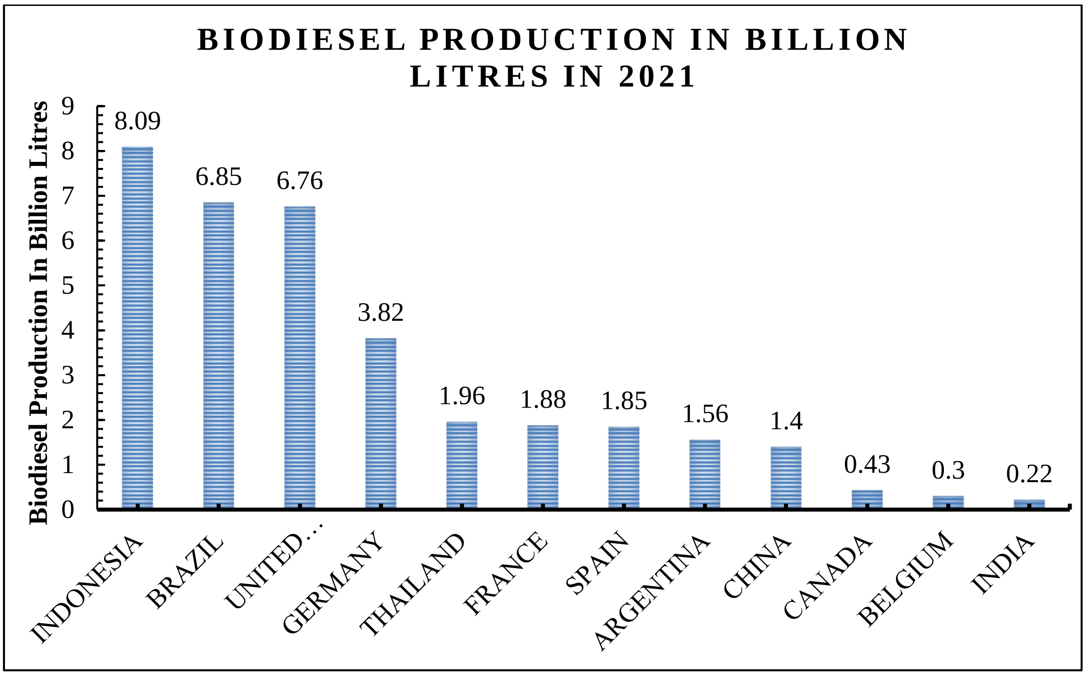



Figure 1-3: Leading Biodiesel producer country in 2021

Despite its usage as engine fuel, vegetable oil does include many drawbacks, the most significant of which is its extreme viscosity and high pour point, low calorific value, and low volatility[12]. Due to high viscosity, the injection quality is low in the case of vegetable oil and also causes poor combustion in a diesel engine. This can be enhanced by pyrolysis, transesterification, preheating the oil, or combining it with base fuel in an appropriate proportion. Both biodiesel production and a method to reduce the viscosity of vegetable oils are possible. Pyrolysis, micro-emulsification, dilution, and transesterification are among the available methods[13], [14]. Pyrolysis is the process by which heat and the existence of a catalyst change one substance into another. This method is less complicated than other methods. Vegetable oils are added to diesel fuel during the dilution process to lower viscosity and prepare it for use in engines. The process of micro-emulsification results in the creation of micro-emulsions, which have the potential to address the problem of vegetable oils having a higher viscosity.

Transesterification is the most widely used technique for reducing the viscosity of vegetable oils [15], [16]. Alcohol is removed from an ester by another alcohol during transesterification, which is also known as alcoholysis[17]. Reactants are effectively mixed to begin the reversible transesterification reaction, however, the conversion process is accelerated by the presence of a catalyst (a strong acid or base). Fatty acid alkyl esters and glycerol are produced during the transesterification of triglycerides, which are present in vegetable oils. The thicker glycerol layer settles into the reactor at the bottom. The raw biodiesel is created by the methyl ester's top layer. The intermediaries in this process are diglycerides and mono glycerides. Lastly, by water washing and heating, pure biodiesel can be extracted.

## 1.4 Resources of Biodiesel

The American Society for Testing and Materials (ASTM) defines biodiesel fuel as mono-alkyl esters of long-chain fatty acids production of renewable lipid feedstock such as vegetable oils or animal fats and used in internal combustion engines[18]. Depending on the temperature and soil characteristics of a place, several types of Vegetable oils are the recommended choice for for transesterification to produce biodiesel[19]. For example, rapeseed and sunflower oils are more extensively used in Europe for the production of biodiesel, whereas soybean oil is more commonly used for the same purpose in the United States. Similarly, animal fat is utilized in Japan, canola oil is utililzed in Canada, coconut oil is used in the Philippines, and southeast Asia uses palm oil[19][20].

The feedstocks of biodiesel can be classified into main four categories[21]

1) **Edible vegetable Oil**: First-generation vegetable oils that are suitable for human consumption such as rapeseed, soy, sunflower, rice bran, coconut, palm, corn, olive, sesame, Palestinian, peanut, and safflower oil.
2) **Non-edible vegetable oil**: Second-generation vegetable oils that are not suitable for human consumption such as neem, mahua, jatropha, Pongamia, jojoba, cottonseed, orange, linseed, Kusum, sea mango, halophytes, and algae.
3) **Animal fats**: Fish oil (from by-products), tallow, yellow grease, and chicken fat.
4) **Recycled or waste cooking oil**

Among the most significant agricultural products in India are edible oil and oilseeds. Between November and October of 2021, 197 million tonnes of edible oil were generated in the nation. In India, the most widely consumed edible oils in terms of quantity are palm, soybean, mustard, and sunflower oil, with corresponding shares of 38%, 19%, 12%, and 8% in 2021's total oil consumption. Nowadays, imports account for over 60% of total domestic consumption (the two most common imported varieties are palm oil and soybean oil)[22]

India also has a huge area of forestland, which supports a large number of trees and numerous high-yield oil seedlings. Sal oil, mahua, neem, and karanja oil are the most plentiful of these oils, with a potential annual supply of 1 million tonnes in India[23]. Sal oil, mahua oil, neem oil, and karanja oil each have an estimated annual supply of 180,000 tonnes, 10000 tonnes, and 55,000 tonnes, respectively. Hence, it is possible to research the commercial production of biodiesel from non-edible oil in India. These feedstocks can help to green drought-prone areas without compromising the security of food and fodder while simultaneously meeting the demand for oil for biodiesel production. Rural poor people's lives can also be improved by these crops. Due to a large disparity between demand and supply for this kind of edible oils, using them to make bio-diesel is not practicable in India. As a result, in India, only certain oils that fall into the category of non-edible seeds and do not compete with food seeds can be used to make bio-diesel. Another requirement for this kind of non-edible seeds is the potential to grow them through mass production in non-cropped wasteland sites. In India, there are a variety of trees, bushes, and plants which can be utilized to extract oil and produce bio-diesel. There are 77 non-edible plants in India with a seed, fruit, or nut that contains 30% or more oil as listed in Table 1-2 [24][25]. Non-edible species with Botanical names summarize the botanical labels of 77 plants that have been recognized as possible non-edible seeds, fruits, or nuts for biodiesel production in India.

Table 1-2: Non-edible species Botanical names

| | | | |
|---|---|---|---|
| 1 | *Anacardiaceae Rhus succedanea* L. Annonaceae | 40 | *Saturega hortensis* L. |
| 2 | *Annona reticulate* L. Apocynaceae | 41 | *Perilla frutescens* Britton Lauraceae |
| 3 | *Ervatamia coronaria* ( Jacq.) Stapf | 42 | *Actinodaphneangustifolia* |
| 4 | *Thevetia peruviana* Merr. | 43 | *Litseaglutinosa* Robins |
| 5 | *Vallaris solanacea* (Roth) Kuntze | 44 | *Neolitsea cassia* L. |
| 6 | Balanitaceae | 45 | *Neolitsea umbrosa* Gamble Magnoliaceae |
| 7 | *Balanites roxburghii* Planch. Basellaceae | 46 | *Michelia champaca* L. Malpighiaceae |
| 8 | *Basella rubra* L. | 47 | *Hiptage benghalensis* Kurz Meliaceae |
| 9 | *Canarium commune* L. Cannabinaceae | 48 | *Aphanam ixis polystachya* Par k |
| 10 | *Cannabis sativa* L. Celastraceae | 49 | *Azadirachta* indica |
| 11 | *Celastrus paniculatus* L. | 50 | *Meliaazadirach* L. |
| 12 | *Euonymus acanthocarpus* Franch. | 51 | *Swietenia mahagoni* Jacq Meni spermaceae |
| 13 | *Euonymus acanthocarpus var. lushanensis* (F.H.Chen& M.C.Wang) C.Y. Cheng Combretaceae | 52 | *Anam irta cocculus* Wight & Hrn Moraceae |
| 14 | *Terminalia bellirica* Roxb. | 53 | *Broussonetia papyrifera* Vent Moringaceae |
| 15 | *Terminalia chebula* Retz . Asteraceae | 54 | *Moringa concanensis* Nimmo |
| 16 | *Vernoniacinerea* (L.) Less.Corylaceae | 55 | *Moringa oleifera*Lam Myristicaceae |
| 17 | *Corylus avellana* L. Cucuribi taceae | 56 | *Myristica malabarica* Lam Papaveraceae |
| 18 | *Momordica dioica* Roxb. Ex Willd. Euphorbiaceae | 57 | *Argemone Mexicana* Fabaceae |
| 19 | *Aleurites fordii* Hemsl. | 58 | *Pongam ia pinnata* Pierre Rhamnaceae |
| 20 | *Aleurites moluccana* Wild | 59 | *Ziziphus mauritiana* Lam Rosaceae |

| | | | |
|---|---|---|---|
| 21 | *Aleurites Montana* Wils | 60 | *Princepia utilis* Royle Rubiaceae |
| 22 | *Croton tiglium* L. | 61 | *Meyna laxiflora* Robyns Rutaceae |
| 23 | *Euphorbia helioscopia* Hausskn. ex DC. | 62 | *Aegle marmelos correa* Roxb Salvadoraceae |
| 24 | *Jatropa curcas* L. | 63 | *Salvadora oleoides* Decne |
| 25 | *Joannesia princeps* Vell. | 64 | *Salvadora persica* L. Santalaceae |
| 26 | *Mallotus phillippinensis* Arg | 65 | *Santalum album* L. Sapindaceae |
| 27 | *Putranjiva rosburghii* | 66 | *Nephelium lappaceum* L. |
| 28 | *Sapium sebiferum* (L.) Roxb. | 67 | *Sapindus trifoliatus* L. |
| 29 | Flacourtiaceae | 68 | *Schleichera oleosa* Oken Sapotaceae |
| 30 | *Hydnocarpus kurzii* Warb. | 69 | *Madhuca butyracea* Mac |
| 31 | *Hydnocarpus wightiana*Blume Guttiferae | 70 | *Maduca indica* JF Gmel |
| 32 | *Calophyllum apetalum* Blanco | 71 | *Mimusops hexendra* Roxb Simaroubaceae |
| 33 | *Calophyllum inophyllum* L. | 72 | *Quassia indica* Nooleboom |
| 34 | *Garcinia indica* Choisy | 73 | *Ximenia Americana* L. Sterculaceae |
| 35 | *Garcinia echinocarpa* Thwaites | 74 | *Pterygota alata* Rbr Ulmaceae |
| 36 | *Mesua ferrea* L. | 75 | *Holoptelia integ rifo lia – not a promising plant* Urticaceae |
| 37 | *Garcinia Morella* Desr | 76 | *Urtica dioica* L. Verbenaceae |
| 38 | *Mesua ferrea* L. Icacinaceae | 77 | *Tectona grandis* L |
| 39 | *Mappia foetida* Milers Illiciceae *Illicium verum* Hook Labiatae | | |

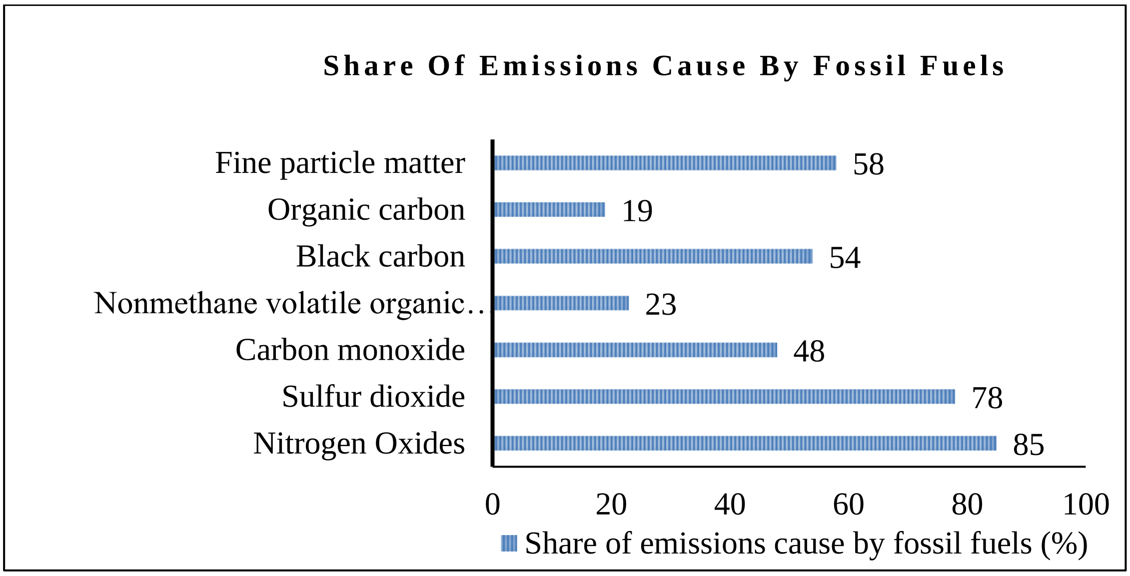
The most significant pollutants produced in biodiesel-fuelled CI engines are CO, HC, and NOx, out of which NOx contributes to more than 50% of emissions.[26]. To mitigate the $NO_X$ emission, the chemistry and the behaviour of the $NO_X$ emission have to be understood.

## 1.5 $NO_X$ Emissions

NOx includes both nitrogen oxide and nitrogen dioxide, and both of them are harmful to health and the environment.[27]. NOx contains NO as the main ingredient with a small quantity of $NO_2$. Nitrogen has other oxides like $N_2O$ (nitrous oxide), $NO_3$ (nitrogen trioxide) and $N_2O_5$ nitrogen pentoxide are so less that they can be ignored. The three main NOx types are thermal-based $NO_X$, prompt or instantaneous $NO_X$, and fuel-based $NO_X$. The Zeldovich mechanism, which happens at high temperatures, produces thermal NOx. Within the combustion chamber, nitrogen oxides form when atoms/molecules of $N_2$ and atoms/molecules of $O_2$ react at high temperatures, furthermore the $NO_X$ production rate quickly boosts up with the rise in temperature. Thermal NOx is thought to be the most significant part of the whole $NO_X$ generation in an IC engine. Fenimore $NO_X$ is another name for prompt NOx, and it is formed when intermediate hydrocarbon components combine to make it, mainly C-H and C-$H_2$, react with Nitrogen in the combustion process to generate C-N, which then combines with Oxygen dioxide to make $NO_X$, because HC components are required for quick NOx production, and it is possible when rich fuel condition is there. Within the combustion chamber, fuel components containing nitrogen- are oxidised, and fuel $NO_X$ is created. The formation of fuel NOx can be neglected for the diesel and biodiesel as both the fuel contains comparatively low nitrogen content. Nevertheless, a fuel that has an excessive amount of nitrogen can be effectively addressed by using additives.[28]. NOx emissions are highly undesirable, and laws governing the limits on the amount of NOx that can be emitted are becoming more stringent..[29].Acid precipitation, earth surface-level ozone generation, nutrient enrichment, and smoke formation are all caused by NOx emissions[27]

## 1.6 Emission Norms of India

A Pollution of the air refers to the presence of hazardous compounds in the atmosphere, which can have detrimental effects on human health, as well as on animals, plants, and property. Figure 1-4 Shows the %shares of various emission cause by the fossile fuel sources.




Ref: https://www.statista.com/statistics/1441273/fossil-fuel-contributions-to-air-pollutants-worldwide/

Figure 1-4:Share Of Emissions Cause By Fossil Fuels

The primary origin of NOx, CO, and HC emissions is motor vehicle exhaust, thereby necessitating their monitoring and regulation. In an attempt to regulate the emission of these detrimental pollutants into the surroundings, numerous nations have introduced and enforced diverse pollution regulations for car producers. To ensure optimal air quality, it is crucial to take into account the specific type of vehicle being utilized. For instance, the Environmental Protection Agency (EPA) in the United States and the European Union Research Organization (EURO) in Europe have established stringent regulations for automobiles in order to restrict the release of harmful exhaust emissions into the environment. European countries have accepted the EURO emission regulations, while the USA has adopted the Tier E emission requirements. The Indian government adopted the Air (Prevention and Control of Pollution) Act in 1981 to regulate air pollution. Subsequently, the Environment (Protection) Act of 1986 cleared the way for the regulation of motor vehicle emissions in India. India has implemented emission standards through the Motor Vehicles Act of 1988, which grants the government the authority to enforce these standards. Starting in 2000, petrol vehicles were required to meet EURO emission requirements, which were first implemented in 1991. Similarly, diesel vehicles had to adhere to EURO emission regulations, which were introduced in 1992. The Auto Fuel Policy of 2003 outlines the schedule for the implementation of different phases of emission regulations across India, including the adoption of these standards in specific cities as well as the rest of the country. The Indian emission standard India 2000 (BS I) is derived from the EURO 1 emission regulations as a benchmark. Table 1-3 displays the chronological implementation of emission standards in different phases in India. Figure 1-5[30]. displays the different emissions produced by heavy diesel vehicles and their respective maximum permissible thresholds. The data clearly illustrates a consistent reduction in the maximum permissible NOx emission levels for heavy diesel cars, from 18 g/kWh in 1991 to 0.46 g/kWh in accordance with the BS VI emission requirements. There exists a stringent rule on the acceptable threshold of emissions originating from automobiles[30].

Table 1-3: Indian emission standards (4-wheeled vehicles)

| Standard | Reference | Year | Region |
|---|---|---|---|
| India 2000 / Bharat Stage I | Euro 1 | 2000 | Nationwide |
| Bharat Stage II | Euro 2 | 2001 | NCR*, Mumbai, Kolkata, |
| | | 2003 | NCR*, 14 Cities† |
| | | 2005 | Nationwide |
| Bharat Stage III | Euro 3 | 2005-04 | CR*, 14 Cities† |
| | | 2010 | Nationwide |
| Bharat Stage IV | Euro 4 | 2010 | NCR*, 14 Cities† |
| | | 2017 | Nationwide |
| Bharat Stage V | Euro 5 | (skipped) | |
| Bharat Stage VI | Euro 6 | 2018 | Delhi |
| | | 2019 | NCR* |
| | | 2020 | Nationwide |

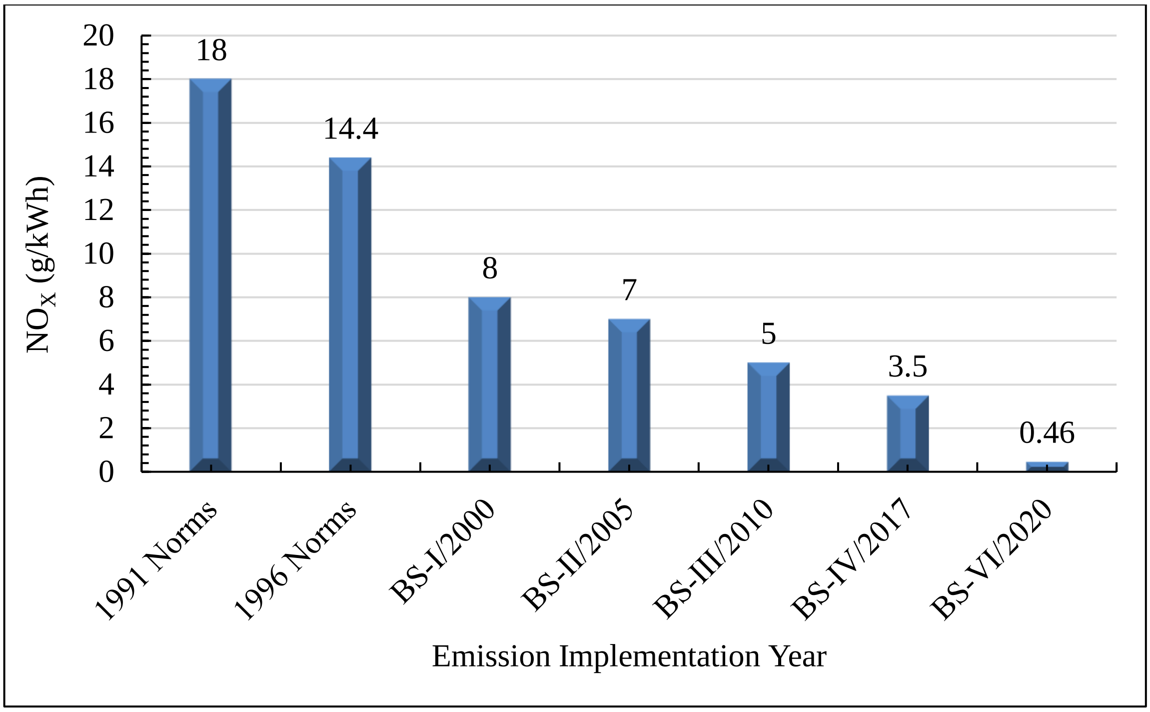



Figure 1-5:Maximum Allowable NOx emission from Heavy Diesel

## 1.7 Effect of $NO_X$ Emission on Environment and Health

The released oxides of nitrogen have numerous detrimental effects on human health, the environment, and biological ecosystems, including the degradation of the ozone layer and the occurrence of acid rain. According to Figure 1-6[31], nitrogen oxide emissions from transportable sources account for approximately 50% of total $NO_X$ production. The nitrogen oxide ($NO_X$) family has extensive health and environmental effects. Nitric oxides disperse throughout the entire respiratory system. Nitrogen oxides permeate through the alveolar cells (epithelium) and the nearby capillary capillaries of the lungs, causing damage to the alveolar structures and impairing their function in the lungs [32]. Nitric acid has a significant role in the chemistry of polar stratospheric clouds, and the nitric acid trihydrate is crucial for the creation of the ozone hole. Ground-level ozone is not emitted directly into the atmosphere. Instead, it is produced by chemical reactions between nitrogen oxides and volatile organic compounds (VOCs) in the presence of sunshine and/or heat[33]. Short-term exposure to NOx leads to respiratory health issues, including compromised immune system, increased lung inflammation, and decreased lung function. Respiratory function and growth. Microscopic particles resulting from NOx pollution and acid rain efficiently penetrate the lungs, leading to respiratory ailments such as bronchitis and emphysema, and worsening cardiovascular issues in humans[34].

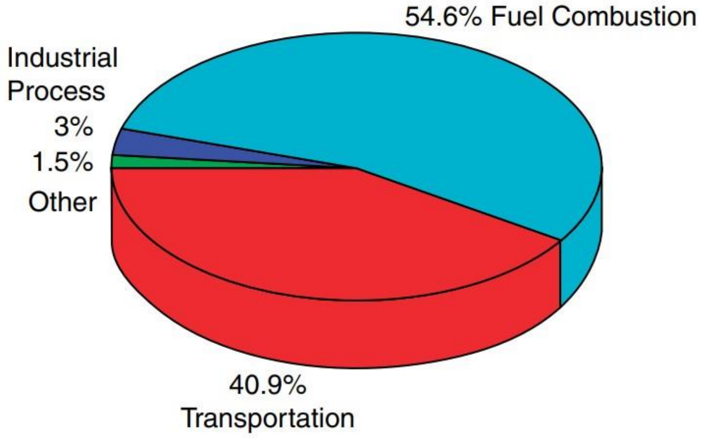



Figure 1-6:Nitrogen oxide emissions by source category (USA)

## 1.8 $NO_X$ Mitigation Techniques

$NO_X$ reduction technical can be classified into two major categories: (1) pre-combustion and (2) post-combustion as shown in Figure 1-7[35].

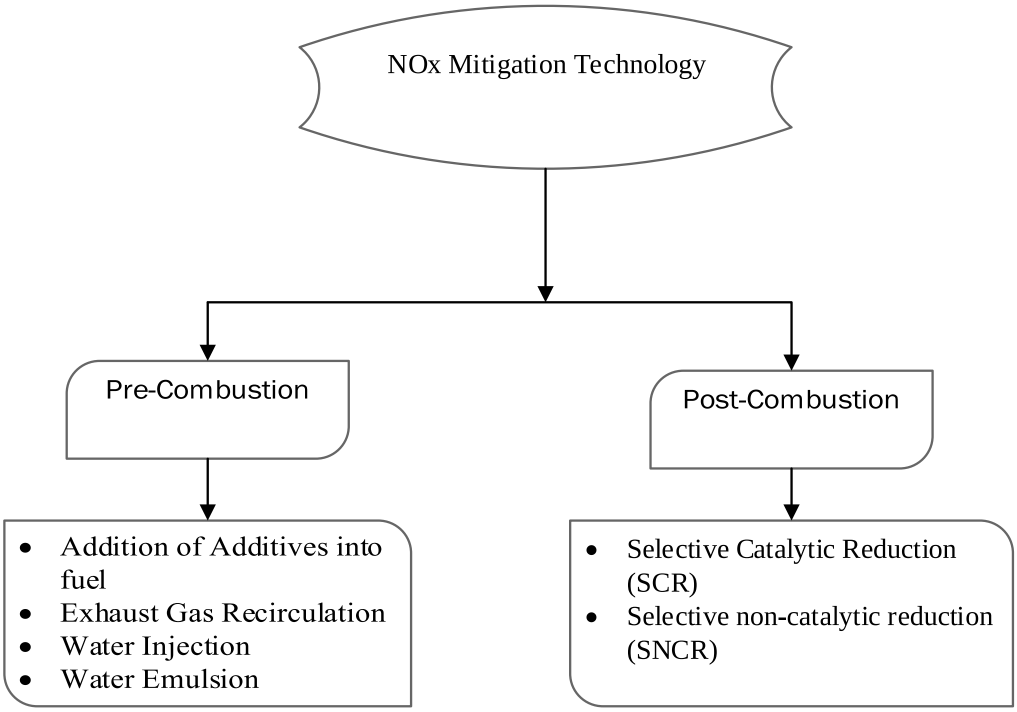



Figure 1-7:Classification of $NO_X$ mitigation Techniques

### 1.8.1 Exhaust Gas Recirculation

The EGR technique is supposed to be a helpful method of lowering $NO_X$ emissions from flue gases. EGR technique replaces oxygen and nitrogen by dioxides of carbon and aqua vapour in new air entering the combustion chamber as shown in Figure 1-8 [36]. The heat storage capacity of a mixture is increased when a part of an emission gas is recirculated through the intake airline while lowering the oxygen concentration. By combining these two elements, there is a substantial reduction in NOx emissions. The proportion of emission gas which has to be mixed (MEGR) in the overall intake mixture is specified as EGR (percentage).[37]

$$\%EGR = \frac{(Amount\ of\ air\ permitted\ w/o\ EGR - Amount\ of\ air\ permitted\ with\ EGR)}{Amount\ of\ air\ permitted\ w/o\ EGR} \quad \text{(i)}$$

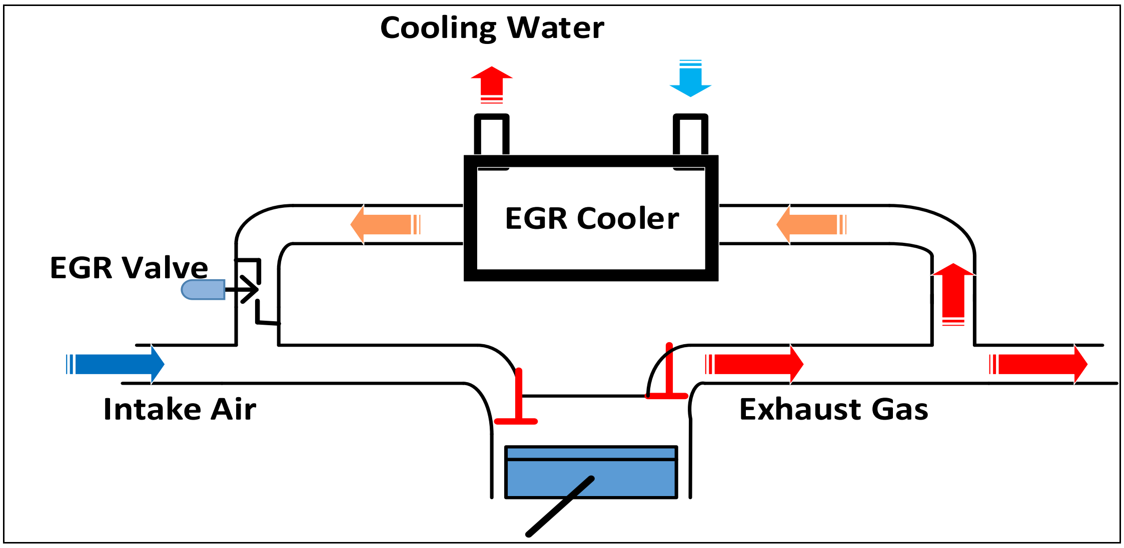



Figure 1-8: Exhaust Gas Recirculation Technique

### 1.8.2 Water Emulsion

In this process, a portion of the heat generated is soaked up by atoms of $H_2O$ (L) in the cylinder during the fuel-burning process, reducing the temperature gradient of the chamber and cutting down the NOx emissions. An emulsion is formed by two moderately miscible liquids, one of which is water, which is disseminated in its counterpart (biodiesel). The presence of an aqua portion in the emulsified biodiesel enhances expansion, which provides more force and so improves brake thermal efficiency[38].

*Micro-explosion*

Inside the combustion chamber, larger drops of fuel are transformed into smaller droplets [39]. With the help of the surfactant, the oil and water combined quickly. Initially, at the starting point of the operation, the droplets of fuel which contain water droplets can be transformed into smaller droplets by increasing the temperature (rapid evaporation) [40]. This phenomenon is presented in Figure 1-9[41].

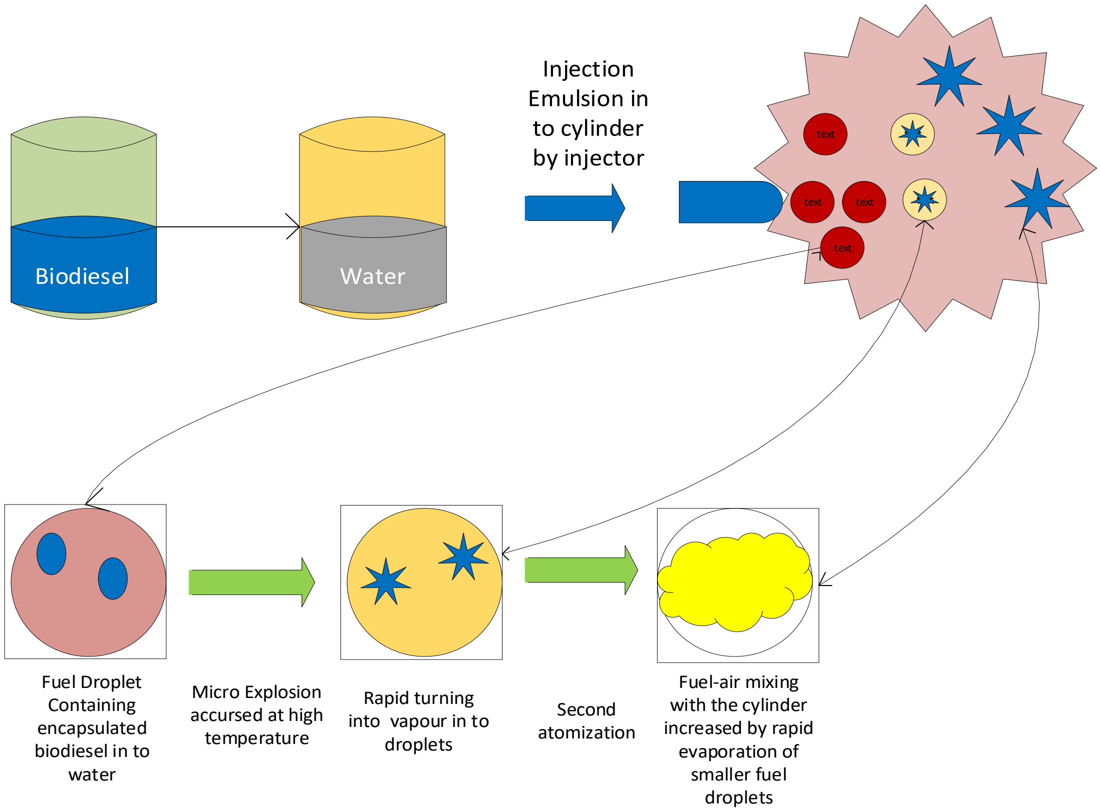



Figure 1-9:Transformation of fine droplet via micro-emulsion

### 1.8.3 Water Injection (WI)

Two ways of Water Injection have been identified: Water injection at the inlet manifold and water injection directly inside the cylinder [42][43][44]. Although WI technology reduces NOx, it has several drawbacks, such as considerably increasing CO-HC emissions, as well as specific fuel consumption, when the engine is running at minimum load and minimum combustion temperature. Either Injection of water directly inside the chamber, or through the intake manifold, is an essential approach for reducing nitrogen oxide emissions from a diesel engine. WI (water injection) has the advantage of being able to mitigate nitrogen oxides for all the engine load ranges while having a small rise in particulate matter emissions [43]. Water absorbs the heat of evaporation from the adjacent adiabatic flame, lowering the temperature as a result, NOx emissions are lowered [42]

### 1.8.4 Fuel Additives

Fuel additives are extensively utilized. for various reasons whether it's an additive to change the burn rate of fuel, enhance the surface area, avoid corrosive effects, or simply change the colour. Researchers have developed a variety of additives over the past few decades that provide base fuels with an additional attribute that meets a pressing customer demand. Additives added to petroleum-based fuels are commonly associated with climate protection, pollutant reduction, and increased mileage. Additive technology has a wider impact based on changeability, altercation, or improved specific attributes of a fuel, irrespective of the phase of fuel like liquid, solid, or gas. Additives are supposed to be developed to boost combustion rates, act as anti-oxidants, affect burn rates, allow fuels to operate at high temperatures, minimise toxic emissions, and more.

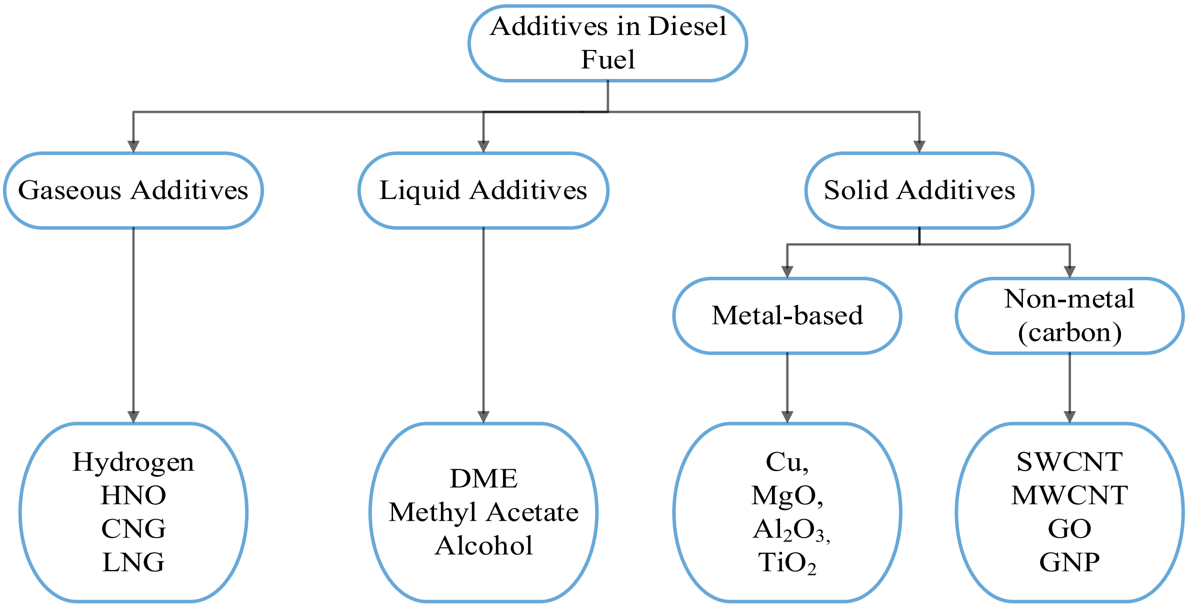



Figure 1-10:Classification of additives

The additives can be categorized into liquid, gaseous, and solid forms. The solid additives can be categorized into two groups: metal additives and non-metal additions.Figure 1-10[45] depicts this classification.

### 1.8.5 Selective Catalytic Reduction (SCR)

To change the structure of dangerous NOx emissions from toxic to non-toxic $N_2$ structure, the SCR process is used. It is made up of catalysts along with certain NOx-reducing agents. Ammonia is often used as a NOx reduction agent ($NH_3$) (Figure 1-11). Under lean conditions, ammonia selectively reacts with NOx along with the catalyst to form $N_2$ [46]. The $NH_3$-SCR technique is non-feasible for use in automotive diesel engines since storing toxic $NH_3$ (in gaseous form) is unsafe. As a result, urea-SCR was proposed, where ammonia is created on-vehicle by urea decomposition. Urea first decomposes into $NH_3$, which then interacts with NOx to form $N_2$. SCR conversion rates are typically in the 70-90 percent range. Higher rates of reduction are also achievable, but they are not cost-effective.

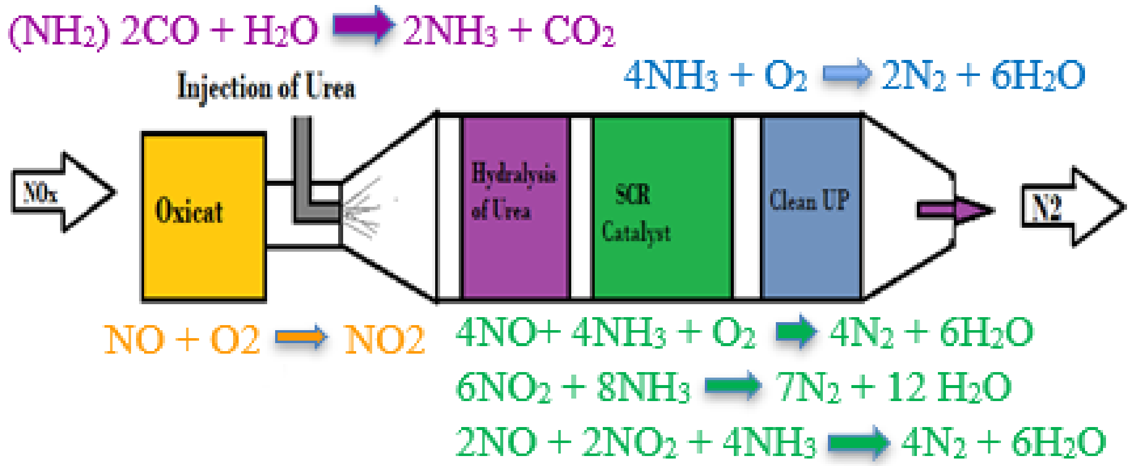



Figure 1-11:Schematic View of SCR System

### 1.8.6 Selective Non-Catalytic Reduction (SNCR)

The SNCR method utilizes a catalyst-free chemical process, employing an urea-based solution such as urea or ammonia, that turns NOx into nitrogen ($N_2$) and water ($H_2O$). This reaction occurs when the reagent is introduced into the exhaust gas flow following combustion, at temperatures ranging from 1600°F to 2400°F (870°C to 1320°C).[47]. Fewer researchers have implemented this method for diesel engines to mitigate $NO_X$. One significant drawback of the SNCR method is that the operating temperature range in which NOx agents can effectively work is somewhat limited.[48].

## 1.9 NOx and CO Emission Reactions with Water

Nitrogen gas ($N_2$) is a diatomic molecule that is chemically unreactive and constitutes approximately 80% of the Earth's atmosphere. As a solitary atom, nitrogen (N) can exhibit reactivity and possess valence states ranging from plus one to plus five. Table 1-4. provides a comprehensive list of the NOx compounds together with their respective characteristics. Nevertheless, their existence in the atmosphere is characterized by extremely low concentrations, leading to a tendency to overlook both their presence and their impact. Two molecules of nitrogen dioxide ($NO_2$) combine to generate dimeric nitrogen tetroxide ($N_2O_4$), which exhibits similar reactivity to $NO_2$. This dimer has the potential to obscure the presence of $NO_2$ due to its higher abundance. $N_2O_5$ is the most extensively ionized nitrogen oxide[49]. Nitrogen dioxide ($NO_2$) is found in both the atmosphere and acid rain. When this substance is dissolved in water, it generates nitric acid ($HNO_3$). When nitrogen dioxide ($NO_2$) undergoes photochemical reaction with a photon, it transforms into nitric oxide (NO), whereas oxygen

($O_2$) is converted into ozone ($O_3$). The NO is rapidly oxidized to $NO_2$ within a few hours by radicals generated by the photoreaction of volatile organic compounds (VOCs). Hence, the present level of ozone in our atmosphere is a consequence of the combined pollution from both NOx and VOC. Dinitrogen trioxide ($N_2O_3$) and dinitrogen tetroxide ($N_2O_4$) are present in low concentrations in flue gas. Nevertheless, their existence in the atmosphere is characterized by extremely low concentrations, leading to a tendency to overlook both their presence and their impact. Due to its dimeric nature, $N_2O_4$, which consists of two $NO_2$ molecules, has similar reactivity to $NO_2$. Consequently, the higher concentration of $NO_2$ can mask the detection of $N_2O_4$. Dinitrogen pentoxide ($N_2O_5$) is the nitrogen oxide with the highest degree of ionization.

Table 1-4: Nitrogen Oxides (NOx)

| Formula | Name | Nitrogen Valence | Properties |
|---|---|---|---|
| $N_2O$ | Nitrous Oxide | 1 | Colourless gas<br>Soluble in water |
| NO<br>$N_2O_2$ | Nitric Oxide<br>Dinitrogen dioxide | 2 | Colourless gas<br>Soluble in water |
| $N_2O_3$ | Dinitrogen trioxide | 3 | Soluble in water,<br>decomposes in water |
| $NO_2$<br>$N_2O_4$ | Nitrogen dioxide<br>Dinitrogen tetroxide | 4 | Red-brown gas, very soluble in water, decomposes in water |
| $N_2O_5$ | Dinitrogen pentoxide | 5 | Very soluble in water,<br>decomposes in water |

It is only present in the air in minor quantities unless it is intentionally released by an intended approach. $N_2O_5$ is a highly reactive compound that undergoes decomposition in water to produce nitric acid ($HNO_3$). For environmental purposes, use the concentration of $NO_2$ as a substitute for the concentration of NOx appears to be adequate [49]. The difficulties of NOx abatement and control technology are inherently intricate. Our goal is to categorize the various technologies for the prevention and control of NOx pollution by initially presenting the fundamental ideas. Next, we will outline the most effective methods and approaches for preventing pollution and controlling emissions.

Combustion sources emit oxides of nitrogen in a significant volume of exhaust gas, whereas nitric acid producing plants and pickling baths make efforts to control NOx. Wet scrubbers, also known as absorbers, are capable of managing emissions of NOx from acid factories and pickling processes. They can utilize hydrogen peroxide, water alone, or alkali in water, as the liquid medium to collect the oxides of nitrogen, as seen in equation (ii) [49] the interactions between $NO_2$ and water

$$NO_2 + H_2O \rightarrow HNO_3 + HNO_2 \quad \text{(ii)}$$

The water–gas shift reaction (WGSR) equation (iii)[50] describes the reaction of carbon monoxide and vapour to form carbon dioxide and hydrogen:

$$CO + H_2O \rightarrow CO_2 + H_2 \quad \text{(iii)}$$

The water gas shift reaction was discovered by Italian physicist Felice Fontana in 1780

## 1.10 Government Policy on Biodiesel

India is currently experiencing rapid economic growth and is expected to maintain this trend for several decades. Additionally, India will benefit from its favorable demographic situation during this time. The development objectives prioritize inclusivity, a unified vision of national progress, technological advancement, skill enhancement, economic expansion, fairness, and the welfare of individuals. Energy has a crucial role in enhancing the quality of life for individuals. Nevertheless, it is imperative that we exercise caution in our utilization of conventional or fossil fuel resources due to their finite nature, lack of renewability, and detrimental impact on the environment. In contrast, renewable energy resources are native to a particular region, do not cause pollution, and are almost limitless. India has a plentiful supply of renewable energy resources. The National Policy on Biofuels (2018) establishes a fresh agenda that aligns with the revised role of developing advancements in the renewable industry.

### 1.10.1 The Vision and Goals

The policy seeks to enhance the utilization of biofuels in the energy and transportation sectors of the country in the coming decade. The policy intends to use, enhance, and endorse indigenous raw materials for the manufacturing of biofuels, with the intention of progressively substituting fossil fuels. This will aid in enhancing national energy stability, mitigating climate change, and responsibly generating fresh job prospects. Additionally, the strategy would promote the utilization of cutting-edge technologies for the production of biofuels[51].

- The objective of the policy is to facilitate the presence of biofuel raw materials in the market and enhance the proportion of biofuel blended with diesel fuel.

## 1.11 The scope of work

Alternative fuels like biodiesel have excellent potential to either be replaced or partly used with diesel so usage of conventional fuel can be reduced. The major issue with biodiesel is that due to the existence of oxygen around 10 to 12% in biodiesel and so at the time of combustion in the internal combustion engine at elevated temperature, it easily reacts with nitrogen and form NOx.

The present work focuses on the quantification of $NO_X$ emission for all the combinations of various diesel-biodiesel fuel blends, compression ratios, and injection pressures at different engine loading conditions of single-cylinder VCR diesel engine. The effect of water on $NO_X$ emission is also studied by injecting the water at different flow rates into the exhaust manifold of the CI engine.

## 1.12 Organisation of Thesis

***Chapter 1: Introduction***

This chapter has presented a preliminary overview of the subject matter and the reasons behind conducting this study. Additionally, it explores the environmental, health, and energy scenarios.

***Chapter 2: Literature Review***

This chapter provides a brief description of the different approaches used to reduce the NOx emissions of the compression ignition engine. This piece of literature discusses the impact of compression ratio and injection pressure on the performance and emission characteristics of a compression ignition (CI) engine. A comprehensive review of existing literature establishes the gap in research and determines the specific research objective of the thesis.

***Chapter 3: Experiments***

This chapter provides a discussion of biodiesel, focusing on its production through the transesterification process. It also covers the preparation of blends of diesel and biodiesel, as well as the measurement of properties of these blends. Additionally, it delves into the specifics of the experimental setup, including the measuring instruments used, the methodology employed, and the management of recorded and stored experimental data.

***Chapter 4: Results & Discussion***

This chapter examines the impact of different compression ratios, injection pressure levels, and fuel blends on brake thermal efficiency, as well as emissions of NOx, CO, HC, and smoke. The chapter further elucidates the impact of water injection on NOx emissions.

***Chapter 5: Conclusions and future scopes***

The chapter provides a concise overview and analysis of all the findings acquired by the author. The chapter also addresses the constraints and assumptions. The prospects of the research study have also been explored.

***Chapter 6: Bibliography***

This chapter includes the list of references used in each chapter and a list of publications and presentations done based on the research work