LIFECYCLE ANALYSIS OF IC ENGINE

Thesis Submitted in Partial Fulfillment of the Requirements for the Degree of

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By

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DECLARATION

I hereby declare that thesis entitled **"Lifecycle Analysis of IC Engine"** submitted by me in fulfillment of the requirement for the degree of Doctor of Philosophy to Delhi Technological University (Formerly Delhi College of Engineering) is a record of bona fide work carried out by me under the supervision of Dr. Amit Pal, Professor, Department of Mechanical Engineering, Delhi Technological University, Delhi.

I further declare that the work reported in this thesis has not been submitted either in part or in full, for the award of any other degree or diploma in any other Institute or University.

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CERTIFICATE

This is to certify that the work embodied in the *thesis* entitled **“Lifecycle Analysis of IC Engine”** is a record of *bona fide research work* carried out by **Mr. Sanjeev Kumar** (**2K16/PHD/ME/44**) in fulfillment of requirements for the award of degree of **Doctor of Philosophy** in **Mechanical Engineering**. He has worked under my guidance and supervision and has fulfilled the requirements which, to my knowledge, have reached the requisite standard for submitting the thesis.

The results in this thesis have not been submitted in part or full at any other University or Institute for the award of any degree or diploma.

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Dedicated

to

My Parents

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ABSTRACT

The automotive industry predominantly relies on fossil fuels like oil, coal, and gas, producing substantial amounts of greenhouse gases (GHGs) that contribute to severe climate change. The adverse consequences of environmental degradation are increasingly evident in the form of ambient air pollutants. Therefore, continued efforts are imperative to mitigate environmental impacts and reduce the transportation sector's dependence on conventional fuels. Since their inception in the real world, IC engines have made significant strides in enhancing fuel efficiency, thanks to innovations like Common Rail Direct Injection (CRDi), Multi-Point Fuel Injection (MPFI), Variable Valve Timing (VVT), and Gasoline Direct Injection (GDI). These technologies minimize wastage, optimize combustion, and improve overall engine efficiency, reducing emissions. Nevertheless, IC engines still release pollutants, and stringent emissions regulations drive ongoing advancements. The compatibility of biodiesel with existing diesel engines with minimal or no modifications underscores its viability. Despite challenges, IC engines will persist owing to their durability, infrastructure advantages, long-range capabilities, and cost benefits. However, complying with emissions standards remains a challenge. To compete with Battery Electric Vehicles (BEVs), IC engines need to enhance efficiency and emissions reduction. Plug-in, as well as hybridization technology, can address these concerns, while cleaner alternative fuels like biodiesel provide a path to reduce their environmental impact. The future of IC engines hinges on a balance of innovation, compliance, and environmental awareness.

The present study incorporates a two-phase LCA. First, it conducts an LCA of biodiesel produced from Karanja and microalgae feedstock. Subsequently, it assesses a generic diesel engine manufactured under Indian conditions using the LCA approach. As biodiesel emerges as a viable substitute for fossil fuels, it becomes essential to identify and assess potential non-edible feedstocks concerning their ecological significance as well as the energy needed for the production of biodiesel. The LCA is employed from the initial stages of production to disposal to evaluate the environmental impacts and energy needed for biodiesel derived from two types of feedstock: Karanja and Microalgae. The environmental impacts of IC engines are assessed using the ISO-

14040 procedure and recommendations, involving four major steps: goal and scope definition, inventory analysis, impact assessment, and result interpretation.

The energy ratios of Karanja feedstock and microalgae are examined, illustrating the possibility of a significant decrease in greenhouse gas emissions, particularly when combined with a sensitivity analysis. The energy ratio of Karanja feedstock is precisely determined to be 5.67, while the energy ratio of microalgae is around 2.49. Although different feedstocks may have opposing environmental characteristics, Karanja demonstrates improved results in LCA when compared to microalgae. For example, Karanja has a net energy value (NEV) of 64.1, whereas microalgae has a higher energy utilization with an NEV of 286.19, albeit it achieves a higher yield.

The LCA of an internal combustion engine (IC Engine) was also conducted in case of a generic diesel engine produced in India. Life cycle inventory is conducted for many phases, including manufacturing, operation, and disposal. The numerical data reveals that Climate Change Potential (CCP) has the most significant environmental effect, measuring at 363513.60 kgCO2eq. It is followed by Fossil resource Scarcity, which stands at 58358.51 kgOileq, and Acidification Potential (AP) at 18193.93 kgSO2eq. In the event of using pure diesel as fuel, the Photochemical Ozone Formation Potential (POFP) contributes greatly with 259.16 kgNOX-eq and the Fine Particulate Matter Formation (FPMF) contributes heavily with 501.4492 kgPMeq. The research emphasizes that the use phase of the engine is the most energy-intensive and ecologically harmful stage throughout its life cycle. The numerical data shows a strong correlation between the main energy demand during the consumption phase and the generation of diesel fuel. Specifically, the CCP, AP, FPMF, and POFP are strongly linked to the engine operating processes.

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LIST OF ABBREVIATIONS

AP	Acidification Potential
AVU	atmospheric Vacuum Unit
ATF	Aviation Turbine Fuel
BTE	Brake Thermal Efficiency
BEVs/EVs	Battery Electric Vehicles/Electric Vehicles
BC	Before Christ
BOD	Biological Oxygen Demand
BEML	Bharat Earth Movers Limited
BBU	Bitumen Blowing Unit
CI	Compression Ignition
CNC	Computerized Numerical Machine
CNG	Compressed Natural Gas
CO	Carbon Mono Oxide
CRDi	Common Rail Direct Injection
CC/CCP	Climate Change/Climate Change Potential
CGE	Computable General Equilibrium
CED	Cumulative Energy Demand
COD	Cumulative Oxygen Demand
CCRU	Continuous Catalytic Reforming Unit
CML	Centrum Voor Milieukunde Leiden
C. Vulgaris	Chlorella Vulgaris
CIL	Coal India Limited
DI	Direct Injection
DHDS	Diesel Hydro Desulphurization Unit
DALY	Disability Adjusting Life Year
DWT	Dead Weight

DHDT	Diesel Hydrotreater Unit
ECU	Electronic Control Unit
EGR	Exhaust Gas Recirculation
EP	Eutrophication Potential
ER	Energy Ratio
EDIP	Environmental Design of Industrial Products
ESP	Electrical Submersible Pumps
FAME	Faster Adoption and Manufacturing of (Hybrid &) Electric Vehicles in India
FCV/ FCEVs	Fuel Cell Vehicles / Fuel Cell Electric Vehicles
FD	Fossil Depletion
FU	Functional Unit
FFA	Free Fatty Acid
FPMF	Fine Particulate Matter Formation
GHG	Greenhouse Gas
GDI	Gasoline Direct Injection
GoI	Government of India
GWP	Global Warming Potential
GJ	Gegajoule
GREET	Greenhouse Gases, Regulated Emissions and Energy Use in Transportation
g/gm	Gram
HC	Hydro Carbon
HCCI	Homogeneous Charge Compression Ignition
HRSG	Heat Recovery Steam Generator
HGU	Hydrogen Generation Units
ICE/ ICEVs	Internal Combustion Engine
IAI	International Aluminum Institute
IOCL	Indian Oil Corporation Limited

ISO	International Organization for Standardization
IPCC	Intergovermental Protocol for Climate Change
JRC	Joint Research Centre
kWh	Kilowatt hour
kg	Kilogram
kHz	Kilo Hertz
KB	Karanja Biodiesel
LPG	Liquefied Petroleum Gas
LCA	Life Cycle Analysis
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
MPFI	Multi-Port Fuel Injection System
MT	Metric Ton
MPa	Mega Pascal
MJ	Mega Joule
MLD	Million Litres per Day
Mtpa	Million Tonnes per Annum
MDPL	Mathura-Delhi Pipeline
MTPL	Mathura-Tundla Pipeline
MBPL	Mathura-Bharatpur Pipeline
NOx	Nitrogen Oxides
NG	Natural Gas
NEV	Net Energy Value
NER	Net Energy Ratio
NITI	National Institution for Transforming India
NMDC	National Mineral Development Corporation
OHCU	Once through Hydrocracker Unit
PM	Particulate Matter

POCP	Photochemical Oxidant Creation Potential
POFP	Photochemical Ozone Formation Potential
PMF	Particulate Matter Formation
PHEVs	Plug-in Hybrid Electric Vehicles
Psi	Pounds per Square Inch
SI	Spark Ignition
SPM	Special Purpose Machine
SMPL	Salaya-Mathura Pipeline
SRU	Sulfur Recovery Units
TA	Terrestrial Acidification
US/USA	United States/United States of America
USD	US Dollar
VVT	Variable Valve Timing
VOCs	Volatile Organic Compounds
VBU	Vis Breaking Unit
WHO	World Health Organization ()
WCO	Waste Cooking Oil

CHAPTER 1
INTRODUCTION

1.1 Introduction

The history of human commutation is quite long. People have wanted to live near rivers, ponds or other water bodies from the beginning of human civilization, since water is the most basic necessary for life on Earth. With the expansion of the population, human ancestors began to migrate in all directions and distant locations to live. Thus, transportation system became essential for survival. Initially, the sole form of transportation was Shanks' pony, also known as the human foot. After then, humans learnt to domesticate and employ animals like as donkeys, horses, elephants, and camels for transportation. Meanwhile, in 3,500 BC, the wheel was developed, which is regarded as a significant milestone in the history of transportation. In terms of innovation, the introduction of the steam engine was a watershed moment in rail transit history. This principle was used in railway locomotives, where steam generated from water and coal, powered the engine. The creation of the internal combustion engine (IC Engine/ICE) is a further turning point in the world of transportation since the nearly transporting medium uses the propulsive energy from the IC Engine.

1.2 History of IC Engines

Several researchers claimed to have created the ICE in the 1860s, but the patent for the four-stroke working sequence was held by Nikolaus Otto in 1887. Since its innovation, outstanding scientists and academics have made several improvements to increase its use; power-to-weight ratio, fuel economy, and lesser exhaust emission etc.

Table 1 summarizes the history of the ICE, indicating how we got at contemporary compact and economical state-of-the-art engine [1].

Table 1.1: History of IC Engine

Year	Researcher	Milestones of development of IC Engines
1680	Christian Huygens	Huygens proposed the design of an ICE. In this engine gunpowder was to be used as fuel but it was never built physically.
1807	Francois Isaac de Rivaz	Rivaz designed an ICE that ran on a combination of H_2 plus O_2. He created the first ICE-powered vehicle. However, his design proved extremely unsuccessful.
1824	Samuel Brown	Samuel Brown experimented on an old steam engine (Newcomen), in which he burnt gas, and supplied its energy to a vehicle up London city’s Shooter’s Hill.
1858	Jean Joseph Étienne Lenoir	In 1863, Lenoir fitted an upgraded engine (powered by gasoline and a rudimentary carburetor) onto his transporting wagon and completed a historic fifty-mile highway trip.
1864	Siegfried Marcus	Marcus built a vehicle that momentarily reached 10 mph and is considered by certain scholars to be the world’s first gasoline-powered vehicle.
1873	George Brayton	George Brayton, USA-based researcher, proposed 2-stroke kerosene engine, but he could not run it successfully. Nevertheless, it was regarded as the initial safer and functional oil powered engine.
1876	Nikolaus August Otto	Nikolaus August Otto created and subsequently patented an efficient 4-stroke engine dubbed the “Otto cycle”.
1876	Dougald Clerk.	He proposed a working two-stroke engine.
1883	Edouard Delamare-Debouteville	Edouard performed an experiment using stove gas as fuel on a self-built a four-stroke engine of single cylinder.
1886	Karl Benz	Karl Benz was granted a patent (“DRP No. 37435”) for a gas-fueled vehicle.
1889	Daimler	Daimler developed an upgraded four-stroke engine featuring two V-slant cylinders with mushroom-shaped.
1890	Wilhelm Maybach	Wilhelm Maybach presented a four-cylinder engine working on the principle of four-stroke.
1892	Rudolf Diesel	Rudolf Diesel invented four stroke compression ignition engines and got patent for this great breakthrough in the field of engine.

1.3 Problems Associated with IC Engines

IC engines have been used for a long time to provide the necessary propulsion energy in traditional transportation. These engines use diesel and gasoline fuel derived from petroleum, which results in the emission of a variety of polluting gases that are harmful to the environment. Since there has been a considerable growth in the need for transportation, there has also been a greater mandate for fuels derived from petroleum, like gasoline and diesel. Additionally, greenhouse gases (GHGs) and contaminants have accrued to a significant degree, which has resulted in serious repercussions. The usage of ICE has resulted in the emergence of two significant problems: the environmental pollution problem and the scarcity of fossil fuel [2].

1.3.1 Scarcity of Fossil Fuels

Due to the sheer flexibility and need for personal mobility, the demand for fossil fuel to power ICE-driven vehicles is expanding over the world. This problem was exacerbated by the COVID-19 epidemic, which mandated social distance when traveling. However, because fossil fuels are non-renewable, their reserves are fast depleting. The shortage of fossil based fuels, and political influence on the supply chain, are consistently driving up global fuel costs. The post-COVID rise in demand for fossil fuels has shattered all previous records for petrol/diesel prices throughout the world [3,4]. The demand-supply gap is not only affecting the developing countries but it is now affecting the developed nations also. The highly fluctuating price of crude oil on the global market, the limited native oil reserves, the absence of new major oil reserves, local petroleum oil production that has more or less remained stagnant, and the ever-increasing domestic demand have all contributed to a significant dependence on imported crude oil. As a result, policymakers in India also have been looking for alternative energy sources, particularly for the road transportation sector. The transfer of products and employees from one location to another on highways utilizing motorized vehicles is referred to as road transport [5,6].

As a consequence of the many advantages that they provide, including flexibility, high efficiency of combustion, availability, dependability, and the availability of handling amenities, fossil fuels are responsible for the majority of energy consumption.

Natural gas, oil, and coal will each provide 27% of the overall mix by the year 2035, with the remaining share being supplied by renewable energy sources and nuclear power. Additionally, the proportions of the main fossil fuels are beginning to cluster together. In the process of burning fossil fuels, emissions are produced that have a significant impact not only on the health of humans but also on the health of the environment [7]. Three-eighths of the growth in emissions is attributed to fuel, coal, and gas, while oil is responsible for twenty-four percent of the increase. The worldwide CO_2 emissions that are caused by the use of energy are expected to grow by 29% by the year 2035. From 1990 to 2035, the worldwide emissions will be approximately twice as high as they were in 1990 [8].

1.3.2 Exhaust Emissions

Vehicular emissions are being held responsible for climate change and other associated problems like global warming. Climate change is also causing havoc with extreme weather phenomena like cloud bursts, flash floods, incessant rain patterns, drought, rise in sea levels, and submerging of low-lying regions [9,10]. Air pollution being the greatest environmental challenges in most Asian cities, including India, where the bulk of the urban population is subjected to poor air quality. Air pollution contributes to several health problems, including cardiovascular disease, lung ailments, an increased risk of cancer, and other serious disorders. India, which emitted 2299 MTs of CO_2 in 2018, is expanding quicker compared to other major energy-consuming countries and is now the major GHGs emitter after the United States of America (USA) and China [11]. Led by transport sector as primary fossil fuel products consumer, accounting for up to 55 percent of total national consumption and emitting about 7.5 percent of the country's carbon dioxide. Most Indian cities have seen significant air pollution in recent years, with the quality of air failing to meet World Health Organization (WHO)-recommended safe limits. According to the WHO, New Delhi is the most polluted city in the world, followed by 12 other Indian cities. Major cities of India are choking with a high level of PM, especially the national capital with PM 2.5 pollution throughout the year [11–14]. The dual facet problem of fuel scarcity and pollution had been the greatest puzzle to solve for researchers, policymakers, and governments.

1.4 Recent Developments in IC Engines

Engine technology has advanced significantly throughout the years, ranging from inlet-outlet-valve systems using gravity-based combustible mixtures to contemporary systems of fuel injection. To begin, Direct Injection (DI) encompasses a basic fuel injection method utilized in many previous-generation ICE. Several developments have been made since the introduction of the IC Engine like CRDi, MPFI, VVT, GDI and many others. These developments made the IC Engine to face the challenges of emission and fuel scarcity. Some of the major developments are summarized as below:

1.4.1 Common Rail Direct Injection

Common rail direct injection (CDRi) system, is a way of injecting liquid fuel into the combustion chamber of ICE. A high-pressure common rail injects gasoline into individual valves. This fuel injection method is often employed in current engines due to technical advancements. This approach involves injecting fuel via a single, common line. This single connection connects all of the fuel injectors throughout the system and is referred to as the common rail. The conventional injection process and CRDI differ in that the conventional method requires the system to generate pressure multiple times for each stage of the fuel injection process, whereas CRDI is able to maintain the necessary pressure consistently for each injection cycle, meaning that CRDI will keep the same pressure in the common rail system. The electronic control unit (ECU) regulates pressure as required. The ECU employs sensors located on the crankshaft and camshaft of the engine. The injection pressure is adjusted in accordance with the engine's rpm and load. The whole procedure ensures that the procedure of injection is executed with utmost precision according to the necessary specifications. It enhances the efficiency, affordability, and long-term viability of the system. Currently, piezoelectric injectors are used to precisely achieve higher pressure [15,16].

1.4.2 Multi Point Fuel Injection

The Multi-Port Fuel Injection System (MPFI) is the method or technology that delivers fuel to an ICE by use of several ports positioned close to the inlet valve on each cylinder. It ensures that each cylinder receives the same amount of gasoline at the precise moment it is needed. A regulator to maintain a fuel pressure regulator, cylinders, and a spring for pressure, fuel injectors, and a control diaphragm are all components that make up an MPFI cylinder. The fuel is injected into each cylinder via an intake port that is located upstream of the cylinder's intake value. This is accomplished by using several separate injectors. A fuel pressure regulator is responsible for directing the flow of gasoline. The amount of load and the speed of the engine both have a major impact on the pressure that is present in the intake manifold [16].

1.4.3 Gasoline Direct Injection

Automakers globally pursue efficient IC engines like GDI, blending diesel efficiency and gasoline power for emission and fuel economy competition. The first GDI in 1925 for low-compression truck engines, and Mitsubishi's 1996 electronic GDI marked mass adoption. Usage surged from 2.3% in 2008 models to 50% in 2016 models. GDI offers benefits but faces operational constraints, including direct injection impacting mixture formation and evaporation due to limited time [17].

1.4.4 Dual Fuel

Dual fuel engines combine two different fuels, often diesel and natural gas, allowing flexibility in operation. The diesel-natural gas combination enables running on diesel when natural gas is unavailable. The substitution rate, the natural gas energy percentage, is crucial. Load factor and diesel consumption affect substitution rates, emphasizing real-world usage. Comparing engines requires considering load-matched substitution rates instead of maximum values. The study examined LPG's impact on dual-fuel engine performance, favouring 40% diesel and 30% butane in LPG. Natural gas-diesel dual-fuel reduces NO and soot emissions, impacting BTE, CO, and HC trends [18].

1.4.5 Homogeneous Charge Compression Ignition (HCCI) Engine

HCCI engines integrate the most advantageous characteristics found in traditional CI as well as CI engines. These engines operate by injecting a premixed combination of air and fuel, similar to a typical spark ignition (SI) engine. However, the combustion process occurs by autoignition, similar to a normal compression ignition (CI) engine. Therefore, HCCI is a very promising combustion technique that can achieve near-zero levels of NOx and soot emissions while maintaining great fuel economy. The properties of HCCI engines are heavily influenced by the method of engine operating. It was noted that in the majority of instances, the emissions of HC and CO were significantly affected during HCCI operation as a result of the increased impact of cylinder crevices and local air-fuel equivalency ratio. Nevertheless, the rise in HC and CO emissions during operation of homogeneous charge compression ignition (HCCI) mode may be effectively mitigated by the use of direct oxidation catalysts and by carefully adjusting the timing of the second fuel injection [19].

1.4.6 Variable Valve Timing and Lift

Following the widespread use of multi-valve technology in engine design, Variable Valve Timing has emerged as the subsequent advancement to optimize engine performance, encompassing both power and torque. Valves are responsible for initiating the engine’s respiratory process. The timing of respiration, specifically the time of inhalation and exhalation, is regulated by the angle of phase as well as configuration cams. In order to enhance the efficiency of the engine’s air intake, it is necessary to adjust the timing of the engine’s valves according to the speed at which it is operating. Hence, the optimal resolution is to start the opening of the input valves earlier and prolong the closure of the exhaust valves. To explain, when an engine’s rotations per minute (RPM) increase, it is important to increase the overlap among the intake and exhaust periods. Prior to the adoption of Variable Valve Timing technology, designers would pick the timing that provided the best compromise. For example, a vehicle may employ decreased overlap to improve low-speed performance. A racing engine can employ extensive valve overlap to improve acceleration at high speeds. A conventional sedan may have valve timing that is tuned for mid-range rotations, guaranteeing that the low-speed drivability and rapid output are not greatly impacted. Regardless of the choice, the outcome is only tuned for a certain velocity. Variable Valve Timing allows for the optimization of power and torque across a broad range of engine speeds [20].

1.4.7 Turbo Charger

Since the development of the ICE, automotive technologists, speed enthusiasts, and racing vehicle designers have sought methods to increase its power. One technique to increase power is to create a larger engine. However, larger engines, which are heavier and more expensive to develop and operate, are not necessarily better. Another technique to increase power is to make a standard-sized engine more efficient. You may do this by pumping additional air through the combustion chamber. More air allows more fuel to be supplied, which leads to a larger explosion and more horsepower. Incorporating a supercharger is an excellent method for achieving forced air induction. A supercharger is a device that raises the air intake pressure above atmospheric levels. Either supercharger or turbochargers achieve this. The two gadgets vary in terms of their energy source. Turbochargers are driven by the mass flow of exhaust gasses, which turns a turbine. Superchargers are driven mechanically by a belt or chain that emerges from the engine's crankshaft [20].

1.5 Use of Alternative Fuel/Biodiesel in IC Engine

Several renewable fuels like hydrogen, producer gas, biodiesel [21] biogas, ammonia, etc., have been suggested for powering IC engines in the last few decades [22]. CNG, hydrogen, LPG, and alcohol fuels are the primary alternative fuels for SI engines; for CI engines, these fuels consist of biodiesel and di-methyl ether [23]. However, most of these suffer from technological adolescence and poor efficiency. Furthermore, to address the global challenge posed by GHG emissions, poor air quality, and reliance on finite fossil fuels, a shift in transportation systems to a low-carbon, ecologically sustainable regime is on the horizon. The above-stated are the main reasons for searching for an alternative fuel or alternative powertrain that is technically feasible, environmentally friendly, and ready to use. As a result, usage of biofuels such as biodiesel or ethanol in favour of fossil fuels such as diesel or gasoline has lately garnered a significant amount of interest in a variety of nations all over the globe because it is renewable, produces lower levels of GHG emissions, and is biodegradable [24]. Because of its intrinsic benefits, which include sustainability, efficient combustion, lower CO_2 emissions, superior environmental performance, and efficacy, biodiesel has the capacity to substitute diesel derived from fossil fuels. [10]. It can be acquired from a variety of plants, including microalgae, jatropha, palm, rapeseed, mustard, soy, and karanja. In many nations, blending 20% biodiesel is allowed or even mandatory [25].

The country has a rich supply of non-edible oil sources, which will see significant growth in non-cropped lands. Therefore, it is advisable to use food crops feedstock as the primary option for biodiesel synthesis [26]. Consequently, there is ongoing research into the application of non-edible feedstock for the manufacture of biofuels. In anticipation of the impending surge in demand, it would be advantageous to explore all potential sources of feedstock, since relying on just one or two sources would not suffice in the near future [27]. It has been found that in the search for biodiesel sources, it is important to investigate the feedstocks which do not need agricultural land, are not competing with edible crops, aid in the reduction of GHG emissions, and reduce dependence on other nations. Microalgae have lately become an attractive source for the manufacture of oil methyl esters [28]. India has identified four primary bases that are suitable and sustainable for farming various species of microalgae. These locations include paddy fields used for multiple crop cultivation, the brackish saline geographical area of Kachch, piscary inadequate coastlines covering a combined area of 6.9 million hectares, and metropolitan areas with domestic and industrial wastewater production of 40 billion litres per day. Utilizing the aforementioned opportunities, the production of algal biofuel may assist in reducing the nation's dependence on fossil fuels [29].

Alcohol fuels have become a significant alternative for applications including sustainable mobility and power generation, as they emit less carbon dioxide overall. Alcohol can be utilised in compression ignition engines with lesser mix ratios, but its higher octane rating makes it ideal for spark ignition engines. Numerous authors made suggestions regarding the possibility of using alcohol in CI engines that are neatly powered by alcohol as well as in blends or dual-fuel combustion modes. When compared to traditional diesel combustion, the soot-NOx trade-off characteristic of an alcohol-fuelled CI engine is improved, and this fuel may make it possible to comply with future emissions laws. It is appropriate for environmentally friendly transportation because it uses alcohol as fuel, which results in overall lower CO_2 emissions [30].

Natural gas has been emerged as cleaner fuel than other fossil fuel like diesel and gasoline oil, it is predictable to become the fuel of choice for many countries in the future, as it is the principal energy source with the fastest rate of growth. Pressure at a distribution system ranges between 0.3 and 1MPa. Among the cleanest alternative fuels, natural gas has several advantages over petrol. NG cars have substantially lower air exhaust emissions than gasoline-powered vehicles in light-duty applications. There is a reduction of over 90% in smog-producer gaseous fuels like nitrogen oxides and CO, and a reduction of 30–40% in GHG like carbon dioxide. Natural gas engines outperform commercial diesel engines in heavy-duty and medium-duty applications, reducing CO and particulate matter by over 90% and NOx by over 50% [31].

Alcohol fuels, which have a higher octane value, can be used in conjunction with an increased compression ratio to boost engine performance. Compared to ordinary petrol, alcohol and ether burn much more cleanly and release less carbon monoxide (CO) and nitrogen oxides (NOx). However, ether and alcohol fuels have an energy value that is around 30% less than that of petrol; as a result, while utilising these fuels, the SFC will rise [32].

Liquefied petroleum gas (LPG) is one of the most popular alternative fuels. Its attractiveness stems from the pipelines, processing plants, and storage facilities that are already in place and allow for effective distribution. In addition to being widely available, it produces fewer pollutants than reformulated petrol. Refined crude oil and processed natural gas are the two main sources of LPG production. A crucial ingredient called propane is produced as a byproduct of refining crude oil and processing natural gas [31].

1.6 Innovation of Alternative Powertrain (Battery Electric Vehicles)

Meanwhile, some experts have warned us that changing from an electric powertrain to an IC Engine powertrain is likened to moving a ball beyond a border. However, the majority of experts advise switching from fossil fuel-powered cars to electric cars and trucks in order to replace fossil fuels and expedite sustainable growth (EVs) [33]. In order to improve air quality and decrease the use of fossil fuels, the Indian government has also begun a number of initiatives in this area, such as Faster Adoption and Manufacturing of (Hybrid &) Electric Vehicles in India (FAME) 1 and 2 [34]. Besides, being a founding member of the EV30@30 global cohort, India has sworn to substitute the 30% of its ICEs powered cars with BEVs. However, the existing scenario is in jeopardy and does not correspond to the government's current intentions [35]. Based on a study conducted by the Society of Manufacturers of Electric Vehicles, just 17% of the motorcycles and scooters sold in India during the 2018-19 period, amounting to a total of $1732, were electric vehicles (EVs). In addition, close to 3600 battery-operated electric cars were sold in the same period. India could not find a place in the top 10 countries based on BEVs sales. Government of India (GoI) has granted a refund of up to about the US $ 2300 per car on the interest component of bank-financed BEVs [36].

BEV adoption remains an intractable barrier notwithstanding all of the efforts made by the Government of India and industry bodies. Despite prominent automakers promoting BEVs as the "future of mobility" and the government offering assistance and incentives, BEV's adoption in India is low. Even if the government and business are trying to encourage Indian customers to buy BEVs, there are several safety concerns and concerns about the dependability of new products that keep them from buying BEVs, even if they can afford to buy exquisite and expensive cars but not BEVs. Nonetheless, several studies have indicated that while electric mobility reduces pollution at engine operating sites, pollution at power plant locations will rise because coal is used primarily in the production of electricity [37].

1.7 Present Status and Future Prospects of IC Engines

IC engines have significantly improved fuel efficiency due to innovations like VVT (Variable Valve Timing), CRDi (Common Rail Direct Injection), GDI (Gasoline Direct Injection), and MPFI (Multi-Point Fuel Injection). These technologies optimize combustion, reduce wastage, and enhance overall engine efficiency. Innovations have also led to reduced emissions and pollution. CRDi and GDI systems allow better control over fuel injection, resulting in cleaner combustion and fewer emissions. However, IC engines still emit pollutants, and strict emissions regulations drive further advancements.

The shift to alternative fuels such as biodiesel and bioethanol enhances IC engines' environmental standing by curbing GHG emissions and reducing fossil fuel reliance. Biodiesel's compatibility with existing diesel engines with minimal modifications underscores its viability. Despite challenges, IC engines will endure due to infrastructure advantages, long-range capabilities, and cost benefits. Yet, meeting emissions standards remains a hurdle. To compete with BEVs, IC engines need better efficiency and emissions reduction. Hybridization and plug-in tech can address this, while cleaner alternative fuels like biodiesel offer an avenue for reducing impact. The future hinges on innovation, compliance, and environmental awareness balance for IC engines.

1.8 Life Cycle Analysis

Any product passes through several phases throughout its whole life and during these phases such as manufacturing of that product marketing, use of that product for which it has been manufactured and during the accomplishment of its use, there may be a requirement of getting repair or maintenance. When the said product becomes less efficient or inefficient, the product is not used further and it is then discarded or recycled. To perform the value addition tasks every product requires some energy and material as an input and the energy is produced mainly by burning of fossil fuels which causes to emit the harmful GHG in the environment. The life cycle analysis (LCA) technique is used to examine a product's environmental effect. LCA of a service or product measures the overall environmental effect of the process by accounting for the origin of all resources in addition to the ultimate discarding of all outputs and emissions. LCA includes resource consumption, and balancing of energy, including GHG at various phases of the process within a set process or system boundary to estimate the process's sustainability burden[38,39]. Every product or service includes a life cycle. The product's life cycle is separated into stages, starting with its first initiation and concluding with its ultimate elimination. At this point, significant changes are incorporated for analysing as how the product acts in the market, i.e. its influence on sales to the business that introduced it to the market. Beginning with debut and finishing with growth, maturity, and decline, a new product passes through a succession of stages. This is known as the product life cycle. Product life cycle management is the employment of various strategies to help handle problems and ensure that, regardless of where a product is in the cycle, the manufacturer can optimize sales and profits and make strategic decisions for introducing a new product by withdrawing its older equivalent [40]. LCA is a systematic approach used to assess the impacts of environmental factors on goods, processes, or services. The guideline and procedures of life cycle evaluation has been defined by the International Organization for Standardization (ISO) 14044:2006 standards (ISO 2006) [41].

LCA is a method for assessing a product's, process's, or activity's effects to the environment (i.e., environmental burdens). A LCA enables the evaluation of environmental consequences over the complete life cycle in case of a good or service system, including activities such as material acquisition, manufacture, use, and disposal. An LCA study has four major phases or components, as outlined in the International Standards Organization 14040 series (ISO 2006): goal and scope definition, life cycle inventory (LCI), life cycle impact assessment (LCIA), and interpretation [42].

Researchers gave attention to perform LCA of IC engine with different fuel conventional such as gasoline, diesel and alternative fuel which ethanol and biodiesel and also electric vehicles which have much potential to reduce local air pollution but till now there are some hidden facts due it cannot concluded that Electric vehicles are the ultimate solution of conventional transportation. In the last decade LCA was performed for different countries like Sweden [43], Switzerland [44,45]; United States [46]; Canada [47]; Japan [48]; Brazil [49]; China ([50–52]; and Lithuania [53].

According to the results of a LCA research done in Europe, electronic vehicles (EVs) can lower GHG emissions by up to 29% when compared to gasoline-powered vehicles and by roughly 20% when compared to diesel-powered vehicles [55]. LCA study to compare electrical vehicles and conventional IC Engine vehicles were conducted in various geographical locations (France, Portugal, and Poland), and the results revealed that the EV caused the most air pollution in Poland, as a substantial percentage of Polish electricity is produced from coal. France, but at the other side, had the least pollution because nuclear power plants produce a sizable percentage of French electricity. According to recent research, the environmental performance of battery EVs is strongly influenced by the size of the battery, the electricity used for charging batteries and manufacturing, as well as how the electricity is generated [56–59].

It was demonstrated that the environmental sustainability of EVs and ICEVs radically changes in future energy situations, and the comparative performance of two drive systems differs widely based on situation chosen. Hardly a few research included an impartial uncertainty or sensitivity analysis of the vehicular operation conditions. Further the emergence various alternative fuel like ethanol and biodiesel in optimizing blend must be considered in case of IC engine LCA assessment [60,61].

An LCA that deliberates upon all these factors is required to provide a thorough LCA computation of ICEs, the energy production mix, and an exhaustive life cycle inventory data system. According to the extensive literature review, the majority of the LCA of IC engines have been performed in China, the United States, Canada, Brazil, and European countries such as Italy, but there is not enough literature available for countries such as India, so the author is motivated by this gap. Further a comprehensive assessment of biodiesel's role within ICE is required to pave the way for a greener future in transportation. This endeavour lays the groundwork for the adoption of sustainable practises, guiding us towards environmentally responsible decisions. Our current initiative is embarking on a bold, data-driven journey based on Life Cycle Assessment (LCA). Present study aims to investigate two generations of biodiesels with the goal of determining the most viable alternative fuel for the LCA of IC Engines that have traditionally been powered by fossil diesel. While the sustainability of biodiesel from well to wheel remains largely unknown, our investigation aims to close this knowledge gap. To determine the best production methods, we investigate various feedstock options. It is worth noting that in the Indian context, the LCA of IC engines powered by both fossil diesel and biodiesel is still relatively unexplored. This study aims to fill that gap and contribute valuable insights to the field.

1.9 Dissertation Layout

The present work involves the comparative LCA of biodiesel derived from two feedstocks namely karanja and microalgae followed by the LCA of IC engine using fossil diesel and biodiesel having superior life cycle quality i.e. karanja feedstocks. This section provides a comprehensive overview of the work.

Chapter 1 provides an exploration on the historical background of engine development in order to counter the fuel consumption and emission threat. Need of alternative fuel and introduction of alternative powertrain are explained. Motivation of performing lifecycle analysis of IC engine is presented.

Chapter 2 summarizes a literature review on the global environmental emission issue due to energy conversion technologies like IC engine which consume fossil fuel conventionally. Literature review of lifecycle analysis of biodiesel synthesis especially from non-edible feedstocks like Jatropha, Karanja and Microalgae is performed. LCA of conventional power train and alternative power train also reviewed. Finally, it ends with assessments on identifying research gaps and goals for the present work.

Chapter 3 outlines the methodology of performing lifecycle analysis as per the ISO14040. The chapter also discussed the methods of impact assessments.

Chapter 4 outlines the comparative cradle to grave LCA of biodiesel derived from two feedstocks namely karanja and microalgae.

Chapter 5 outlines the well to wheel LCA of IC engine using fossil diesel and biodiesel having superior life cycle quality i.e. Karanja feedstocks. The chapter consider all three phases of IC engine i.e. production phase, use phase and disposal phase.

Chapter 6 provides a comprehensive summary of the significant results derived from the conducted experiments. Additionally, this chapter presents suggestions for future research endeavours.

CHAPTER 2
LITERATURE REVIEW

2.1 Introduction

An assessment of the literature on the Life Cycle Assessment (LCA) of Internal Combustion (IC) engines is conducted in this study. Essential elements covered in the analysis include a variety of indicators for measuring environmental effect, such as air pollution and GHG emissions. Different methodological approaches are examined for their advantages and disadvantages, ranging from well-established protocols to newly developed frameworks. This study examines the effects of fuel selection—both conventional and alternative—on the overall environmental performance of ICE, taking resource usage into account.

An informed and comprehensive approach is ensured by a thorough examination of these important topics, which provides a solid platform for understanding the environmental impact of IC engines throughout their life cycle. The following subjects are included in the literature review for this research study:

- The status of IC engines in the present world of facing severe environmental threats.
- The Global Environmental Issue
- The LCA of alternative fuels
- LCA of IC engines to assess the environmental footprint.

Lior (2008) [62] explained that major worldwide issues like overcrowding, freshwater pollution, air pollution, deforestation, coastal pollution, biodiversity loss, and deteriorating global weather are rapidly taking centre stage in the energy development process. Large-scale energy-related activities would become increasingly impossible to carry out without ensuring their sustainability to avert catastrophic global repercussions. This is true even for developing nations where the development, use, and production of energy are prioritized over the effects these activities have on the society, environment, as well as the energy sources themselves.

Gunatilake et al., (2014) [63] investigated the role of biofuels in energy security and food security by applying a computable general equilibrium (CGE) model and found that biofuels like biodiesel and bioethanol have a significant impact on the energy and food security on nation as well as creation of new jobs and mitigation of GHGs.

Asif and Muneer (2007) [64] suggest that human life requires energy, and modern societies cannot survive without a reliable and readily available energy source. Several obstacles will make it difficult to continue using fossil fuels: the rapid consumption of fossil fuel reserves, global warming, geopolitical and military conflicts, and a sharp rise in fuel costs. These factors hint to a situation that cannot continue. Renewable power is the optimal resolution to the escalating global energy challenges.

Leach et al., (2020) [65] explained that Internal combustion engines (IC engines) are widely used in many different industries today, where they are essential for powering industrial machinery, transportation, and the production of energy. Because of their enormous environmental impact, ICE are becoming more and more scrutinized and challenging. When it comes to transportation, conventional gasoline and diesel-powered ICE rule the roads around the world, particularly in the car industry. These engines have long served as the backbone of public transportation, business fleets, and private automobiles.

Dutta and Majumdar (2019) [66] said that Industrial uses for IC engines' versatility include powering a broad range of gear, such as generators and heavy-duty equipment that serve multiple industries. However, there are now serious environmental issues as a result of the widespread use of IC engines. Pollutants like nitrogen oxides (NOx), carbon dioxide (CO_2), particulate matter, sulfur dioxide (SO_2), and volatile organic compounds (VOCs) are released when fossil fuels are used in ICEs. These emissions have a major impact on climate change, air pollution, and negative health effects.

Abramovic et al., (2022) [67] explained that particularly the transportation industry contributes significantly to GHG emissions, with ICEs being the main source of carbon dioxide emissions. Beyond exhaust emissions, IC engines hurt the environment during their whole life cycle, from manufacture to disposal, which adds to resource depletion, energy use, and waste production. As the globe struggles to address the serious environmental risks these engines bring, there is a growing need for cleaner technologies and sustainable alternatives. Governments, businesses, and academics are investigating ways to lessen the impact of ICEs on the environment. These initiatives take into account both small-scale efficiency gains and the use of alternative fuels and propulsion technology.

Reitz et al., (2019) [68] explained that ICEs are widely used in a variety of industries and play a vital role in powering industrial applications and transportation. They are essential to the operation of contemporary societies due to their adaptability and effectiveness. In the automobile industry, the great majority of cars on the road are powered by ICEs that are primarily powered by petrol and diesel. They greatly contribute to the world’s transportation needs by providing power for motor vehicles including cars, trucks, motorbikes, and other private and business vehicles. Furthermore, IC engines are the primary source of propulsion for a large number of aircraft in aviation, especially smaller and general aviation versions. These engines supply the power required for takeoff, cruise, and landing. Because of their high energy density and dependability, which make them appropriate for the harsh circumstances of marine applications, ICEs are used to power a wide range of vessels in the maritime industry, including ferries, boats, and ships.

Serrano et al., (2019) [69] said that IC engines are widely used in a wide range of industrial applications outside of transportation. They are used in power plants that run on various fuels, including diesel and natural gas, to produce electricity. This adaptability offers distributed power generation a dependable and effective alternative. Heavy-duty equipment used in mining and construction, like loaders, bulldozers, and excavators, frequently depends on IC engines for their reliable power output and mobility, which allows them to complete difficult jobs.

Dey and Mehta (2020) [70] suggest that the environmental issues are greatly exacerbated by ICEs, which are widely used in automobiles and other industrial uses. Because of the way these engines burn fuel, air pollution is a big worry. Particulate matter (PM) from diesel engines, in particular, can enter the lungs deeply and cause respiratory issues as well as cardiovascular disorders. In addition, when fuel contains sulfur, sulfur dioxide (SO_2) is generated, which contributes to acid rain and air pollution, while nitrogen oxides (NOx) created during burning contribute to smog formation and respiratory problems.

Perera (2017) [71] communicates that the significant environmental issue related to ICEs is GHG emissions. These engines' burning of fossil fuels releases a lot of CO_2, a GHG that greatly accelerates change in climate patterns. Along with incomplete combustion and unburned fuel release, incomplete combustion can also release methane (CH_4), another powerful GHG. These emissions increase the greenhouse effect, which causes climate change and global warming. The implications of climate shift include greater temperatures, a rise in the frequency and severity of severe weather events, and ecological destruction.

Geli et al., (2022) [72] said that ICEs heavily rely on fossil fuels, especially petroleum-based products, they are directly associated with resource depletion. This reliance causes economic vulnerabilities due to changes in oil prices as well as geopolitical disputes over oil reserves and resource depletion. Moreover, an adverse effect of ICEs on both urban and rural areas is noise pollution. The general quality of life, animals, and human health may all be negatively impacted by the noise emissions.

Liu et al., (2020) [73] explained that because ICEs are so widely used and switching to more sustainable alternatives might be difficult, there are multiple obstacles in the way of reducing the environmental impact of IC engines. The current infrastructure and reliance on technology present a big obstacle. The existing system is designed for conventional ICEs, including manufacturing facilities and filling stations. Making the switch to alternative technologies, like electric cars, is difficult and requires large investments as well as a reorganization of the current infrastructure.

Faizal et al., (2019) [74] **e**xplicated that affordability and economic issues are important. Alternative technologies, such as electric automobiles, have higher starting costs than conventional ICEs. Customers still face a major barrier in the form of affordability, which could restrict the widespread adoption of alternative technologies until their costs come down. There are obstacles in the way of switching from fossil fuels to sources of renewable energy for electricity generation, such as the requirement for significant infrastructure development and intermittency. This presents obstacles to the wider energy transition that is necessary to lessen the overall environmental effect of ICEs. Other challenges include development timelines and technological constraints. It takes time to develop and apply cutting-edge technology, especially extremely efficient batteries for electric vehicles. Overcoming technological constraints and guaranteeing the dependability, security, and efficiency of novel technology are perpetual obstacles.

Neubauer and Wood (2014) [75] discussed that concerns unique to electric cars are energy density and range restrictions. To get over these restrictions, battery technology must progress to provide longer driving ranges, which will increase the attractiveness of electric powered vehicles compared with conventional ICEs. An important factor is consumer behaviour and resistance to change. Customers' reluctance to adopt newer technologies is partly due to their ingrained preferences for conventional ICEs as well as worries about the convenience, charging infrastructure, and range of alternatives.

Bobba (2018) [18] emphasized that the key problems also include the availability of resources and the impact of alternatives on the environment. Rare and environmentally sensitive elements are needed in the development of alternative technologies, such as batteries. Hence there are many obstacles in the way of ensuring a sustainable supply chain for these materials and reducing the environmental impact of alternative technologies. Harmonization of laws, rules, and incentives among various jurisdictions is necessary to bring about a worldwide transition to environmentally friendly transportation. Progress can be hampered by hurdles to the widespread adoption of environmentally friendly technologies caused by differing policies and market conditions. Careful planning and coordination are necessary for integrating new technologies with already-existing systems, such as transport and electricity networks. It is a difficult task requiring strategic thinking to ensure a seamless transition without interruptions to vital services and processes.

Atabani et al., (2012) [76] discussed that the use of alternative fuels offers a chance to lessen some of these negative effects on the environment. Because carbon dioxide is absorbed by plants during their growth, biofuels made from organic materials such as garbage or crops can be regarded as carbon-neutral. The only consequence of hydrogen combustion is water vapour, making it a cleaner choice. Even though it is still a fossil fuel, natural gas often generates less pollution than its conventional rivals, which helps to enhance the quality of the air.

Gheewala 2012 [77] said that the crucial component of the comparison is the use of resources. Energy-intensive procedures are used in the traditional extraction and refinement of fossil fuels, which frequently degrades the environment. However, there are big differences in the way alternative fuels are produced. Land, energy, and water are needed for the production and processing of biofuels.

Rivard (2013) [78] demonstrated that natural gas extraction has its own set of environmental concerns.

Kato et al., (2005) [79] explained that the methods for producing hydrogen, such as electrolysis, can be energy-intensive. When evaluating the total impact, energy efficiency is vital. With a large amount of energy lost as heat, ICEs running on conventional fossil fuels usually have efficiency levels between 20% and 30%. However, alternative technologies can achieve higher efficiency, lowering overall energy consumption and environmental effects.

Martins and Brito (2020) [80] described that the integration of alternative fuels with ICEs engines presents several obstacles as well as opportunities for advancement, signifying the wider shift to more environmentally friendly energy sources. The requirement for a comprehensive and easily accessible infrastructure for the production, distribution, and dispensing of alternative fuels is a significant barrier. Moreover, some alternative fuels have a lower energy density than conventional fossil fuels, which presents a technological difficulty and reduces vehicle efficiency and range. For example, to obtain comparable ranges to vehicles fuelled by petrol or diesel, electric vehicles could need larger and heavier batteries.

Agarwal (2006) [81] enlightened that the challenge in incorporating alternative fuels into the current ICEs systems is the need for technological adaptation. Expenses and complexity might rise when engine systems and components are modified to guarantee compatibility and peak performance. Since the development of infrastructure and production costs for alternative fuels may be more than those for conventional fuel systems, their economic viability is also a crucial factor to take into account.

Conversely, there are several possible advantages to using alternative fuels. The lessening of traditional fossil fuels' negative environmental effects is one of the main drivers. Fuels that help reduce GHG emissions, such as hydrogen and biofuels, can support initiatives to slow down global warming.

Ellabban (2014) [82] explained that by reducing reliance on finite fossil fuel supplies, diversifying energy sources for transportation improves energy security and resilience to geopolitical uncertainty. Furthermore, compared to conventional fuels, alternative fuels have the potential to enhance air quality by producing fewer pollutants including particulate matter and nitrogen oxides. The production of several alternative fuels from renewable resources aids in the push to raise the ratio of portio of renewable energy in total energy mix as a whole. In addition to promoting scientific advancements and creativity, the search for alternative fuels also helps to promote energy efficiency, fuel production methods, and environmental sustainability in general. A comprehensive evaluation of multiple aspects, including emissions, resource utilization, and energy efficiency, is necessary to compare the environmental performance of conventional fossil fuels and alternative fuels. Conventional fossil fuels, including petrol and diesel, have long served as ICEs main energy sources. When they burn, they release particulate matter, NO_x, SO_2, and CO_2. These emissions are a key cause of global climate change and contribute greatly to air pollution. Furthermore, the involved process in the refinement, extraction, and transportation of fossil fuels are resource-intensive and pose environmental dangers, such as the possibility of oil spills and habitat damage.

Finnveden and Potting (2005) [83] discussed that a systematic and thorough procedure called LCA is used to assess the environmental effects related to a process, product, or service's whole life cycle. The life cycle encompasses raw material extraction, manufacturing, usage, and, ultimately, disposal or recycling. The primary goal of life cycle assessment (LCA) is to provide a thorough knowledge of the environmental implications connected with a specific system or commodity. This helps to identify areas for improvement and makes it possible to make more educated, sustainable decisions.

Gheewala (2021) [84] explained that a product or system's life cycle consists of several stages, beginning with the extraction of raw materials, which are obtained from nature. Water, energy, and other resources are frequently needed at this stage. The movement of raw materials, components, and completed goods between various places is included in the ensuing transportation phase, which also accounts for the energy use and emissions produced by the various modes of transportation. The product performs as planned during the usage or operation phase, taking into account emissions, energy consumption, and other environmental effects. Throughout the product's life cycle, maintenance and repair tasks can be required, which would affect the product's overall environmental impact. The end-of-life phase comprises recycling, management of waste, and disposal while taking into account the environmental effects of different disposal techniques such as recycling, incineration, and landfilling.

Girardi et al., (2015) [85] concluded that there are various steps in the LCA process. The first step is aim and scope definition, which entails stating the purpose of the assessment as well as the boundaries of the system and the particular environmental impact categories that will be assessed. Gathering and quantifying information on inputs and outputs for every life cycle stage is part of the next stage, known as the life cycle inventory (LCI). Data on resource utilization, emissions, and energy use are included in this. The next step is Life Cycle Impact Assessment (LCIA), which uses recognized impact categories like eutrophication, acidification, and global warming to assess the possible environmental effects of the data collected. The last phase, known as interpretation, is analysing the data to derive conclusions and offer suggestions for enhancement. This process frequently entails contrasting different scenarios or locating “hotspots” in the environment.

Jiao (2013) [86] Internal combustion (IC) engines have a life cycle that includes multiple crucial stages, all of which have an impact on the ecosystem as a whole. Extracting and processing raw materials, such as metals and other components required for the production of IC engines, is the first step in the process. These energy-intensive procedures, which include mining, refining, and manufacturing, add to the initial environmental impact. The next stage is manufacture and production when different engine components are made from processed raw materials. This complex process requires a lot of energy, equipment, and resources. It involves casting, machining, heat treatment, and assembly. The construction of IC engines frequently involves various phases and suppliers, resulting in a multitude of components that contribute to their environmental effects. Engine parts are shipped to assembly companies for further processing, including assembly and transportation. Because of fuel use and emissions from moving vehicles, the transportation phase adds to the environmental footprint of the entire life cycle. Energy and resources are needed for assembly since parts must be assembled to form the entire IC engine.

Tribioli (2017) [87] described that a significant amount of the IC engine’s life cycle is made up of the use and operation phase. This phase entails installing the engine and keeping it running in machinery or cars. Air pollution is caused by fuel consumption and emissions during this phase, and the type and quantity of fuel utilized directly affect environmental performance. An IC engine may require maintenance and repairs throughout its lifetime to guarantee peak performance. These tasks need more energy and resources, and the final environmental impact can be influenced by the maintenance strategy selected. The IC engine retires from active service during the end-of-life and disposal stages. There are several different disposal techniques, such as landfilling, recycling, and scrapping. Scrapping is the process of removing reusable parts, whereas recycling attempts to recover precious resources like metals. Environmental issues may arise from improper landfilling, particularly if hazardous materials are not managed properly.

Hawkins et al., (2012) [55] A Comparative Environmental Life Cycle Assessment was used to assess the environmental effects of electric vehicles (EVs) with ICEs vehicles (ICEVs). The results showed that when EVs were powered by the European energy mix, their global warming potential was reduced by 10–24%. However issues with EVs' supply chain's increased toxicity, ecotoxicity, eutrophication, and metal depletion surfaced. Variations in impact were associated with assumptions about lifetime, energy consumption, and power supply. The report underscores the need for comprehensive steps for a greener automotive industry future and stresses the need to address production supply chain difficulties and promote clean energy adoption to boost EV sustainability.

Alagumalai (2014) [16] noticed that the engine industry has experienced tremendous growth in the research and development of new-age technologies in recent years. MPFi, CRDi, GDI, EGR, and HCCI are some of the technologies made remarkable contributions to reducing fuel consumption and emissions. He further explained that the increasing market of IC engines has to be countered by the tailpipe emissions of the engine and the fuel consumption. Due to these two major problems, international pressure to reduce the emissions of GHGs and other environmental pollution national government has stricted the emission regulations for IC engines. Various developments are necessary to follow these new norms and regulations. However MPFi, CRDi, and GDI engines are developed to counter various problems of the engines, still stricter norms are compelling to innovate further to sustain the IC engine future in energy conversion systems. For example in HCCI engines more research is required to short out the lack of stability problem and higher emissions of CO as well as HC. Similarly lean burn emits more NO_x which requires to be controlled. Further to enforce biofuel technology systems, optimization techniques, proper planning, and standards are needed. Although the widespread use of IC engines in various industries highlights their energy density, dependability, and versatility, it also prompts worries about the effects they may have on the environment, notably concerning indoor pollutants and emissions of GHGs.

Guardiola et al., (2015) [88] explained that despite the stringent norms of CO_2 emissions and other pollutants IC Engine technology will be able to survive near future. There are many technologies already equipped and performing well like EGR, VVT, stop-start, and many others. Engine control plays an important role at the subsystem level to fulfil the requirement of the exact control of the operations of various advanced technologies. There are numerous research works going on to boost the IC Engine technology in the future to compete with its counterparts in terms of fuel consumption, emissions, and efficiency. Charge Composition and Temperature Control with the different EGR systems, Full-Flexible Variable Valve Timing, After-Treatment System Control and Diagnosis, and system integration are expected to boost the engine technology further. The author also discussed that alternative fuels like biofuel are expected to further reduce the emission threat.

Kalghatgi (2018) [89] expressed his concern about the possibility of the disappearance of the IC-engine-driven transport system through his study. Any new technology entered the market with the hype cycle and this is supported by media houses generally by focussing only on the positive things of a technology. The author suggests that IC Engine technology has proven itself in the past and can improve by adapting to the changes in the market through new developments and innovations. The introduction of biofuels like biodiesel and ethanol has significant capability to counter the environmental emission issue. Production of biofuels will generate an income source for farmers as well as utilization of marginal land and wastewater bodies and the creation of new business and job opportunities are additional benefits to the national economy and energy security. Introduction of a fully electrified transportation system has zero tailpipe emission but the electricity production is almost coal-based, which will inversely impact the environment. In addition, various power generation units are not so far from the urban areas due to which urban air will be affected. Hence it is the subject of LCA to estimate the consequences of the available transport systems in terms of environmental issues to ensure better technology.

A summary of the literature studied for assessment of the environmental impacts of IC engines and alternative fuel through the life cycle approach has been given in Table 2.1.

Table 2.1: A Literature Review Summary

Author(s)	**Theme**	**Brief Outcome of the Study/Research**
		Developments in IC Engine
Alagumalai (2014) [16]	*"Internal combustion engines: Progress and prospects"*	• Over the last decade, the engine industry has seen significant expansion in the development and research of new technology. • Major developments are Combustion geometry, MPFi, CRDi, VVT, and GDI.
Guardiola (2015) [88]	*"A Challenging Future for the IC Engine: New Technologies and the Control Role"*	• The paper discussed IC engine midterm specifications. • Stricter environmental laws vs. globalization, time constraints, and fuel quality variabilities pose environmental challenges. • Despite challenges, IC engines will remain important due to expected efficiency gains and ongoing societal role.
Kalghatgi(2018) [89]	*"Is it the end of internal combustion engines and petroleum in transport?"*	• Liquid fuel-burning ICEs dominate transport, driven by rising global demand for energy. • Shifting light-duty vehicles (LDVs) to electric requires substantial battery capacity, with potential GHGs impact. • Innovations like MPFI, CRDi, GDI, and HCCI offer advantages over electric vehicles if energy isn't decarbonized.
		LCA of Biodiesel
Niederl-Schmidinger (2008) [90]	*"Life Cycle Assessment as an engineer's tool"*	• LCA is a valuable estimation tool for drawing conclusions and facilitating participant discussion: importantly to identify process steps that have a significant environmental impact. • A process LCA of producing tallow biodiesel and WCO. • There is considerable agreement between the results of impact evaluations that use the problem-oriented methodology and Sustainable Process Index (SPI). • This heavily consolidated marker SPI allows choices to be compared. It aids in decision-making and offers "a bigger picture" of the effects on the environment.
Sajid et al., (2016) [91]	*"Process simulation and* LCA *of biodiesel production."*	• The feedstock was taken as jatropha and WCO. • The overall ecological effect was found 74% lowered compared to the feedstock of Jatropha C.
Portugal-Pereira et al., (2015) [92]	*"Comparative energy and environmental analysis of Jatropha bioelectricity versus biodiesel production in remote areas"*	• LCA method was employed to evaluate the Jatropha seed generation systems for generating bioelectricity with the production of biodiesel. • The energy and environmental indicators were used in this comparison include fossil depletion. • Possibility of improvements of GWP and PMF indicators if expelling efficiency increases and electricity is produced from renewables.

Author(s)	Theme	Brief Outcome of the Study/Research
Das and Sahoo (2009) [93]	*"Process optimization for biodiesel production from Jatropha, Karanja and Polanga oils"*	• Petroleum fuels may be replaced by biodiesel, which is made from oil crops like polenta, Karanja, and jatropha. • This renewable fuel source is carbon neutral. • Biodiesel is produced by the method known as transesterification, where oil or fat reacts with monohydric ethanol in with the aid of a catalyst. • The transesterification process is influenced by several factors, including the molar ratio of alcohol to oil, the specific kind of alcohol used, the type of catalysts used, the temperature at which it occurs, the length of the response, and the quality of the reactants.
M. Soledad Díaz et al., (2016) [94]	*"Life Cycle Analysis of Jatropha Curcas as a Sustainable Biodiesel Feedstock in Argentina"*	• In Argentina, the ecological impact of biodiesel derived from jatropha is evaluated employing LCA. • Processes of transesterification, oil extraction, seed transportation, and Jatropha seed cultivation were considered. • The study looks at trade-offs between agricultural inputs and land use type in two cultivation scenarios. • The ReCiPe impact assessment approach was utilized to gather and analyze system inventory data. • Results reveal a reduced kg CO2 equivalent up to 21% in case of Jatropha methyl ester generated when using lower input agriculture as well as fertile land.
Janulis (2004) [95]	*"Reduction of energy consumption in biodiesel fuel life cycle"*	• Rapeseed oil feedstock is considered. • The energy ratio for the methyl ester process for Lithuanian environments was estimated.
Chandrashekar et al., (2012) [96]	*"Life cycle assessment of biodiesel production from Pongamia oil in rural Karnataka"*	• This article examines the global warming potential, life cycle energy balance, and acidification capacity of an a smaller scale biofuel system in a rural setting. • The technique of producing and using biogas using seed cakes for energy generation has been updated and its environmental impact evaluated. • The findings indicate that the Pongamia biodiesel system requires twenty-eight times less non-renewable energy than fossil diesel. • If the wood wasn't utilized as fuel, the global warming potential would be shattered.
Nanaki and Koroneos (2012) [97]	*"Comparative LCA of the use of biodiesel, diesel, and gasoline for transportation"*	• Greece's petrol, diesel and biodiesel are compared using LCA. • The effects of acidification, fossil fuels, eutrophication, ecotoxicity, GWP, and carcinogenic effects were noted along with the effects of organic and inorganic respiration. • When compared to petrol and diesel, there are notable drops in GHG emissions when biodiesel is used. • It also emits less methane from the well to the wheel. However, the primary causes of eutrophication—higher emissions of nitrous oxide, PM10, nutrients, nitrogen oxides (NOx), including nitogen and phosphorous—are also present.

Author(s)	Theme	Brief Outcome of the Study/Research
Mishra et al. (2021) [98]	*"Farm-to-fire analysis of Karanja biodiesel"*	• According to the LCA, Karanja biodiesel requires 0.54 GJ of non-renewable energy compared to 1.26 GJ for fossil diesel to produce 1 GJ of energy as fuel. • Karanja biodiesel is responsible for 63% lower CO_2 emissions than diesel fuel production. • The energy-equivalent CO2 emission from an engine running on biodiesel, the seed's value of gross energy, the yield of Karanja seeds, and the BTE of the end-use system all have an impact on the decrease of equivalent CO_2 emissions. • The techno-economic analysis indicates that the cost of biodiesel was lowered in case of greater production plant and a lengthier investment-recovery time for the recovery of variable cost to the tune of 3 and 10 years.
Khandelwal and Chauhan (2013) [97]	*"Life Cycle Assessment Of Neem And Karanja Biodiesel: An Overview"*	• A methodical evaluation of the energy released by GWP and biodiesel fuels made from Karanja and neem was done. • The predicted life cycle energy ratios for neem and Karanja biodiesel are 1.6479 and 1.6425, respectively, demonstrating the renewable nature of these feedstocks. • From the perspective of GHG emissions, neem, and karanja trees offer the benefit of carbon sequestration.
Yadav and Singh (2010) [99]	*"Energy estimations for life-cycle analysis of jatropha, neem, and Karanja biodiesels – a parametric study."*	• The feedstock was taken as jatropha, Karanja, and neem • LCA was applied to estimate environmental impacts in terms of GHGs.
Pragya et al., (2017) [100]	*"Biofuel from oil-rich tree seeds: net energy ratio, emissions saving, and other environmental impacts associated with Agroforestry practices in Hassan district of Karnataka, India."*	• Kalanja, Simarouba glauca, Madhuca indica, Neem, Calophyllum I. Amoora rohituka, and J. curcas have been utilized as feedstocks. • Adding co-product energy resulted in increased NER ranging from 4.2 to 6.44, compared to 1.35 and 0.88 excluding co-products. • Estimating GHG emissions of raw materials revealed soybean and corn had negative values.
Shukla et al., (2020) [101]	*"Comparative energy and economic analysis of different vegetable oil plants for biodiesel production in India"*	• The feedstock was jatropha C., Neem, Mahua, Coconut, Palm, Pongamia Pinnata, Jojoba, and Tung. • The energy and economic costs were assessed. • All feedstocks were assessed as positive net energy. • The energy Ratio and energy productivity of Neem were the highest.

Author(s)	Theme	Brief Outcome of the Study/Research
Sen et al., (2014) [102]	*"Raceway pond cultivation of a marine microalga of Indian origin for biomass and lipid production: A case study"*	• A 400 L raceway ponds that had a 150 L capacity for operation was used to study the growth dynamics and lipid buildup in Chlorella variabilis, a marine microalga from Indian waters. The culture had a 10% total lipid content and an average rate of development (μ) of 0.36 per day based on dry cell weight. • In the raceway pond culture, an mean biomass efficiency of 5.78 g/ day was attained. Summertime saw the highest biomass productivity at 8.1 g/ day. • Hexane was used as the solvent for the lipid extraction, and GC and MALDI-ToF analyses were used to establish the fatty acid content in order to assess the lipid's suitability for biodiesel generation.
Saranya.and Ramachandra (2020) [103]	*"Life cycle assessment of biodiesel from estuarine microalgae"*	• The lifecycle analysis of the microalgae-based biodiesel manufacturing process and the value-added product valorization are presented in this communication. • Various nutrient inputs were considered for the relative assessment of feedstock cultivation. (i) Minimal nutrient addition; (ii) wastewater for nutrient input; (iii) fertilizer addition. • Acid catalyst and Biocatalyst were the two transesterification processes used to turn microalgal oil into biodiesel. Using OpenLCA v1.10.3, the environmental effects of the various scenarios were evaluated. • The amount of fossil energy required varied from 3.6 to 5.7 MJ/kg, and the amount of GHGs per kilogramme of biodiesel ranged from 0.85 to 1.46 kg CO_2eq. • This indicates about 87.3% decrease in the amount of fossil energy. The wastewater-biocatalyst scenario demonstrated the greatest NER of 18.8, along with the added benefit of wastewater clean-up at a cheap cost.
Woertz, et al., (2014) [104]	*"Life Cycle GHG Emissions from Microalgal Biodiesel − A CA-GREET Model"*	• Based on a thorough engineering and economic analysis, a life cycle assessment (LCA) was conducted with an emphasis on GHGs from the manufacturing of algal biodiesel. • This LCA, based on the CA GREET model, follows the California Low Carbon Fuel Standard and LCI data for process inputs.
Kendall et al., (2014) [105]	*"Mass balance and life cycle assessment of biodiesel from microalgae incorporated with nutrient recycling options and technology uncertainties"*	• The life cycle assessment (LCA) for energy and GHGs of a simulated microalgae biodiesel manufacturing system is presented in this paper together with mass balances. • The system's primary parameters are the algae's lipid content, which is 25% for normal nitrogen levels and 16 and 25 g/sq m/day for low nitrogen conditions. • Based on a 73.6% oil extraction efficiency from wet biomass and methane yields of 0.31 to 0.34 l/gm of volatile solids from anaerobically digested lipid-extracted biomass, the mass balance demonstrates that reusing growth media and recovering nutrients from residual biomass through anaerobic digestion can lower the total demand for phosphorus by 90% and nitrogen by 66%. • For normal nitrogen conditions, recycling CO_2 from biogas combustion can reduce carbon requirements by 40% and freshwater requirements by 89%, respectively.

Author(s)	Theme	Brief Outcome of the Study/Research
Shirvani et al., (2011) [106]	*"Life cycle energy and greenhouse gas analysis for algae-derived biodiesel"*	• The LCA reveals that the energy needed to make algal biodiesel is approximately 2.5 times greater than the cost used to produce traditional diesel and is almost equivalent to the substantial energy use of oil shale diesel throughout its fuel cycle. • When each step of the manufacturing process is completely optimized and made free of carbon emissions, biodiesel derived from advanced biomass has the potential to effectively leverage its inherent environmental benefits by lowering GHG emissions. This encompasses the optimal use of coproducts, the reduction of carbon emissions in the heat and electrical systems, and the secondary energy requirements for construction materials, transport, and fertilizer. • GHG emissions can only be completely mitigated and the cost of heat and energy can only be lowered by accounting for all of these factors.
Sharma and Singh (2016) [28]	*"Microalgal biodiesel: A possible solution for India's energy security"*	• The study examines the demand of energy and GHG emission statistics of various countries in a methodical manner. It also covers every stage of the process, from selecting the right algae strain to producing biodiesel. • High oil content strains can be chosen, growth rates can be increased, algae can be used in bioremediation, and effective methods for oil extraction and harvesting may be developed to increase the production of algal biodiesel. • It is essential for reducing GHG emissions, collecting waste water, and producing biomass that has a variety of medical uses. It is advised that many countries implement policies to promote the production of biodiesel, and that related government initiatives be made in order to address these issues.
Sen et al (2020) [107]	*"A comparative life cycle assessment of microalgae production by CO_2 sequestration from flue gas in outdoor raceway ponds under batch and semi-continuous regime"*	• This study assessed an outdoor raceway pond system's capacity to generate biomass and sequester carbon dioxide through using flue gas under various circumstances. • The production of areal biomass was decreased in batch microalgal cultivation when there was no external carbon supplementation (0.04% CO2, v/v). However, the rate of carbon-dioxide fixation was improved when flue gas was introduced to the medium, increasing the concentration of dissolved carbon. • A semi-continuous regime was implemented to enhance the system's performance even more. • SimaPro 8.3.0.14 software was then used to carry out a "cradle-to-gate" LCA in order to determine any possible environmental effects related to the production of Chlorella vulgaris biomass.

Author(s)	Theme	Brief Outcome of the Study/Research
		• According to estimates from the GWP 100 IPCC 2013, CED, and ReCiPe Endpoint approach, the cultivation process has a large environmental impact (>75%) in terms of energy needs, GHG emission, and several other influence subclass. • Sensitivity analysis was employed with a particular focus on the combined position of farms and flue gas generating point sources. • When semi-continuous cultivation is used, the carbon footprint of microalgae using waste gas in outdoor raceway ponds is reduced. This is especially true when raceway ponds are situated next to thermal power plants.
LCA of IC Engine		
Hawkins et al., (2012) [55]	*"Comparative Environmental Life Cycle Assessment of Conventional and Electric Vehicles"*	• LCA compared the environmental impacts of ICEVs and EVs, revealing EVs reduce GWP by 10-24% using the European energy mix. • EVs show potential increases in eco-toxicity, toxicity, metal depletion and eutrophication due to supply chain. • Impact results vary based on power supply, usage energy, and longevity assumptions; Enhancing EV sustainability requires tackling the production supply chain and clean energy.
Jiao et al., (2013) [86]	*"Life cycle analysis of internal combustion engine, electric, and fuel cell vehicles for China"*	• A LCA of China's current (2009) and expected (2020) conditions assesses ICEVs, EVs, and FCVs. • EVs and FCVs relying on water-electrolyzed H_2 and Chinese grids pose energy, and environmental challenges, requiring electricity mix adjustments. • In 2009, ICEVs and subsidized EVs were cheaper than FCVs; in 2020 pricing debates continue due to tech progress and regulations.
Karakoyun et al., (2014) [108]	*"Holistic life cycle approach for lightweight automotive components"*	• The study presents a holistic life cycle approach, assessing sustainability across a product's entire life cycle using performance criteria. • Closed-loop PLM gathers life cycle data and shares performance attributes among stakeholders for evaluation. • Sustainable products consider technological, economic, environmental, and social aspects; lightweight, especially with aluminum, impacts auto industry sustainability.
Jang and Song (2015), [109]	*"Well-to-wheel analysis on greenhouse gas emission and energy use with petroleum-based fuels in Korea: gasoline and diesel"*	• To give policymakers and stakeholders results that are specific to Korea, a well-to-wheel LCA for the assessment of GHG emissions on Korean petrol and diesel was conducted. • The well-to-pump GHG emissions of diesel as well as petrol are 11,025–11,643 g CO2 equivalent/GJ and 12,047–12,677 g CO2 equivalent/GJ, respectively. • The primary distinction is caused by the fact that petrol refines with greater GHG emissions than diesel. Diesel cars have lower overall well-to-wheel emissions than petrol models when their weights are comparable.

Author(s)	Theme	Brief Outcome of the Study/Research
Tribioli et al., (2017), [87]	*"Comparative environmental assessment of conventional, electric, hybrid, and fuel cell powertrains based on LCA"*	• ReCiPe Midpoint methodologies and cumulative energy demand (CED)-based environmental indicators were employed for the comparison. • LCA was utilised to evaluate electric and hybrid vehicles in addition to conventional powertrains. • The comparison was limited to powertrain production, phase of vehicle use, and end of life. • The least amount of savings is possible when a traditional petrol powertrain is swapped out for a similar 100% electric one, but it is still significant. According to our analysis, the systems under consideration have a 15% reduction in CC value, a 12% reduction in CED value, and a 28% reduction in FD value. This analysis highlights the flaws in a tank-to-wheel comparison, which claims that the conventional vehicle is the most energy-intensive.
Joshi et al., (2022), [110]	*"Comparative life cycle assessment of conventional combustion engine vehicle, battery electric vehicle, and fuel cell electric vehicle in Nepal"*	• The findings indicate that, with 32% of India's electricity now imported, BEVs and FCEVs emit 187 and 922 gCO2-eq of GHG per km, correspondingly, compared to 507 gCO2-eq/km for ICEVs based on a 200,000 km lifetime estimate. • With Nepal's excess electricity scenario, the upstream emissions of both BEVs and FCEVs are expected to drop by 88%, accounting for 50% of BEV emissions and 82% of FCEV emissions overall. This would help to create a cleaner local and global environment.
Sahni et al., (2010) [111]	*"Engine Remanufacturing and Energy Savings"*	• The estimated total life cycle energy consumption of the remanufactured engine and the new engine was approximately equal. • Conversely, there have been no regulations placed on diesel engines used in combination trucks, which has led to historical stability in their fuel efficiency. Therefore, the net energy savings across the engine's life cycle are anticipated to represent the initial savings made during the manufacturing process of a remanufactured engine as opposed to a new one. • Remanufacturing of diesel engines for combination trucks appears to be a feasible approach to reduce energy use.
Liu et al., (2013) [112]	*"Environmental emissions and energy consumptions assessment of a diesel engine from the life cycle perspective"*	• The aim of this study is to identify the stage that has the biggest environmental impact by measuring the emission and energy consumption throughout the LCA of a newly made ICE. • The complete life cycle of the diesel engine and its three main consequences— potential of global warming, basic energy demand, and photochemical ozone formation potential—account for 19.47%, 50.37%, and 17.54% of the overall influences, correspondingly. • The engine life cycle's utilisation process uses maximum energy and has the biggest ecological effects; it is followed by the procurement of feedstocks and the generation of component parts.

Author(s)	Theme	Brief Outcome of the Study/Research
Smith and Keoleian (2004) [113]	*"The Value of Remanufactured Engines Life-Cycle Environmental and Economic Perspectives"*	• To find out how much energy and pollution can be avoided in the US by remanufacturing a midsized automobile petrol engine as opposed to having new product. • A full-service machining shop inventory, representative of 55% of engine remanufacturers in the US, was analysed to assess three scenarios for component replacement. The lifecycle model indicated that the remanufactured engine could be produced with 68% to 83% less electricity and 73% to 87% fewer carbon dioxide emissions. • The life-cycle model resulted in significant reductions in CO, NOx, SOx, and nonmethane hydrocarbons (50–61%). The use of raw materials decreased by 26% to 90%, while solid waste production decreased by 65% to 88%.
Zhang et al., (2013) [114]	*"Diesel Engine Block Remanufacturing: Life Cycle Assessment"*	• For remanufactured diesel engines, LCA was conducted to determine the adverse environmental effects over the engine's entire life cycle and evaluate the possible energy savings and environmental protections that remanufacturing offers. • The environmental effects of remanufacturing are illustrated by contrasting the results of the study with those of a newly made counterpart. • The findings demonstrate that, when compared to the original manufacturing process, remanufacturing an ICE has a lower environmental impact. • The largest benefit is the reduction of 79% in EP, followed by reductions of 67%, 32%, and 33% in GWP, POCP, and AP, respectively.
Luo et al., (2021) [115]	*"Life cycle assessment of electric vehicles and internal combustion engine vehicles: A case study of Hong Kong"*	• LCA was carried out for plug-in hybrid electric vehicles (PHEVs) and internal combustion vehicles (ICEVs) using petrol and diesel engine. Furthermore, under the aforementioned circumstances, PHEVs with diesel were the second best option for minimizing environmental impacts. On the other hand, across all damage category outcomes, the petrol ICEV has the most environmental impacts. • A lower environmental impact at the midpoint estimation throughout the whole LCA than the other vehicles. This is because electric vehicle batteries are recharged by renewable energy sources, which account for a sizeable share of the electricity mix (85%).

2.2 Gaps in Literature

- Insufficient LCA-Based Research on Environmental Impacts of Biodiesel: The available literature lacks a sufficient number of studies that utilize LCA, especially when it comes to thoroughly considering the well-to-wheel strategy for evaluating the environmental effects of biodiesel.
- Lack of Comparative LCA Studies on Biodiesel derived from Karanja and Microalgae: No study has been found in the current literature that undertakes a comparative LCA of biodiesel obtained from both Karanja and Microalgae feedstock sources, creating a significant gap in the research.
- Insufficient literature on LCA of ICEs in the Indian context: The existing literature lacks comprehensive coverage of the LCA of Internal Combustion (IC) Engines, particularly in the Indian setting. This reveals a notable deficiency in the present knowledge base.

2.3 Formulation of Research Objectives

The present work is envisaged for the following research objectives:

- Evaluate the developmental stages of Internal Combustion (IC) engines.
- Conduct a comprehensive LCA of Biodiesel.
- Perform a thorough LCA of the IC Engine.

CHAPTER 3

METHODOLOGY

3.1 Introduction

The current study includes a well-to-wheel LCA of biodiesels derived from two feedstocks, Karanja and Microalgae, followed by an LCA of an IC Engine fueled by biodiesel derived from Karanja feedstock and an assessment of alternative power systems to the IC Engine. Cradle to Grave LCA was carried out in accordance with ISO 140/14044 guidelines. Figure 3.1 depicts a graphical representation of the current work's methodology.

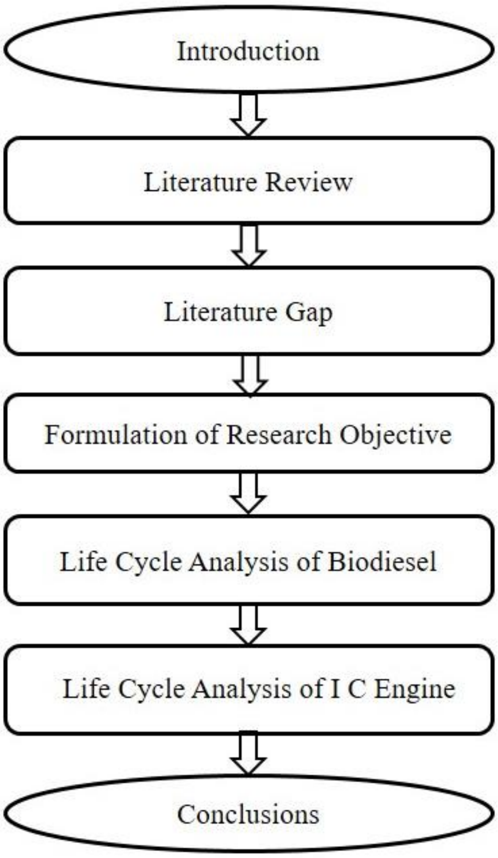

Figure 3.1: Methodology

3.2 Literature Review

The literature review of this thesis have four parts, which includes Development in IC Engine from its invention, Global Environmental Problem, Invention of Alternative fuel and employment of LCA in IC engine to evaluate the environmental footprint. Various research papers, articles and related books has been studied. Literature review and the identified research gap is given in chapter 2.

3.3 Formulation of Research Objectives

The research objectives of the present work are as follows:

- Assessment of the stages of the development of IC engines.
- LCA of Biodiesel.
- LCA of IC Engine

3.4 Life Cycle Analysis

Evaluating how products and activities affect the environment has become critical in a time of growing environmental concerns and sustainability awareness. A potent methodology known as LCA is developed to thoroughly evaluate the environmental impact of the goods or services over the course of its whole life cycle, from the raw material extraction to the manufacturing, distribution, usage, and final disposal or recycling. LCA studies comprise of consumption of resources, energy balancing, and GHG emissions through the different stages of the process in the predefined boundary of process or system to assess the sustainability burden of a process [116,117].

Life Cycle Assessment (LCA) is regarded as the most significant method for evaluating the environmental impact of biofuel life cycles. Life cycle assessment

(LCA), which considers the direct effects at each stage as well as the indirect effects that cascade across interconnected systems, provides a thorough method of evaluating environmental impacts [101]. LCA examines the materials required to move energy, how waste is eventually disposed of, how to reduce carbon emissions, and how to minimise reliance on non-renewable resources. With Life Cycle Assessment (LCA), decision-makers can reduce negative environmental effects and encourage sustainable practices by meticulously accounting for resource use, emissions, and other environmental stressors while making decisions [118,119].

The use of this analytical tool has grown in popularity as businesses, governments, and consumers realise how crucial it is to embrace ecologically friendly activities. Informed decision-making and the identification of opportunities for product design and manufacturing process improvement are two benefits of using life cycle assessments (LCAs). These efforts ultimately lead to the development of more environmentally friendly and sustainable products.

The Life Cycle Assessment (LCA) framework, which incorporates best practices through the ISO 14044 and ISO 14040 environmental standards system, has become a global standard for estimating requirements and the effects of processes, technologies, and products. An LCA study is divided into four separate but connected stages [120,121]. These stages consist of:

I. Goal and scope

II. Life Cycle Inventory Analysis

III. Life Cycle Impact Analysis

IV. Interpretation of the above

General steps or phases/sub phases to accomplish the LCA of a product is depicted graphically in figure 3.2.

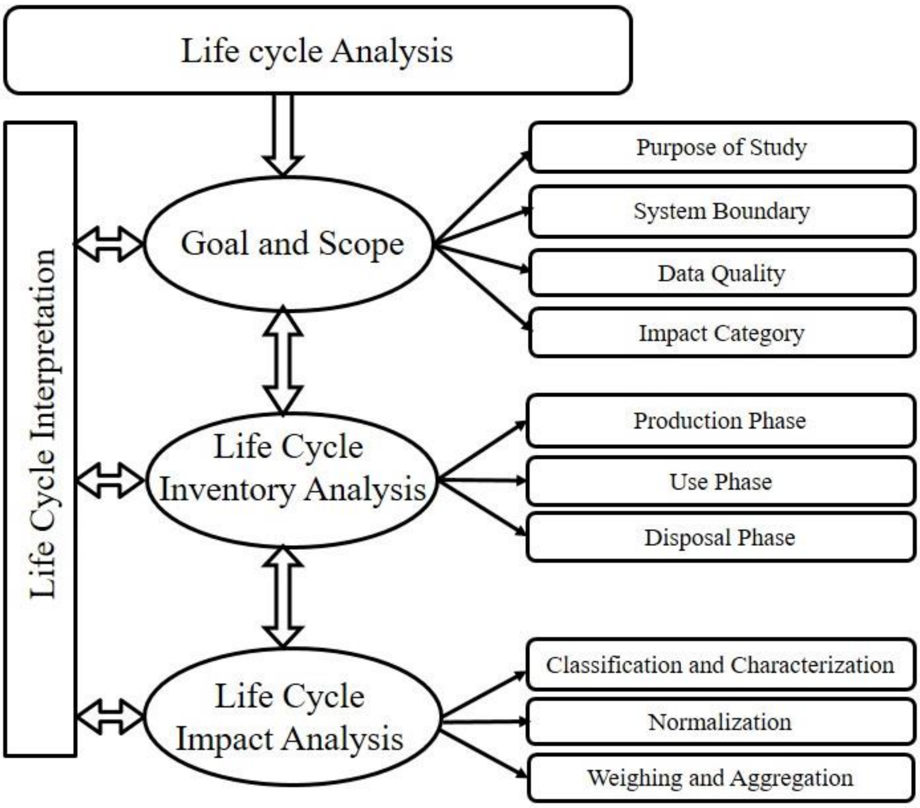

Figure 3.2: Steps of Life Cycle Analysis

3.4.1 Determination of Goal and Scope

An LCA's goal outlines the general objective or justification for carrying out the assessment. It offers a comprehensive overview of the goals of the study with regard to comprehending and assessing how a process or product affects the environment. The goal aids in determining the assessment's focus and direction.

Typical objectives of an LCA could be:

- To measure the effects a product has on the environment over the course of its life.

- To evaluate how environmentally friendly different products or processes are.
- To locate the main areas of environmental concern throughout a product's life cycle in order to make improvements.

Present study consists of comparative LCA of biodiesel production firstly followed by LCA of IC Engine.

Thus, in order to estimate the possible effects of laboratory-scale biodiesel produced from two types of feedstocks, namely Karanja and microalgae, in terms of GHG emission and energy ratio under Indian settings, the life cycle study of biodiesel has set the following initial goal:

- Estimation of the requirement of energy for the biodiesel production from both the feedstock i.e. Karanja and Microalgae separately.
- Estimation of Energy obtained from biodiesel and by-products i.e. glycerine and residual biomass.
- Estimation of GHGs emission in the production of biodiesel for both the feedstock i.e. Karanja and Microalgae separately.
- Determination of significant parameters responsible for GHG Emission and Energy ratio through execution of sensitivity analysis.

Further the purpose of LCA of IC Engine is to explore the potentials and drawbacks of the IC Engine in India. Hence the Goal for performing LCA of IC Engine has been established as follows:

- Estimation of environmental emissions in manufacturing of an IC Engine.

- Estimation of environmental emissions in operation phase of an IC Engine using fossil diesel and biodiesel.
- Estimation of environmental emissions in disposal of an IC Engine.

An LCA's scope describes the precise parameters and restrictions of the investigation. It outlines the environmental effect categories that are examined as well as the life cycle stages that are taken into account while making the assessment. For the purpose of making the scope of the assessment clear, it is essential.

Typically, the scope includes determining the system boundary, functional unit, geographical border, and environmental implications.

3.4.1.1 System Boundaries

It defines the life cycle stages that will be taken into account, including extraction of raw materials, manufacture, transportation, product consumption, and end-of-life.

In case of LCA of biodiesel the scope is extended from the cultivation of feedstock to the consumption of biodiesel in a stationary diesel engine. The Well-to-Wheel, or cradle-to-grave, study evaluates GHG and resource utilisation. Evaluation takes place in the following processes: manufacturing of chemicals, energy conversion, feedstock cultivation, biofuel production, and transportation.

The Scope for the LCA of IC Engine comprise from the manufacturing, use and disposal phase of the IC engine. Production phase of IC engine includes extraction of raw material and metal preparation, parts production and final assembly of the engine. Use phase comprise of production of diesel fuel, biodiesel and their combustion in the engine in order to release the useful energy. Lastly Disposal or End of Life phase consists of refurbishing of reusable parts and recycling of disposable items.

3.4.1.2 Functional Unit

The functional unit specifies the unit of analysis to allow for relevant comparisons. It serves as a focal point for the feed and result. It is justified to compare fuels solely on the basis of their calorific value in the case of LCA of biodiesel, where the functional unit is defined as 1 MJ of energy from biodiesel "well-to-wheel"[122]. A comparison of the GHG balances, expressed in gCO_2eq/MJ, is also made for each energy production unit at the same time [123]. Based on several LC processes, the Net Energy Ratio (NER) is calculated by dividing the energy output by the energy input. One of the energy outputs is biodiesel; additional co-products include glycerol, biogas, and so forth [124,125].

$$\text{Net energy ratio} = \frac{\sum \text{Energy output}}{\sum \text{Energy input}} \quad (1)$$

The net energy gain is calculated as follows [126]:

$$\text{Net energy Gain (NEG)} = \text{Energy output} - \text{Energy input} \quad (2)$$

For the LCA of IC Engine, engine manufacturing, operation, and disposal are the focus areas of evaluation. Also, engine is assumed stationary at the time of operation and used for irrigation purposes. So the functional unit of this LCA is taken as "One Diesel Engine" following the study of Liu et al. 2013. (Liu et al. 2013)

3.4.1.3 Environmental Implications

During the life cycle impact assessment phase (LCIA), different impact categories are evaluated for measuring environmental impacts. The impact factors are selected to ensure that the majority of the major, frequently occurring effects of IC engines in cars have been covered. In Table 3.1, a few of the impact groups are mentioned. In this work, the guiding principle supplied by Joint Research Centre (JRC 2011) in the charter of the European Console on Life Cycle Assessment in selecting the methods to evaluate the implications were followed very closely as available in EPLCA [127].

Table 3.1: Environmental Impact Category

Impact Category	**Reference Substance**	**Reference Indicator**	**Unit of Measure**	**Reference**
1. Global Warming Potential	CO_2	IPCC	$kgCO_2$ eq.	[128] [129] [129] [129] [130]
2. Photochemical Oxidant Development Potential	NMVOC	ReCiPe	kgNMVOCeq.	
3. Potential of Acidification	SO_2	CML 2002	$KgSO_2eq$	
4. Potential of Particulate Matter	PM10	ReCiPe	gPM10eq	
5. Potential of Eutrophication	PO_4	CML2002	$kgPO_4eq$	
6. Potential of Resource depletion	Antimony	CML2002	kgSbeq	

Today world is facing a major threat to its environment in terms of air pollution and water pollution due to various industrial activities [131]. Joint Research Centre (2011) provides various environmental impacts [127]. In case of biodiesel, Global warming potential was chosen as the impact category because they are the primary threat caused by conventional IC engines [101,121,132–134]. In addition, NEV [21,28,126,135], and ER [28,126,136] were also evaluated to perform life cycle energy analysis. Global warming potential is taken according to JRC (2018) which is measured in $kgCO_2$ and the reference material indicator for this parameter is carbon dioxide as per the IPCC. In this work, the guiding principle supplied by JRC (2018) in the charter of the European Console on Life Cycle Assessment in selecting the methods to evaluate the implications was followed very closely [127].

3.4.2 Life Cycle Inventory (LCI)

The phase of inventory analysis includes flow and release allocation, collection of data, and calculation process to estimate related inputs and outputs. The collection of the data can be accomplished by utilising specific data in-built in the LCA software and/or specific data generated by your system [137]. Ecoinvent is a database integrated with software like OpenLCA used for the assessment of environmental impacts through LCA. Other inventory needs for Karanja crop growing, harvesting, extraction of seed oil, transesterification, and biodiesel consumption were derived from the existing literature [98,99,101,122,138]. Similarly, inventory data for various processes involved in biodiesel production from microalgae and its consumption was collected from the available literature [24,117,139–142].

In the case of Life cycle Inventory analysis of IC Engine, manufacturing stages, usage and disposal steps were considered. Manufacturing steps includes, Ore Extraction and Metal Production, Transportation of Materials, Engine parts manufacturing and final assembly of diesel engine. Various sources were used to collect the data to compile the environment emission. Operation or use phase includes burning of fuel, maintenance of diesel engine, production of diesel and biodiesel. In disposal phase recycling and refurbishing were also considered. Ecoinvent provides data on emissions produced during engine manufacturing, combustion of diesel-like fuel, and recycling of various products. Existing literature was also used to fill the data gap [115].

3.4.3 Life Cycle Impact Assessment

The Life Cycle Assessment (LCA) inventory analysis offers the standards by which LCIA approaches weigh the different environmental effect categories. Environmental emissions from the life cycle inventory phase, such as CO_2, SO_2, NO_X, COD, BOD, and HCL, are utilised for determining the influence on the environment and subsequently on humans or other living things [143].

The Life Cycle effect Assessment (LCI) step involves the association of LCI results with environmental effect indicators and categories. This is accomplished using LCIA techniques, which first divide emissions into impact categories and then characterise them using characterization factors to enable comparison. It is the phase of life cycle assessment involving the compilation and quantification of inputs and outputs for a given product system throughout its life cycle." (ISO 14040) It is the third stage of a life cycle assessment (LCA) focuses on comprehending and assessing the possible environmental effects of the product system or systems under investigation, including their scale and relevance [127]

ISO 14040 [42] provides the guidelines to perform the Life cycle impact assessment (LCIA) which generally includes:

- Classification,
- Characterization, and
- Normalization.

Emissions come in many different forms, including carbon dioxide, methane, COD (Cumulative Oxygen Demand), and NOx, among others. These emissions can have multiple negative effects on the ecosystem. For instance, both CO_2 and NOx have a quantitatively different impact on global warming and acidification, although they are both accountable for these phenomena. As a result, each emission collected during the inventory phase is categorised based on its impact category. This process is referred as classification for the purpose of life cycle impact assessment. Characterization process is the calculation of an impact category quantitatively due to a certain type of emission substance. This is achieved by the multiplication of the emission quantity with the characterization factor [42].

Purpose of normalisation and weighing is linked to the purpose and scope of the study and therefore depends on the quantity and type of alternatives and impacts included and on the system boundaries and intended audience. Normalization is not mandatory but optional according to the ISO 14040. By providing a response to the question of whether the results' order of magnitude is believable, normalisation can be very helpful in guiding the interpretation stage of LCA. In order to help with the interpretation and dissemination of the impact results, it can also be utilised to compare the outcomes with a reference scenario that is separate from or unrelated to the case studies [144]

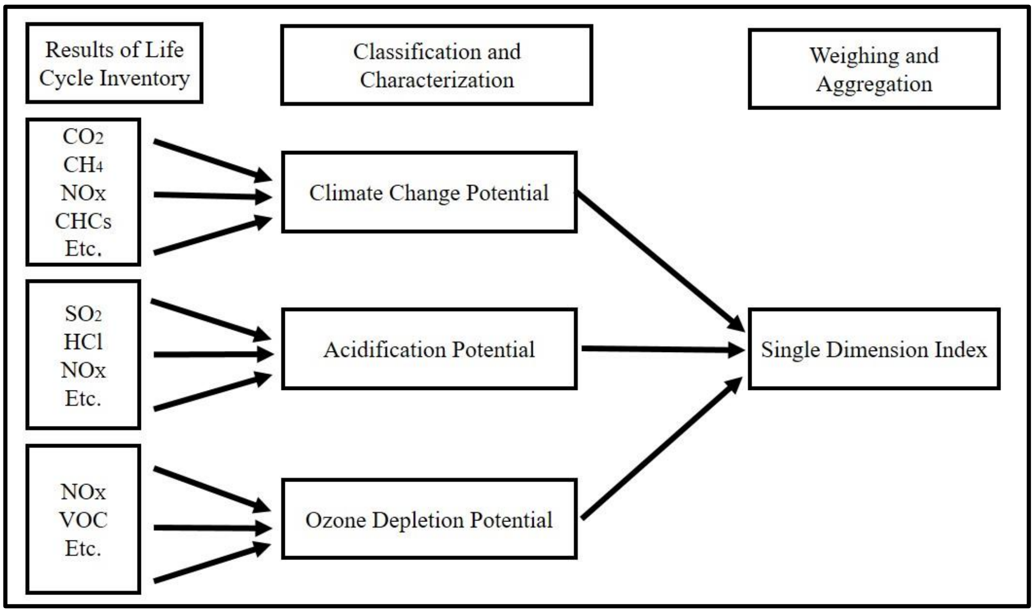

Figure 3.3: General Procedure of Life Cycle Impact Assessment

There are various method developed for life cycle impact assessment by different agencies from time to time. According to the ecoinvent database, a few of the techniques are listed below [145].

- CML 2001
- Eco-indicator 99
- EDIP - Environmental Design of Industrial Products 1997
- EDIP - Environmental Design of Industrial Products 2003
- Ecological Footprint
- IMPACT 2002+
- Ecological scarcity 2006
- IPCC 2001 (Global Warming)
- IPCC 2007 (Global Warming)
- Ecological scarcity 1997

A few of the aforementioned techniques exclusively define environmental emissions at one level, also referred to as the midpoint level indicator. The midpoint level indicator conveys the effects of environmental changes, such as rising temperatures. Other approaches divide the environmental emissions into two categories: endpoint and halfway. Three primary kinds of endpoint level indicators are listed below [130]:

- Human health
- Ecosystem Quality
- Resource Scarcity

The endpoint level indicators are further computed on a temporal basis based on the three perspectives. These three viewpoints are egalitarian (for a long period up to

1000 years), hierarchist (for a medium period up to 100 years), and individualist (for a short period up to 20 years).

The ReCipe method is used, offering midpoint and endpoint indicators. When compared to methods that focus solely on one approach, ReCiPe stands out as a versatile tool that caters to a broader range of applications. It provides detailed data at the midpoint level for precise analysis as well as user-friendly endpoint information for the average person [32]. Despite its goal of impartiality and offering a variety of ideological options, the endpoint weighting in ReCiPe may be perceived as a bit random. Interpreting LCAs aids in regulatory compliance and risk management by informing resource allocation decisions [33]. It boosts stakeholder engagement and encourages continuous improvement. Overall, it enables decision-makers to prioritise safety, health, and sustainability while dealing with complex environmental issues. Graphical representation of ReCiPe impact method is shown in figure 3.4.

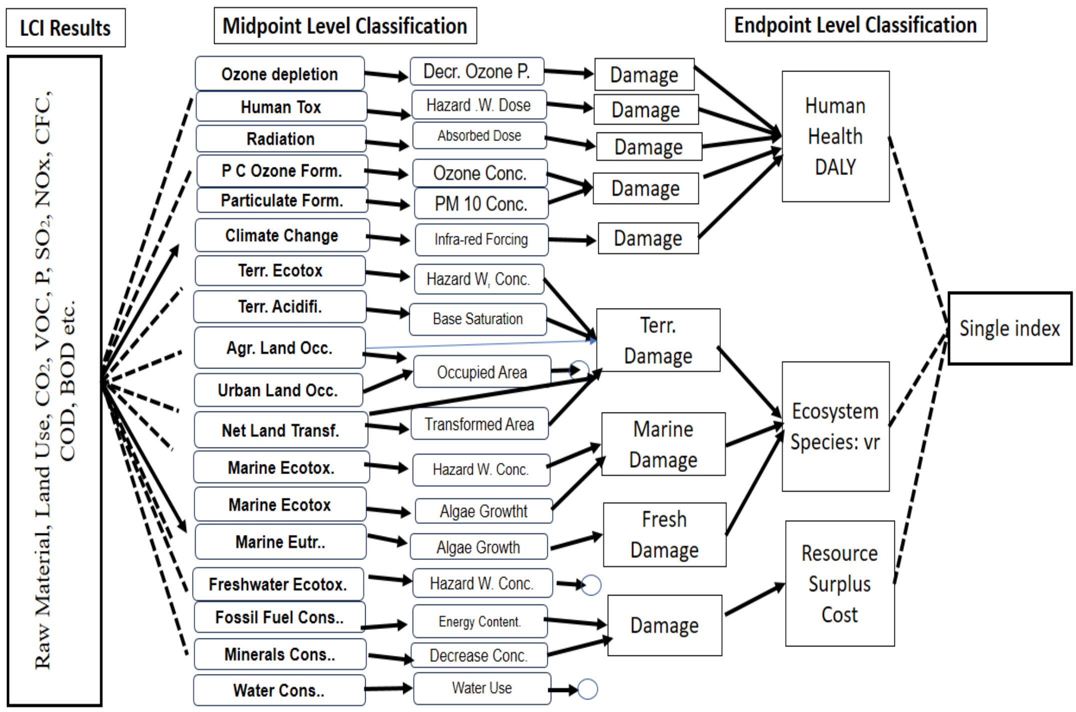

Figure 3.4: Steps of ReCiPe Impact Method

3.4.3.1 Classification and Characterization at Midpoint Level

The emissions obtained in the second step of LCA i.e. lifecycle inventory analysis is classified in the lifecycle impact assessment. Following the ReCiPe, the operation is carried out. To get the midpoint level indicator, multiply the value for a particular type of emission that comes from the life cycle inventory by the characterisation factor. Table 3.2 provides information on the study's environmental impact at the midpoint indication. [129]:

Table 3.2: Classification and Characterization of Midpoint Level Indicator

Emission Type Derived from LCI	Midpoint Level Indicator	Unit of Midpoint Level Indicator	Characterization Factor
CO_2	Climate change (GWP)	$kgCO_2eq$	1
CO			5.53
CH_4			2.62E+01
NOx			3.67E+02
NOx	Fine particulate matter formation	kgPM10eq	0.47
SO_2			1.26
PM			4.99
NH_3			0.26
NOX	Photochemical ozone formation	kgNMVOeq	1
VOC			0.18
NOx	Terrestrial acidification	$kgSO_2eq$	0.36
SO_2			1
NH_4			1.96
Crude oil	Fossil resource scarcity	kgOileq	1
Natural gas			0.84
Coal			0.3

3.4.3.2 Classification and Characterization at Endpoint Level

Each impact category has a fixed midpoint to endpoint factor, and the endpoint level impact is calculated by multiplying the midpoint level impact amount by a midpoint to endpoint level conversion factor. ReCiPe provides the conversion factor to convert the midpoint level impact into the endpoint level impact. The study's environmental impact at the endpoint indication is shown in Table 3.3 [129].

Table 3.3: Conversion Factor to convert the Midpoint Impact into the Endpoint Impact

End Point Indicator	Midpoint Level Indicator	Characterization Factor		
		Individualist	**Hierarchist**	**Egalitarian**
Human Health (DALY)	Climate change (GWP)	8.10E-08	9.30E-07	1.30E-05
	Fine particulate matter formation	6.30E-04	6.30E-04	6.30E-04
	Photochemical ozone formation	9.10E-07	9.10E-07	9.10E-07
	Terrestrial acidification			
Ecosystem Quality (Year)	Photochemical ozone formation	1.30E-07	1.30E-07	1.30E-07
	Terrestrial acidification	2.10E-07	2.10E-07	2.10E-07
	Climate change (GWP)	5.30E-10	2.80E-09	2.50E-08
Resource Scarcity (USD)	Fossil resource scarcity by Oil	0.46	0.46	0.46
	Fossil resource scarcity by Coal	0.03	3.00E-02	3.00E-02
	Fossil resource scarcity by Natural Gas	3.00E-01	3.00E-01	3.00E-01

Endpoint impact are aggregated into single index using the weighing scale followed the work of Martin and Simon (2014) using ReCiPe for all three perspective given in the table 3.4 [143].

Table 3.4: Weighing Scale for Endpoint Impacts

Perspective	Human Health	Ecosystems	Resources
Individualist	0.55	0.25	0.2
Hierarchist	0.3	0.4	0.3
Egalitarian	0.3	0.5	0.2

3.4.4 Interpretation

The initial step in the interpretation process is to identify the concerns that may be important, and examples of these issues are provided for each phase of the process, which includes aim and scope definition, inventory analysis, and effect assessment. As the last stage of an LCA, interpretation involves taking all of the previous stages' findings and analysing them collectively while taking the applied data's uncertainties and previously determined, documented assumptions into account. When enhancing the study's data basis is not feasible, the results are utilised to inform earlier phases and, in those cases, to re-evaluate the study's purpose and scope definition.[146] Important problems that considerably increase the product system's environmental impact are also noted. In this sense, "key issues" might refer to important procedures, supplies, tasks, elements, or even a stage of the life cycle. Analysis is done on the outcomes of life cycle impact assessments and life cycle inventory analyses. The guidelines for the study's interpretation are provided by ISO 14044 [147].

3.5 Summary

The methodology of this study initiates from the literature review which leads to identify the research gap and research objectives. Methodology to perform the LCA in this study can be summarized as follows:

- Determination of the scope and goal of the comparative LCA of biodiesel using karanja and microalgae feedstock.
- System boundary of biodiesel production of karanja feedstock was established.
- System boundary of biodiesel production of microalgae feedstock was established.

- System boundary of IC Engine was established.
- Global warming potential was considered as environmental impact for the LCA of karanja and microalgae.
- Climate Change Potential (CCP), Acidification, Particulate Matter Formation Potential, Photochemical Ozone formation potential (PCOF) and Resource Sarcicity were considered as impact categories for the LCA of IC Engine.
- Life cycle inventory of biodiesel includes cultivation, transportation, and extraction of vegetable oil, transesterification process to obtain biodiesel from karanja and microalgae feedstock.
- Life cycle inventory of IC Engine includes manufacturing, operation and disposal phase of the engine.
- Life cycle impact assessment was performed following ISO 14040 guidelines and using ReCiPe methodology.
- Midpoint level indicator like CCP, Acidification, Particulate Matter Formation Potential, PCOF and Resource Scarcity were determined.
- Endpoint level indicator which are human health, ecosystem quality and resource scarcity are established using suitable endpoint conversion factor provided by ReCiPe.
- Key issues are identified for the LCA of biodiesel and LCA of IC Engine.

CHAPTER 4

LIFECYCLE ANALYSIS OF BIODIESEL

4.1 Introduction

IC engines have long provided the required propulsion energy in conventional transportation by burning petroleum-based diesel, which emits various pollutant gases that harm the environment. As the demand for transportation has increased significantly, emissions of GHGs and other pollutants have accumulated to a large extent, with far-reaching consequences [148,149].

India, has more than tripled its primary energy consumption since 1990 throughout the past ten years [150]. Catering such a huge amount of energy with fossil-based fuel is harmful to our environment owing to tailpipe emissions. It also poses a danger to the country's energy security since India imports the majority of petroleum fuel from other nations [24].

Biodiesel is capable of replacing fossil-based fuel owing to intrinsic benefits like sustainability, proficient burning, lower CO_2 emanations, excellent attainment of environment, and competence. [10]. It can be derived from feedstock, including Jatropha, Karanja, Palm, Soybean, Rapeseed, Calophyllum inophyllum, Maize, Microalgae, Macro-algae, and others. In several countries, 20% biodiesel blending is either allowed or made mandatory [25].

Most biofuels are currently categorized into three main generations: first-generation ethanol and biodiesel. Ethanol is made from edible biomass like corn and sugarcane, whereas biodiesel is made using non-edible as well as edible oils. Soyabean, sunflower, palm, and rapeseed are examples of edible feedstock, while non-edibles include Jatropha, Karanja, canola, and others. Various feedstocks, including non-edible lignocellulose, are used to produce second-generation biofuels. Second-generation biofuel biomasses are homogeneous (wood chips and waste wood), quasi-homogeneous (crop-based and forestry waste wood), and also non-homogeneous (low-priced feedstock such as municipal wastes). Third-generation biodiesel is extracted from algae biomass [151].

Despite its numerous benefits, biodiesel has some drawbacks also, such as high energy requirements of recovery facilities, inaccessibility of feedstock, lower earnings than fossil diesel, and a scarcity of consistent supply. Furthermore, biodiesel has a detrimental influence on the microbial community's structure and activity [117]. Moreover, if edible feedstock is used in biodiesel production, the world will face a massive food security crisis. Non-edible oil sources are abundant in the nation and will grow substantially in non-cropped marginal areas and wastelands. Hence, non-edible feedstock should be the preferred choice for biodiesel production [26,152]. As a result, the use of non-edible feedstock for biofuel production is being investigated. For the upcoming massive demand, searching for all possible feedstock will be beneficial, as only one or two feedstock will not be able to meet the situation shortly [27].

LCA analysis is considered a methodical device for assessing the conservational influences of products, processes, or activities [135]. The study of life cycle assessment has been demarcated through the International Organization for Standardization (ISO) 14044:2006 standards (ISO 2006) [153]. It includes land availability for agronomy, energies supplied and obtained, GHG emissions, pesticide use, soil destruction, and fecundity, contribution to biodiversity value damages, logistic charges, feedstock's price counting its by-products, job creation, water accessibility, and requirements, and feedstock impacts on the environmental air [117,154].

The technique in use for biodiesel production is determined by the feedstock to be used as raw material. As a result, the quality and source of the raw feedstock should be verified before use [155]. However, all feedstock has some advantages based on the region where they are produced and other properties like availability, oil yield, and energy requirements, Karanja and microalgae have good properties establishing these as quality feedstock for biodiesel production [132,156,157].

Karanja has higher survivability, generating almost 30 to 40% oil with greater oil density (0.87 g/cm^3). Numerous catalysts, such as CaO, MgO, Ni– W bimetallic catalysts, and calcined waste skeletal remains, are used as supplemental catalysts for Karanja biodiesel synthesis [98,138]. Because the decortication operation (removing the fruit shells to drive the oil seeds) was not needed in the case of Karanja, the power demand in fruit breaking is assumed to be zero. India can produce 55000t per year^{-1} Karanja oil [101,158]. For generating 1GJ energy approximately 26.26kg of Karanja oil is required, which means India can generate 2094440 GJ year^{-1} using Karanja as feedstock. Using a usual calorific value of 43.1 MJ kg^{-1} for diesel fuel, 2094440 GJ of biodiesel energy equates to 48594900kg of fossil diesel. Though this is a tiny portion in contrast to India's yearly fuel usage of 45-75.6 million tonnes, it saves foreign exchange expended on imports [101,159].

Microalgae has the most significant advantage in that it is not an established food source, minimizing the resource allocation problem of the food-energy supply nexus. Microalgae can be grown in freshwater and seawater [136].

It was discovered that when looking for biodiesel sources, feedstocks that do not require fertile land, do not compete with food crops, help reduce GHGs emissions, and reduce reliance on other countries should be considered. As a result, microalgae have recently emerged as a very promising feedstock for the production of biodiesel [28].

Microalgae are grown and gathered to produce algal fatty acids via a solvent-based extraction process. The derived oil is subsequently transesterified in a closed photobioreactor for 90 minutes at 60°C. The lipids in microalgae are triacylglycerols that are reacted with methyl alcohol, thus forming biodiesel [160]. In the presence of a catalyst, the triglycerides in fatty acids are transformed into esters via the common transesterification reaction. Heliamphora coffeaeformis, N. gregaria, and Navicula cincta are established sources of feedstock for biodiesel generation [151].

Viable algae generation would also posit that agriculture amenities would be sited on marginal lands rather than valuable fertile agricultural lands. The nation’s aggregate land area is projected to be 55.27 million hectares, which accounts for around 18% of the overall land area. If India allocates a mere 10% of its unused and unproductive land (5.5 million hectares) for the cultivation of algae, it has the potential to generate a substantial amount of algal oil, ranging from 22 to 55 million metric tons. This quantity of algal oil may potentially replace a significant portion, ranging from 45% to 100%, of the country’s present diesel consumption. The quantity of algae mentioned would absorb a total of 169-423 million metric tons of carbon dioxide, so compensating for 26%-67% of the existing GHGs emissions [161].

Wastewater generated by municipalities and industries in metropolitan cities requires treatment to remove biodegradable COD. If anaerobic processes are used, no aeration is required for methane conversion, and methane is used for energy purposes. Anaerobic reactors also produce CO_2, which can be supplied to photobioreactors to grow microalgae, which can then be used to produce biodiesel for further energy purposes in massive quantities, as 35 metropolitan cities in India with populations exceeding 10 million produce 1.56 104 million litres per day (MLD) sewage [162].

In India, four major locations have been identified for suitable and sustainable farming of various microalgae species, including various paddy fields as a multitier crop, the saline brackish region of Kachch, fishery deficient seashores providing 6.9 Mha combined, and metropolitan domestic and industrial wastewater 40 billion L/d. Algal biofuel production using the above opportunity can help to alleviate the country's reliance on fossil fuels [29].

According to the literature review, there is no relative LCA-based research in the open literature that takes into account the well-to-wheel approach for environmental impacts and energy analysis on Karanja and microalgae-based biodiesels. Hence the present endeavour is to attempt to undertake a data-driven LCA-based renewable energy exploration on two different generations of biodiesels. The idea of biodiesel sustainability from well to the wheel has yet to be investigated in the present framework. As a consequence, researchers are evaluating the possible feedstock of different generations of biodiesels to discover the optimal biodiesel production resource. LCA emphasizes the significance of environmental sustainability and the difficulties linked with biodiesel emissions in this scenario. The current study compares biodiesels produced from Karanja and microalgae. These feedstocks represent first-generation non-edible feedstock and third-generation feedstock. These feedstocks are known for their higher oil yield, accessibility, rapid growth speed, commercial viability, and substructure requirements. This study employs LCA to examine and evaluate the performance of chosen biodiesels in aspects of GHG releases, energy intake, and responsiveness.

The ISO standard distinguishes LCA's conceptual framework from its many applications, which include product development, Eco-labeling, ecological footprint, and other estimations [147]. It is assumed in cradle-to-grave LCA that a product goes through several stages throughout its life, including the extraction of materials required to manufacture that product, the manufacturing of that product, its use for the purpose for which it was designed, and finally the disposal or end of that product [125,163]. The impacts of both GHG emissions and the balance of energy are evaluated for the chosen oil feedstocks at each stage of the Well-to-Wheel module [126,164]. The LCA template for generational cohorts of biofuel production was designed using the GREET framework developed by the Argonne National Laboratory in the United States. The ecoinvent database's Karanja and Microalgae LCA inventory library emission variables were adjusted in the current investigation utilizing the Gabi program.

LCA of service or product quantifies the impact on the environment of the entire process by taking into account the origin of all inputs as well as the final disposal of all products and wastes. LCA studies comprise of consumption of resources, energy balancing, and GHG emissions through the different stages of the process in the predefined boundary of process or system to assess the sustainability burden of a process [116,117].

For estimating requirements and the influences of processes, technologies, and products, the framework of LCA has been a norm globally with engrained best practices through a system of environmental standards - ISO 14044 and ISO 14040. LCA basically comprises four interrelated parts [120,121]. These are:

I. Define research objectives and scope.

II. Conduct inventory analysis of GHG emissions and resource usage.

III. Implementing the influence assessment technique

IV. Interpreting the results.

LCA is regarded as the most essential approach for determining the ecological impact of biodiesel life cycles [101]. This assessment concentrates on three aspects of the economy: industrial production, agriculture, and energy. LCA looks into the materials needed for energy flow, the final disposal of wastes, and the minimization of Carbon footprint and dependence on non-renewable resources [118,119].

4.2 Goal and Scope

To quantify the potential influences of lab-scale biodiesel synthesis from two types of feedstocks i.e. Karanja and Microalgae, in terms of energy ratio and GHG emission in Indian conditions, the following were required:

- Estimation of the requirement of energy for the biodiesel production from both the feedstock i.e. Karanja and Microalgae separately.
- Estimation of Energy obtained from biodiesel and coproduced i.e. glycerine and residual biomass.
- Estimation of GHG emission in the production and use of biodiesel for both the feedstock i.e. Karanja and Microalgae separately.

- Determination of significant parameters responsible for GHG Emission and Energy ratio through execution of sensitivity analysis.

As the cradle-to-grave approach of LCA was applied, this study's scope is extended from the cultivation of feedstock to the consumption of biodiesel in a stationary diesel engine.

4.2.1 Functional Units

In LCA, the functional unit (FU) is a point of orientation for the feed and outcome. The functional Unit for the present study's LCA is 1 MJ of energy from biodiesel "well-to-wheel" for life cycle energy analysis, which justifies the comparison of fuels directly based on their calorific value [122]. At the same time, balance of GHGs for each unit of energy production is also compared which was measured in gCO_2 eq/MJ [123]. Net Energy Ratio (NER) is estimated as the energy output divided by energy input during different LC processes. Biodiesel and other co-products are among the energy outputs (such as biogas, glycerol, etc.) [124,125].

$$\text{Net energy ratio } = \frac{\sum \text{Energy output}}{\sum \text{Energy input}} \quad (1)$$

The net energy Value is calculated as follows [126]:

$$\text{Net energy Value (NEV)} = \text{Energy output} - \text{Energy input} \quad (2)$$

4.2.2 System Boundary and Data Sources

Well-to-Wheel, or cradle-to-grave, study assesses resource utilization as well as GHGs emissions. Assessment occurs during chemical manufacturing, converting energy usage, feedstock cultivation, producing biofuel, and shipping. The literature provided detailed information on agricultural processes for Karanja and microalgae. The total energy and emissions influences of varied alternative road transport fuels and sophisticated vehicle systems can be calculated using GREET. Before this study, the GREET LCA system and roadmaps for diesel, petro-fuel, and vegetable oil-based biodiesel were well documented and incorporated into the GREET model [133,134].

4.2.2.1 System Boundary of Karanja

In the present LCA framework, the system boundary for biodiesel production from Karanja includes farming of Karanja plants followed by obtaining seeds and their transportation to the oil extraction unit. This oil is further transported to the biodiesel production unit where oil processing, transesterification, and purification occur. Farming of Karanja starts with the plantation of Karanja plants, manuring and watering plants, followed by the collection of seeds, which are used to obtain Karanja oil feedstock [98]. The main steps considered were oil extraction, pretreatment of feedstocks, trans-esterification, methyl alcohol recycling, and clarification of crude biodiesel. Deacidification, drying (removing FFA, water, and lipids) and degumming were the main steps considered vital for the feedstock treatment process [99]. Biodiesel is made by transesterifying oil with methyl alcohol in the presence of catalysts at constant pressure and temperature. The extra methyl alcohol can also be recycled, to obtain the final product of crude biodiesel after the washing and drying [165]. In Figure 4.1, the system boundary for biodiesel production from Karanja, input, and output of the system is depicted.

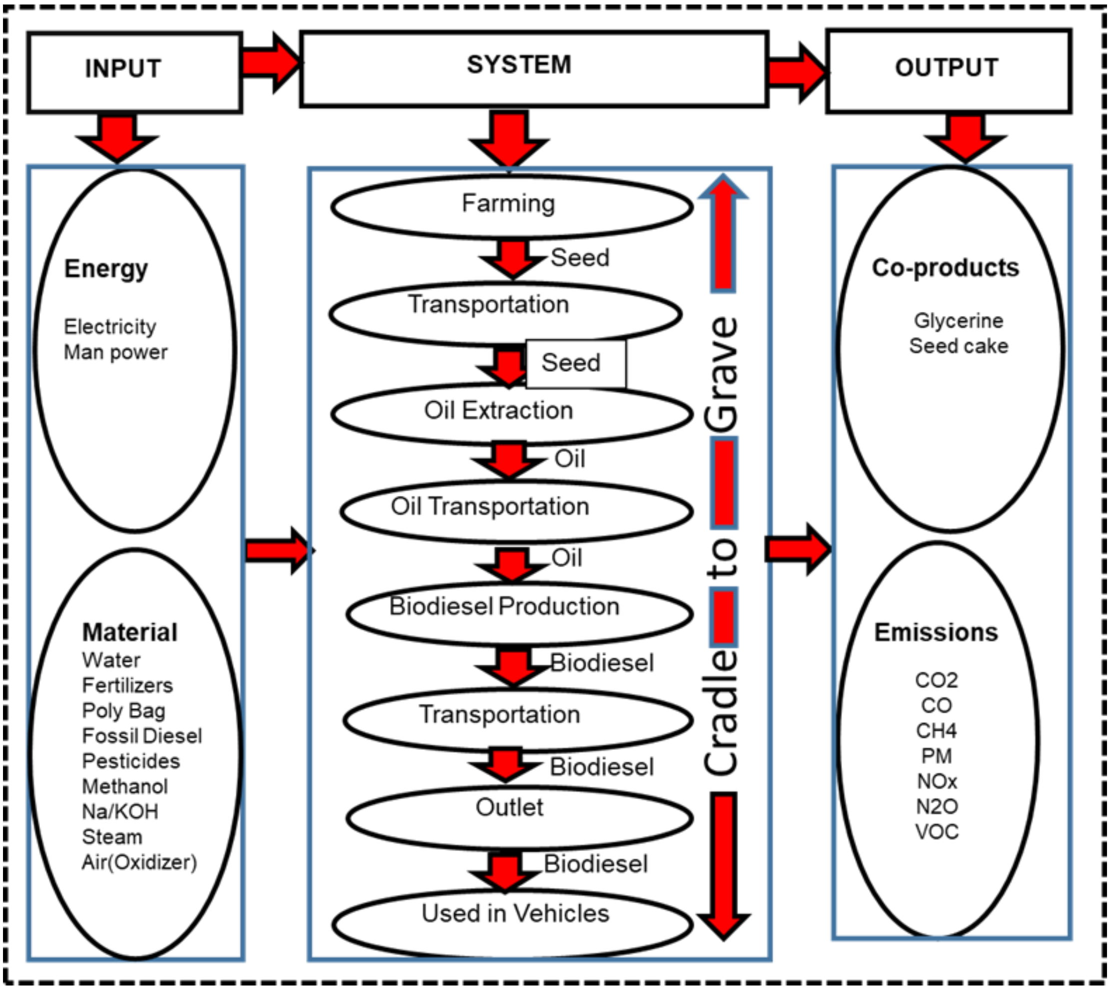

Figure 4.1: Karanja Biodiesel Production System Boundary

4.2.2.2 System Boundary of Microalgae

In the case of algal biodiesel production using conventional microalgae, the life cycle system boundary consists of various processes like the cultivation of microalgae, pre-treatment, transesterification, and finally, purification. There are various methods of microalgae cultivation, i.e. centrifugation, filtration, gravity-based sedimentation, flocculation, and floatation [136]. Biodiesel pre-treatment is cell disarranging methods like the distraction of cells, autoclaving, sonication, thrashing in a blob, microwave-based treatment, and palpitation in the electrical field. Transesterification is a chemical process to convert the oil feedstock into required biodiesel. Transesterification using acid, base, biocatalysts, and supercritical CO_2 as catalysts is generally employed for biodiesel production. Finally, purification is performed by washing or dry washing technologies [166,167]. Because of the benefits, the case study postulates that microalgae were grown in open ponds mixed with paddle wheels. When working on a large scale, open pond algae cultivation was less expensive than photo-bioreactors. In comparison to photo-bioreactors, they consumed less energy and were easier to maintain and clean [168,169].

Photosynthesis is required for the growth of microalgae, which requires sunlight, water, CO_2, and nutrients. The amount of water lost through evaporation is determined by the climate, precisely temperature, and humidity. In tropical climatic conditions, dehydration is about 4.6 m^3 /m^2 per year from evaporation loss, seep losses, and operation water discharge. These losses increased the water demand for microalgae cultivation in tropical environments. Microalgae production was assumed to be located near a power plant for reusing CO_2 from the combustion process to allow for the monitoring of exhaust pollutants in aspects of economic and environmental benefits. In Figure 4.2, the system boundary along with input and output is shown, for the production of biodiesel from Microalgae.

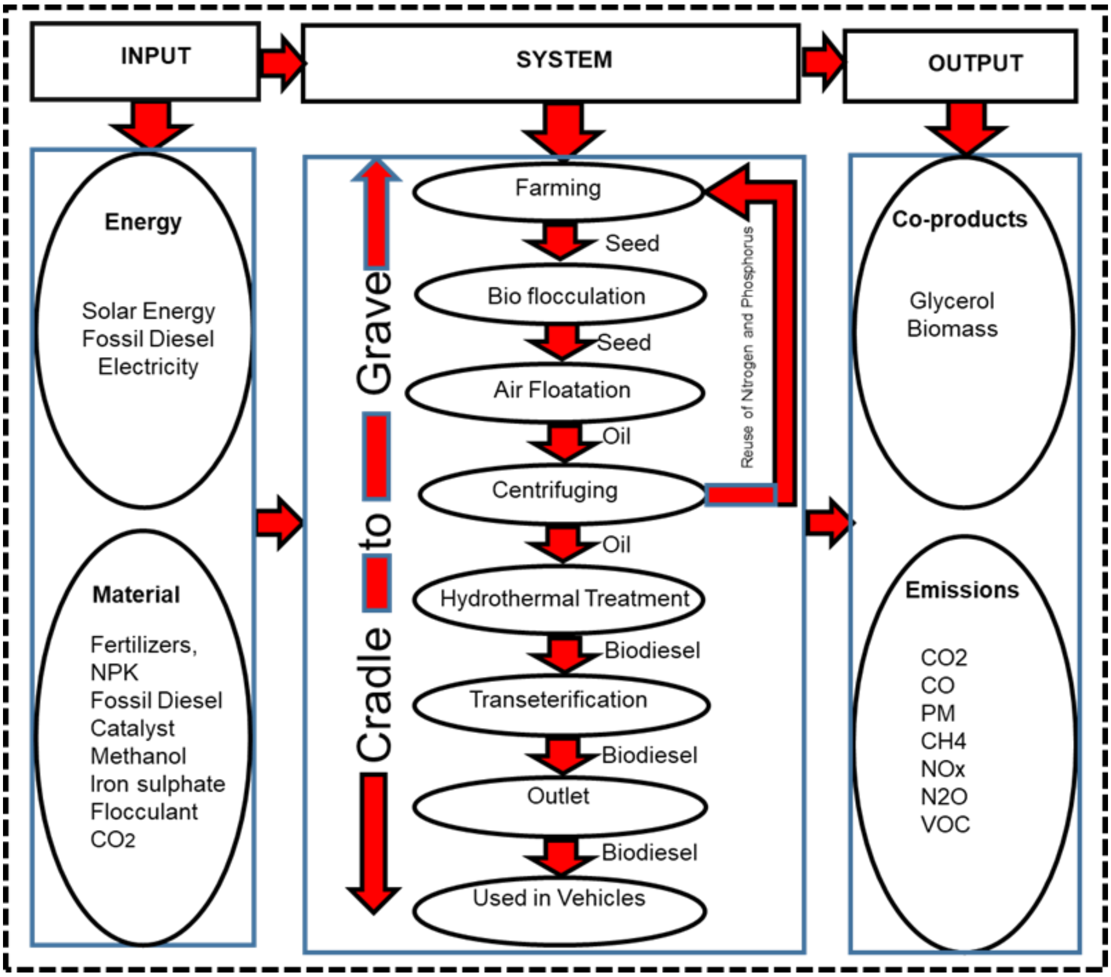

Figure 4.2: System Boundary of Biodiesel Production from Microalgae

4.2.3 Environmental Impact (Impact Categories)

Today the world is facing a major threat to its environment in terms of air pollution and water pollution due to various industrial activities [131]. Joint Research Centre (2011) provides various environmental impacts [127]. As per one study conducted, the amount of water and nutrients required in microalgae biodiesel production was found in huge amounts if grown in freshwater which can be reduced with the recycling of yield water by 84%. Geographic and species variations have significant impacts on the water requirements for microalgae biodiesel production [170]. Further, the growing of Karanja plants requires low water and fertilizers comparatively [171]. Generally, Karanja trees are planted on roadsides canals and wasteland and humid tropical lowlands, and rain-fed locations throughout the globe [172]. Biodiesel production can be equipped with advanced technologies and a selection of management to reduce water requirements. The world mainly is facing twin crises i.e. environmental degradation and scarcity of fossil fuel [173]. Global warming potential has been selected as the category for assessing the impact because they are the primary threat caused by conventional IC engines [101,121,132–134]. In addition, NEV [21,28,126,135], Non-Renewable Energy Value [117,166,168], and ER [28,126,136] were also evaluated to perform life cycle energy analysis. Global warming potential is taken according to JRC (2018) which is measured in Kg CO_2 and the reference material indicator for this parameter is carbon dioxide as per the IPCC. The net Energy value is the total energy used in life cycle of biodiesel obtained from both feedstocks. It is considered a critical parameter because more energy consumption hurts the environment. However, the renewable energy used in biodiesel production has less environmental impact so the Non-Renewable Energy Value is also taken to assess the energy used obtained from fossils. The last parameter considered in this LCA is the Energy Ratio, which is the ratio of energy consumed in biodiesel production from cradle to grave and energy obtained from biodiesel when it is burned in the IC engine. In this work, the guiding principle supplied by JRC (2018) in the charter of the European Console on Life Cycle Assessment in selecting the methods to evaluate the implications was followed very closely [127].

4.2.4 Assumptions

It was assumed that Karanja farming began with a nursery, and there were 550 Karanja trees in a one-hectare plantation area. The plantation site has average soil quality and rainfall, and it takes 10 years for Karanja trees to reach full seed yield [99,101]. The green alga C. Vulgaris species of microalgae was chosen for this research because it grows faster and produces more oil [174]. The wet algae biomass is collected off the open pond after it reached a substantial lipid content, dewatered to an a slurry and dried to make dry biomass [175]. The main byproducts are biomass seedcake and glycerol. In the research lab, Karanja oil, and microalgal oil were refined using simple purification techniques [93]. Surplus electricity for the operation of process plant would be supplied by India's main grid [175].

4.3 Life Cycle Inventory Analysis

Inventory requirements for Karanja harvesting, seed oil extraction, transesterification, and biodiesel consumption were derived from the existing literature [98,99,101,122,138]. Similarly, inventory data for various processes involved in biodiesel production from microalgae and its consumption was collected from the available literature [24,117,139–142].

Production of biodiesel includes various steps like farming trees of seeds containing oil, collection, and transportation of seeds, extraction of oil from dried seed, and conversion of oil into biodiesel through the transesterification process. The inventory for these processes is various types of materials and energy utilized to perform these operations. Inventory requirements biodiesel production from Karanja were derived from the existing literature [98,99,101,122,138]. Similarly, inventory data for various processes involved in biodiesel production from microalgae and its consumption was collected from the available literature [24,117,139–142]..

4.3.1 The Production System of Karanja

Production of biodiesel from Karanja feedstock includes farming of Karanja trees, collection and transportation of Karanja seeds, extraction of karanja oil from Karanja seeds and lastly converting the Karanja oil into biodiesel through the transesterification process.

4.3.1.1 Farming

The Madenur Biofuel Park, located in Karnataka's Hassan district, serves as an exemplary model for studying the production system used in cultivating biofuel crops. The intricate process begins with careful attention to detail in the nursery, where seedlings are raised in poly bags. This method gives them more control over their growth and development. The planting medium is critical, and a carefully prepared mixture of local compost and soil is used to provide the best conditions for the young seedlings.

Manual watering approach ensures that each plant gets enough moisture, promoting healthy root development and overall vigor. Plant pits were meticulously dug on wastelands and agricultural field bunds as the seedlings mature, taking into account the landscape and the specific requirements of the crop being grown.

The spacing of seedlings during transplantation is an important consideration that varies according to the nature of the field and the farming practices associated with the specific crop. The general practice is to plant seedlings 40 to 50 feet apart on bunds, which provides ample space for growth and efficient resource utilization. However, in the case of wastelands, degraded lands, or silvicultural land, where conditions may be more difficult, a higher planting density is used to maximize land productivity. In such cases, an impressive 300 to 330 seedlings per hectare can be accommodated, optimizing land use for biofuel production.

The Pongamia tree is notable for its exceptional hardiness and adaptability to a variety of soil types. This tenacity stems from its remarkable nitrogen-fixing abilities, which allow it to thrive in a wide range of environmental conditions. As a result, no inorganic or organic fertilizers are applied regularly throughout the tree's lifecycle. The ability of the Pongamia tree to naturally fix nitrogen in its root zone provides a self-sustaining source of essential nutrients, reducing the need for additional fertilization. However, during the early stages of seedling establishment, a small amount of farm yard manure, typically ranging from 2 to 3 kg per planting pit, is applied sparingly. This practice promotes the growth of young trees and aids in their successful establishment. The farmyard manure acts as a nutrient-rich supplement, giving the plants an extra boost during the critical early stages of development. Once the Pongamia plantation is established, any type of fertilizers are no longer required. The trees use their natural ability to fix nitrogen, ensuring a constant supply of this critical nutrient without the need for external intervention. The prevailing rainfall patterns in India's southern region facilitate tree growth and contribute to overall productivity.

Pongamia trees begin to produce seeds as they mature, marking an important step in the biofuel production process. Typically, the fifth year marks the start of seed production, which gradually increases with each passing year. Between the tenth and fifteenth years, the trees reach their peak yield, demonstrating their ability to provide a significant biomass feedstock for biofuel extraction. A ten-year-old Pongamia plantation can produce 3 to 5 tonnes of seeds per hectare on average. The tree's high productivity, combined with its longevity, strengthens its appeal as a sustainable biofuel crop. Pongamia trees live for more than 80 years, allowing for long-term cultivation and a consistent supply of biomass for biofuel production. Inventory for the farming process of Karanja trees is given in table 4.1 and 4.2.

Table 4.1: Inventory Requirement of Karanja Farming

Input		
Name of Item	**Required Amount**	**Reference**
Polybag	330.00 Numbers (4kg)	[97,100,101,176]
Diesel	140.00 litres	
Electricity	-	
Manpower	15 Man days	
Farm Yard Manure	600kg	
Water	32967L	

Table 4.2: Emissions by Diesel Combustion, Polybag Production, and Electricity Production

Item/ Material	Emission by			Unit	Reference
	Diesel (1Litre)	**Polybag Production (1 kg)**	**Electricity (1 kWh)**		
CO_2	2703.1	70.29	1.34	Gm	[177] [178] [179] [180] [97] [122] [3] [181]
CO	118	1.39	0	gm	
CH4	0.6	5.60E-03	0	gm	
NOx	75.5	0.71	0.001761	gm	
SOx	0	8.58E-02	0.000656	gm	
PM	3.05	8.58E-02	9.11E-05	gm	
VOC	0	0.19	7.76E-05	gm	

4.3.1.2 Transportation of Seeds

In the context of analysing the energy and other materials input in the transportation of seeds from the field to the biodiesel unit via an IC engine tractor trolley, consider a specific scenario in which Karanja seeds are transported 50 kilometers from the farming field to the oil extraction unit.

Transportation is critical to any biofuel production process's overall energy efficiency and environmental impact. We can assess the efficiency and identify potential areas for improvement by analyzing the energy and material inputs involved in this specific aspect.

A Tractor-Trolley of General Use having a Capacity: of 4 tons (4000 kg), Dimensions of length: of 3.5 meters, Width: of 1.8 meters, Height: of 1 meter of Steel frame with a wooden load bed with removable sideboards and a foldable tailgate was used. The tractor typically consumes 1 liter of diesel for every 4 kilometers of travel to carry the load of its maximum capacity. To transport 7.7 tonnes of Karanja seeds for 50 kilometers, it must complete two rounds of 50 kilometers each, for a total distance of 200 kilometers.

We can estimate the energy input for transporting Karanja seeds over a 50-kilometer distance by taking these factors into account and using relevant data and models. This analysis will provide valuable insights into the energy efficiency of the transportation process and aid in the identification of potential optimization strategies.

4.3.1.3 Extraction of Oil

A 1 ton oil expeller has been chosen for the purpose of energy calculation. Table 4.3 displays the movement of materials throughout the seed processing procedure for extracting oil and Table 4.4 depicts the outputs of extraction process. Pongamia seeds are not subjected to decortication and are instead immediately processed in oil expellers. Subsequently, the seeds were subjected to pressure in order to extract the oil. The oil expeller had a power output of 5 horsepower (equivalent to 3.73 kilowatts) and achieved an average oil expelling rate of 25 kilograms of seeds per hour. The oil yield from pressing one kilogram of Pongamia Pinnata seeds is 279 grams, and the remaining seed cake still contains residual oil after the extraction process. Subsequently, the seed cake underwent a process to remove the fat content. The yield of defatted seed cake from each kilogram of Pongamia Pinnata seeds is 690 grams. About 550 Karanja trees have been planted per hectare, resulting in a yield of roughly 7.7 tons of seeds as well as 1.8095 tons of oil [100].

Table 4.3: Input for Extraction Process

Item/ Material	Amount	Unit	Reference
Karanja Seeds	7700	kg	[100]
Electricity Time taken for 100kg seeds = 4 hr So, for 7700kg = 4*77= 308hr Energy Consumed = 308 * 3.73 = 1148.84 kWh≈ 1200kWh	1200	kWh	

Table 4.4: Output for Extraction Process

Item/ Material	Amount	Reference
Crude Oil	1809.5 kg/ha ≈1800kg	[100]
Seed Cake	5760.7 kg/ha	

4.3.1.4 Transesterification

In 1853, scientists Roudolf Diesel and J. Patrick conducted the transesterification of based on plant- oil, which occurred before the first diesel engine was operational by a few years. Rudolf Diesel's prototype, consisting of a 10 foot (3m) iron cylinder with a flywheel at its base, was first operated in Germany. This engine demonstrated Diesel's idea by use peanut oil, a biofuel, nevertheless it did not technically meet the criteria for biodiesel since it lacked transesterification. The employment of straight vegetable oils is limited due to several unfavorable physical qualities, including their viscosity. The increased viscosity of straight vegetable oil leads to inadequate fuel atomization, inefficient combustion, and the accumulation of carbon on the injector and valve seats, ultimately causing significant engine fouling. According to reports, the use of pure vegetable oil as fuel in direct injection engines results in the clogging of injectors after a few hours of operation. This leads to inadequate fuel atomization, less effective combustion, and the contamination of lubricating oil with partly burned vegetable oil. One potential approach to address the issue of increased viscosity is to combine vegetable oil with diesel in an appropriate ratio, while another option is to perform transesterification of oils to generate biodiesel [182].

Transesterification is a chemical process where a triglyceride (fat/oil) combines with an alcohol, employing alkaline, acidic, or lipase catalysts, to provide a biodiesel and glycerol as the form of a mono alkyl ester. However, the presence of strong acids or bases accelerates the conversion process. The process of transesterification, which is catalyzed by alkaline substances, is well recognized for its high speed and may be easily set up. Therefore, in this study, the oil extracted from Pongamia pinnata was treated with methyl alcohol by transesterification. This process was carried out using a batch-type transesterification reactor employing strong alkaline catalysts such as KOH or NaOH. The transesterification reaction, that has been widely used, is described here. This approach successfully reduces the increased thickness of triglycerides [183].

Variables involved in the Process

The key factors that significantly impact the duration and efficiency of the transesterification process are [184]:

I. Temperature of the reaction,

II. The proportion of the alcohol to oil,

III. The type and concentration of catalyst.

Temperature of the Reaction

The reaction rate is significantly affected by the temperature of the reaction. Nevertheless, with sufficient time, the reaction will progress towards almost complete conversion even under ambient conditions. Typically, the reaction is carried out at a temperature near the point of boiling of methanol (60 to 70°C) under normal atmospheric pressure. The optimal temperature range for achieving the highest amount of esters is between 60 and 75°C, with a molar ratio of 6:1. Any additional rise in temperature is known to negatively impact the conversion process [185].

The Proportion of the Alcohol to Oil

It is also a crucial factor in influencing the production of esters. The stoichiometry of the transesterification process necessitates a ratio of 3 moles of alcohol to 1 mole of triglyceride, resulting in the production of BD's 3 moles and glycerol's 1 mole. To promote the forward direction of the transesterification reaction, it is vital to employ a significant surplus of methanol. Previously, molar ratios of 4:1, 6:1, 8:1, 10:1, and 12:1 were utilized. It was observed that the 6:1 molar ratio resulted in the maximum conversion. However, it was found that the surplus alcohol could impede the separation of glycerol following the transesterification process [184].

The Type and Concentration of Catalyst

Alkali metal alkoxides outperform acidic catalysts in terms of transesterification efficiency. Sodium alkoxides are very excellent catalysts for this reason, although NaOH and KOH may also be utilized. Alkaline catalysts aren't as corrosive as acidic ones. Most commercial transesterification procedures employ alkaline catalysts. Previous study has indicated that catalyst concentrations between 0.5% and 1.0% by weight result in the highest conversion. Raising the catalyst concentration above this range will not improve the conversion rate [186].

Production of Biodiesel from Karanja Feedstock

Figure 4.3, depicts an illustration of the schematic diagram of the mixed process reactor. A supply container is connected to a stirrer (250rpm driven by a 180 w motor), a reciprocating pump (600psi maximum, 3hp, 950rpm, and 36 LPM), and an ultrasonic based reactor. A couple of piezoelectric transducers, which can operate at a frequency of 30 kHz and power of 400W are employed for allowing ultrasonic waves to penetrate the reaction mixture effectively. The liquid is returned to the reciprocating pump, where it is continuously circulated.[187]

5kg karanja oil is heated to 120°C for 5-7 minutes to remove water content in the oil before cooling to 60°C. Methyl alcohol (CH_3OH) and sodium hydroxide (NaOH) are combined and stirred until the sodium hydroxide is completely dissolved in the alcohol. This liquid mixture is then mixed with karanja oil and fed into the reactor's feed tank before the reactor is turned on. At regular intervals, a sufficient number of samples were gathered at the feed tank's bottom. Once the reaction was finished, the mixture was put into a separating funnel. The glycerol as well as methyl ester combination was left undisturbed for a period of 8-10 hours to allow for settling. Following the settling process, the raw glycerol and methyl esters were manually separated. The methyl ester was subsequently washed with heated water to eliminate any residual sodium hydroxide contaminant. Biodiesel was neutralized using phosphoric acid. Subsequently, the cleansed product underwent distillation to eliminate any remaining moisture, and the resulting high-quality biodiesel was submitted to chemical analysis.

Experiments were conducted with methanol-to-oil molar ratios of 9/1, 6/1, and 4.5/1, as well as catalyst concentrations of 1.5, 1, 0.75, and 0.5 %w/w oil. At 70% of maximum ultrasonic power irradiation, an optimal biodiesel yield of 96.8% was obtained for a 50-minute reaction time, a 6/1 molar ratio, and a 1% catalyst concentration. The catalyst (NaOH) and methanol amounts are 0.5kg and 1.104kg, respectively.

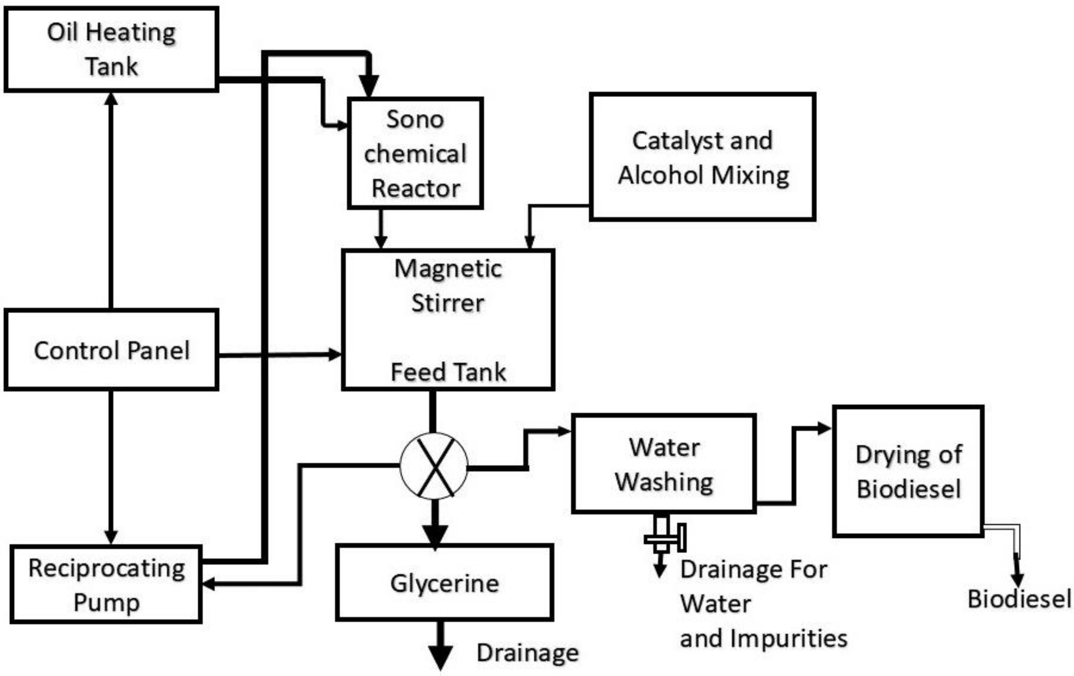

Figure 4.3: Block Diagram of Combined Ultrasonic Cavitation and Mechanical Stirrer Reactor

The input data on flow for the transesterification for soy oil was obtained from the ecoinvent database. For every kg of soybean oil, the following quantities are needed: 0.0009 kg of NaOH, 0.09 kg of CH_3OH, 0.044 kg of HCl, 0.0006 kg of phosphoric acid, 0.023 kg of sodium methoxide, 0.036 kWh of electricity, and 0.88 MJ of heat energy from Natural gas. According to the ecoinvent database, the anticipated conversion efficiency from crude oil to biodiesel is 90%.

As already estimated that one hectare of land can yield 1809.5 kg of karanja vegetable oil in total. The amount of biodiesel produced is 90% 0f 1809.5 kg, or 1.628 kg. Hence, one-hectare can generate up to 1.62855 tons (1628kg= 1628/0.88≈ 1850L) of biodiesel.

4.3.2 Production System Microalgae

Algae is a phrase used to describe a vast collection of photosynthetic organisms that live in water and do not possess the real roots, stalks, and leaves seen in higher plants. Production of biodiesel includes cultivation or farming of microalgae of some specific species in water, extraction of oil from the dried microalgae, and lastly the transesterification of the microalgae oil. There are several species of microalgae grown throughout the world. In this study microalgae strain of Chlorella Vulgaris has been considered. As discussed in an earlier section, the production system of microalgae includes cultivation, transportation, extraction of vegetable oil and transesterification [107,188,189].

4.3.2.1 Cultivation

Microalgae cultivation entails microbe inoculation, flocculation, and drying of the microalgae. Freshwater or waters with widely varying temperatures, pH, and salinity, including hyper-salinity, can be used to grow microalgae. In cultivation, microbes are added to a body of water known as a pond, and a mixing arrangement is created to ensure that the microbes are evenly distributed throughout the water. Previously, an open pond system was used to cultivate microalgae, but other methods of large-scale microalgae production were introduced. Open ponds/raceway ponds, closed photobioreactors, and hybrid systems are now the most common production systems. Raceway ponds are the most prevalent kind of open ponds, characterized by their many forms and sizes [188]. The structure is a closed loop rectangular grid with a recirculation channel. They usually function at water depths ranging from 15 to 20 cm due to the fact that these depths allow for biomass concentrations of 1 g dry weight per litre and productivities of 60 to 100 mg per liter per day [190]. A paddle wheel is used to mix and circulate the algal biomass driven with a 0.5hp electric motor. Baffles are used to direct the flow around curves in the flow channel. Raceway channels are fabricated from either concrete or compressed earth, and may exhibit variations in both length and diameter. These channels are often coated with white plastic on the inside. Throughout the day, the culture is continuously nourished in front of the paddlewheel, wherever the current originates. After the circulation loop is finished, the broth is collected behind the paddlewheel. In order to avoid sedimentation, the paddlewheel operates continually. An inherent drawback of open systems is their susceptibility to water loss via evaporation, which occurs at a similar rate as land crops. Additionally, these systems are prone to contamination by undesired species because to their exposure to the atmosphere. Typically, open ponds are mostly occupied by a few number of species, ranging from two to six, which possess several evolutionary benefits like fast development, predator resistance, and high tolerance to elevated amounts of dissolved oxygen [191].

Photobioreactors are superfluous in a nation such as India due to its tropical environment, specifically located 37° over the equator. India's plains and coastal locations are suitable for cultivating microalgae. The raceway pond method for cultivating biomass must be authorized in order to get elevated and consistent rates of growth and oil production, which are necessary for the development of a business focused on biofuels derived from algae. During the study, wastewater is considered as an operational input because to its nitrogen and phosphorus content, which serve as nutrients for the growth of microalgae [192,193]. A schematic diagram of open raceway pond for microalgae cultivation is shown in figure 4.4.

The productivity of chlorella vulgaris is measured at 2.05g/L [194]. Hence to produce a biomass of 2kg pond size should be enough to hold a volume of water 1000L i.e. one cubic metre. Hence to fulfil the requirement of the capacity size of the raceway pond is taken as 10m*2m*0.20m= 4m^3 having a capacity of 4000Lwater. A 0.5-horsepower engine was used to connect a paddle to the pond in order to mix the culture. The pond was fed with water from the nearby water supply via a pipeline. The pond had been filled with water and the necessary quantities of fertilizers were added. The mixture was then consistently agitated for 1 hour using a motor-driven paddle. A total of 40 liters of mature Chlorella culture was subsequently introduced into the pond. The mixture was stirred vigorously with a paddle to prevent the accumulation of algae. The water loss resulting from spillage and evaporation was offset by the addition of new water each morning.

Microalgal culture may be used with wastewater treatment facilities to effectively utilize nutrients such as nitrates and phosphates derived from wastewater from cities and waste from agriculture. An additional need for promoting the development of microalgae is to provide CO_2, which may be fulfilled by using the residual biomass's anaerobic digestion post oil extraction [175].

Following the significant transfer and growth of biomass, the ponds underwent frequent monitoring for pH, the temperature, or cell density. After reaching the desired state, a significant amount of biomass was collected by passing it through a filter with a particle size of 50 µm. The collected biomass was then kept at a temperature of 25°C [195]. After twenty-one days the biomass productivity was 2.03 g/L/day [194,196].

In addition, several species of microalgae, including Chlorella vulgaris, are being identified as bio-flocculants, meaning they may clump together sans the need for any external flocculating agent. Following cultivation, the biomass was separated from the media using the sedimentation technique. Sun drying is a reasonable process due to its availability; however, certain disadvantages include the need for extended time, a larger surface area for drying, and the possibility of contamination as well as material loss [28,107].

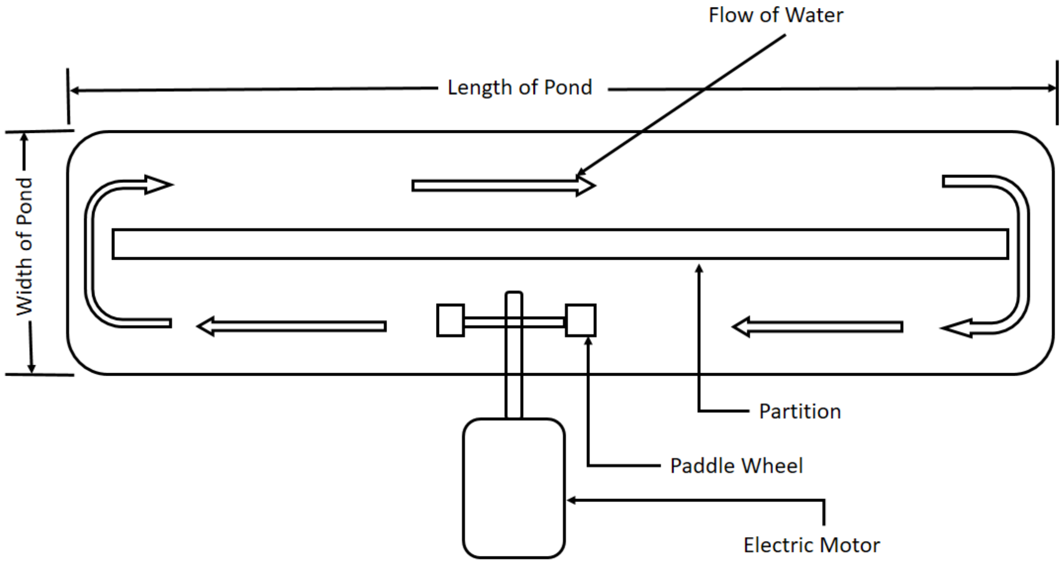

Figure 4.4: Line Diagram of a Raceway Pond for Microalgae Cultivation

4.3.2.2 Transportation

The distance and tractor trolley for transportation of microalgae biomass from the cultivation site to the biodiesel production unit was assumed.

4.3.2.3 Extraction

According to previous research sans enzymatic hydrolysis, the lipid’s yield in case of bead-milled biomass in the Chlorella vulgaris genus was found to be 75%; however, these results were greatly enhanced by the application of enzyme treatments. Following the bead-milled biomass’s enzymatic hydrolysis through lipase at pH 7.4 ad 37 °C for 24 hours, the highest recovery yield for all components was reached, producing 88% lipids in the solid phase [197]. Algae oil pressing machines with 5.5kW power and a capacity of 80 to 100 kg per hour of dry algae biomass are available.

4.3.2.4 Transesterification

The experimental setup for the transesterification of microalgae was the same as the Karanja Oil transesterification and the inventory is given in the table.

4.4 Use Phase

Following the production phase, the use phase of LCA is critical because emissions are assessed when the product is used in the real world. The current work describes the environmental impact of biodiesel combustion in an IC engine. In a single-cylinder diesel engine, 1000L of biodiesel combustion produced from both feedstocks, Karanja and microalgae, is evaluated.

4.5 Results and Discussion

4.5.1 Life Cycle Impact Assessment

This section summarises the contribution of environmental consequences and energy estimates from farming to use as biodiesel in IC engines of the Karanja and Microalgae biofuel. The life cycle effect of these feedstocks was calculated using the emission of GHGs and lifecycle-based energy calculation. A sensitivity assessment is conducted to analyse the feedstock's life cycle by estimating the outcome dependence on a certain control factor.

4.5.1.1 Global Warming Potential

In the process of obtaining biodiesel from both the feedstock i.e. Karanja and Microalgae, consumption GHGs are emitted during various stages of their respective life cycles, including farming, haulage to the mill, extraction of oil, biodiesel conveyance, and finally, its burning in a diesel engine. Table 4.5 shows GHG emissions from biodiesel production as well as the consumption of biodiesel from both of the feedstocks. The major contribution of GHGs is from the cultivation, transportation, Oil extraction, and Biodiesel production for both the feedstock i.e. Karanja, and microalgae. GHG emissions for cultivation, transportation, Oil extraction, and Biodiesel production are 0.33, 0.09, 0.87, and 1.95 kgCO_2 eq for the production of 1 L biodiesel from Karanja feedstock. These four processes contribute 9.7, 3.0, 25.7 and 57.5% of GHGs. Out of these 57.5% of emissions are due the transesterification only. It is due to the burning of fossil diesel production of methanol and electricity use. Further Pongamia trees of standing biomass of wasteland are capable of sequestration of a part of CO_2 at the rate of 0.5 to 1 t per hectare per year while the Pongamia feedstock system releases about 1.5 t ha^{-1}, which is helpful to mitigate the GHGs emission [176]. In the extraction process, the emission is due to the use of electricity, and the decortication operation (removing the fruit shells to drive the oil seeds) was not needed in the case of Karanja, the power demand in fruit breaking is assumed to be zero [101,138]. Metal production and electricity use in transesterification are the main contributors to the production phase. The co-products (glycerol and seed cake) equivalent CO_2 emissions from of the biodiesel system were calculated [132]. In the case of microalgae, emission values are 10.02, 1.59, 4.8, and 1.95 kgCO_2eq for cultivation, transportation, and biodiesel production processes. Only the cultivation part is responsible for 54.1% of emissions while oil extraction and biodiesel production contribute 25.9% and 10.5%. According to another research, the responsibility of algae culture and slurry drying accounts for more than 84% of overall effect. The electrical power need and the fabrication of the building materials for the two-stage airlift tubular photobioreactor as well as the raceway pond constitute input elements that substantially contribute to the total environmental load [198]. A large amount of electricity was used for microalgae biodiesel production. Nearly half of all GHG emissions were caused by electricity use in various stages like farming, reaping, and biodiesel production. It was observed by Adesanya (2014) [175] that the cultivation stage's electricity demand accounts for 62% of the total GWP [175]. Further, the contribution of transportation will be further reduced if the vehicle uses biodiesel by replacing conventional fossil diesel because CO_2 emissions can be reduced by up to 78% if engines run on 100% biodiesel (B100) [101].

Figure 4.5 depicts the GHGs emissions from Karanja and microalgae graphically. Karanja was found to emit fewer GHGs than microalgae. Almost half of all GHG emissions were caused by electric power use in varying phases like farming, transportation, oil extraction, and biodiesel production. GHG emissions from Karanja cultivation were estimated to be 3.39 kgCO_2Eq/MJ, which is low compared to microalgae cultivation, which produced 18.51 kgCO_2Eq/MJ.

Table 4.5: GHG Emissions during Biodiesel Production

Cradle to grave GHG Emissions ($kgCO_2eq/L$)						
Feedstock	**Cultivation**	**Transportation**	**Oil Extraction**	**Transesterification**	**Biodiesel Consumption**	**Reference**
Karenja	0.33	0.0908	0.87	1.95	0.15	[20] [56] [29] [70] [75] [77]
Activity wise contribution	9.7%	3.02%	25.7%	57.6%	4.4%	
Microalgae	4.53	1.59	4.80	1.95	0.15	
Activity wise contribution	54.1 %	8.5%	25.9%	10.5%	1.1%	

Figure 4.5 also shows the results of GHG emissions at each phase, from farming to biodiesel commuting and consumption of each feedstock. The well-to-wheel GHG emissions for biodiesel from Karanja as a feedstock were estimated as 3.39 $kgCO_2$ eq/L, while that for microalgae feedstock was 18.51 $kgCO_2eq/L$. Hence biodiesel production from microalgae costs around 81% higher in terms of GHG emissions.

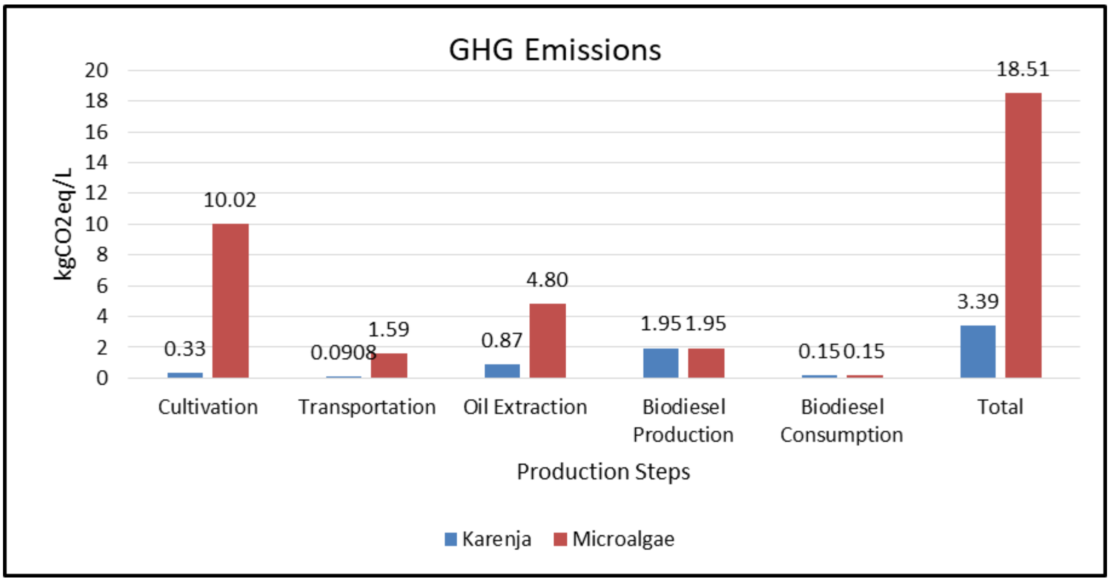

Figure 4.5: GHG Emissions

4.5.1.2 Life Cycle Energy

The two parameters used to calculate energy balance during the life cycle of biodiesel were Net Energy Value (NEV) and Energy Ratio (ER). The analysis outcomes are shown in Table 4.6 and Table 4.7. Energy balance during the life cycle is a decisive unit that ultimately decides a whole system's net energy and evaluates the industrial viability of all stages of the LCA. NEV is the balance energy obtained by subtracting the input energy used for various stages of biodiesel production from the energy output obtained from biodiesel, glycerine, and seed cake.

Energy is required for processes such as seed cultivation, transportation, oil extraction, and transesterification in the production of Karanja or microalgae biodiesel. In the case of Karanja, the highest part of the total energy is required for transesterification as the electrical energy used is more in this step. Further Methanol production and use consume the greatest part of energy during the esterification phase. A major part of the total energy is required for seed cultivation, followed by trans-esterification and oil extraction. Karanja biodiesel requires more diesel fuel for land plowing as well as fertilizers to increase seed yield [98]. Energy in the form of manpower, fossil diesel, polybag usage, and electricity is supplied in the cultivation and oil extraction phase. The extraction phase also consumes a sufficient part of energy because of the electrical energy consumed during the process. The transportation phase consumes the least energy. The energy consumed in transportation is calculated for the burning of diesel fuel, which depends on the distance travelled for seeds or algal broth cultivation sites to the extracting unit [176]. All of these processes are included in the system boundary of the life cycle energy balance: microalgae cultivation, biomass harvesting and drying, lipid extraction, and transesterification. As a result, the total energy required for microalgae cultivation, biomass harvesting and drying, lipid extraction, and transesterification. In the case of microalgae, the highest part of the energy is consumed in the extraction step due to the low yield comparatively. This means a high amount of biomass has to be processed to produce 1 litre of biodiesel from microalgae. However, it can be different for different production methods. A significant amount of energy also consumed in cultivation phase of microalgae because the high amount of energy is consume in paddle wheel operation. required for The total energy produced is calculated by taking into account the energy content of biodiesel and coproducts [193]. Energy output constitutes the Calorific value of biodiesel produced and seedcake and glycerol as coproduced The coproduct glycerine is produced as a coproduct during transesterification and seed cake is produced during the extraction process, the energy value for the coproducts is calculated as the calorific values of seed cake/deoiled cake and glycerine [102,105,199,200].

Table 4.6: Energy Requirement for Biodiesel Production

Energy Requirement for Biodiesel Production (GJ/L)						
Feedstock	**Cultivation**	**Transportation**	**Extraction**	**Transesterification**	**Total**	**Reference**
Karanja	3.01	0.99	2.33	7.39	13.73	[101], [176]
Microalgae	61.59	20.3	103.32	7.39	192.61	[133] [175]

Table 4.7: Life Cycle Energy Estimation

Life Cycle Energy Estimation					
Feedstock	**Input (GJ/L)**	**Output(GJ/L)**	**NEV(GJ/L)**	**ER**	**Reference**
Karanja	13.73	77.84	64.1	5.67	[101] [176]
Microalgae	192.6	478.79	286.19	2.49	[133] [175]

The energy input for 1 litre biodiesel is estimated at 13.73GJ and output was estimated as 77.84GJ for Karanja feedstock whereas for microalgae input energy is

192.6GJ and output energy is 478,79GJ. It was discovered that Karanja had lower NEV values than microalgae as feedstock. However, it is due to the energy of coproducts of deoiled cake of microalgae which is very high in amount. According to this, a substantial quantity of energy was spent during each stage of Microalgae LCA for yield, and extraction of oil. The energy ratio for microalgae was 2.49 compared to 5.69 for Karanja. In other words, Karanja can generate a higher output of energy output with a lower input of energy. The eccentricities in ER and NEV values for all three generations are depicted in Figure 4.6.

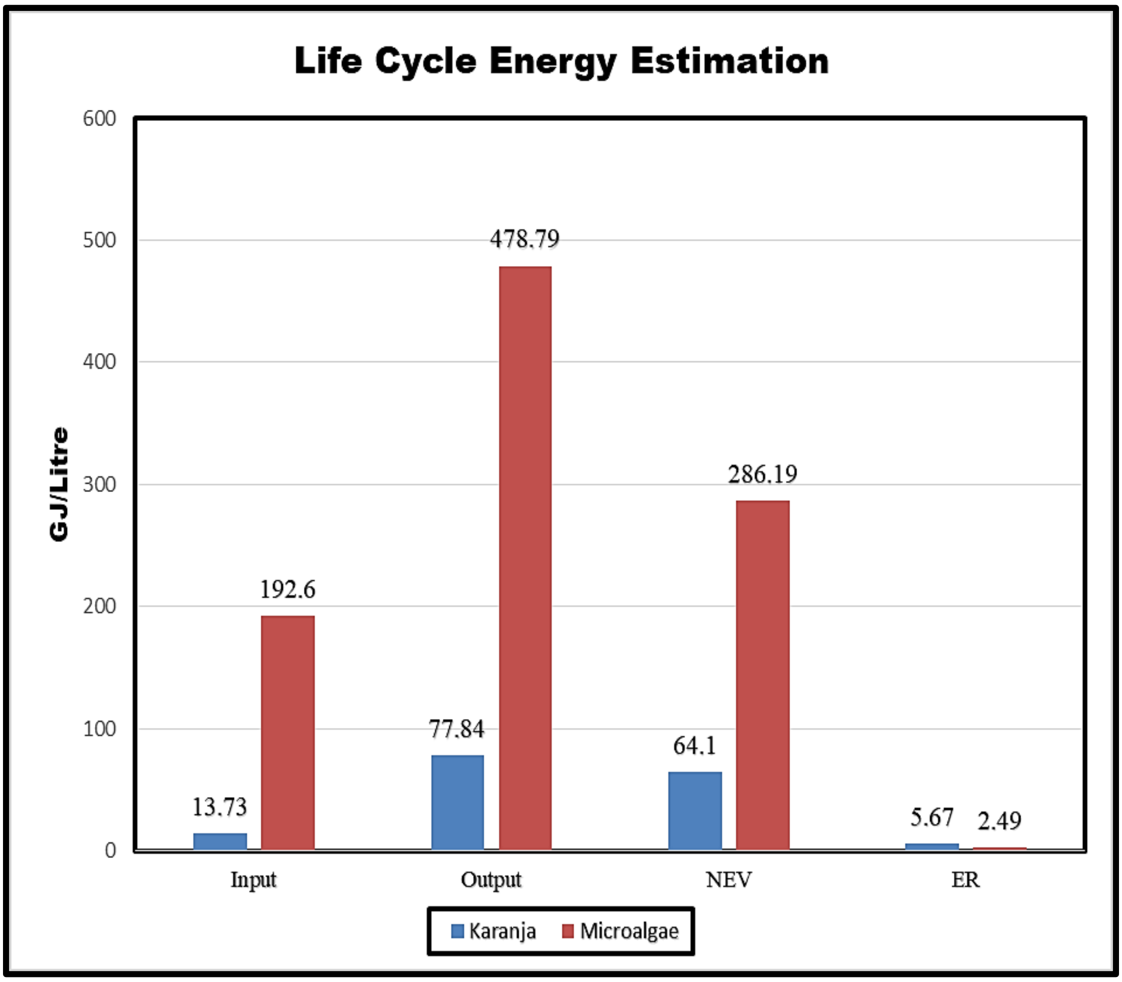

Figure 4.6: Life Cycle Energy Estimation

4.5.2 Sensitivity Analysis

Sensitivity analysis is commonly used in LCA for energy ratio to evaluate the impact and degree of each procedure. In the sensitivity analysis, the input parameters have been supplied with two variations, +10 percent and -10%, as well as another entity with no variation.

4.5.2.1 Sensitivity Analysis for Karanja

LCA sensitivity analysis was performed with a 10% sensitivity range, and the outcomes for ER and GWP change are shown in Table 4.8. Five parameters are selected for their influence on the Energy Ratio due to the variation of the values in these parameters. These parameters are Biodiesel Yield, Oil Yield, Seed Yield, Energy Consumption in Seed processing, and Energy Consumption in Oil processing. The variation in ER for the Seed Yield of Karanja seeds was greater, according to Table 4.8, because the amount of energy output is dependent on the weight of seed production. Variations in energy ratio due to the variation of parameters, Biodiesel yield (-6.6 to 6.6%), Energy Consumption in Oil processing (5.71 to 6.42%), and consumption in Seed processing (3.8 to 4.04%) were also significant after Seed Yield. The variation of ER recorded for oil yield was low i.e. 1.7 to 1.9% because the biomass was utilized for further energy extraction [98,100].

The sensitivity study estimated the change in global warming potential by affecting a +10% variation in the data of the concerned control factors by changing the level of every single parameter each time. The parameters diesel consumption, CO2 captivation ability, seed’s gross energy value, energy input in seed cultivation, and seed yield were chosen for this sensitivity analysis. Because carbon emissions are highest during the cultivation phase, seed yield (11.41 to 8.46%) was the most sensitive [98].

4.5.2.2 Sensitivity Analysis for Microalgae

Table 4.8 depicts the outcomes of sensitivity analysis for microalgae feedstock with a 10% sensitivity for energy ratio. The parameters used for sensitivity analysis of energy ratio are lipid content, growth rate, CED (Cumulative Energy Demand) in Heat Production, CED in Electricity Production, and CED in Fertilizer Production parameters. Sensitivity variations for lipid content are highest (+10 %) followed by growth rate ((+7%). This variation is due to the more lipid obtained with less amount of energy expense [105]. Because of the high electricity consumption, the variation in energy ratio (2.8 to -2.7%) was greatest for Cumulative Energy Demand in Heat Production. CED in Electricity Production and CED in Fertilizer Production was estimated as 0.8 to -0.9% and 0.7 to -0.8%, a low variation [201].

Table 4.8 list the outcome of sensitivity analysis in case of microalgae feedstock with a 10% sensitivity for global warming potential. The growth rate, transportation distance, oil content, and water recycling rate parameters were chosen for this sensitivity analysis. The growth rate was discovered to be the most sensitive parameter, varying from 5 to 7 percent for a 10% change, followed by Oil Content (2.6 to 3.5 percent) [105]. Water Recycling Rate (2.0 to -2.0%), and Transportation Distance (1 to 1.5%) were also found significant variations. This is because higher growth results in less fossil fuel used during cultivation and a higher rate of sequestration [30].

Table 4.8: Sensitivity Analysis for Energy Ratio and GWP

Feedstock	Factor	Parameter	Variation, %	Energy Ratio Change, %	Reference
Karanja	Energy ratio	Biodiesel Yield	-10	-6.60	[98]
			10	6.60	
		Oil Yield	-10	-1.7	[100]
			10	1.9	
		Seed Yield	-10	-23.2	
			10	32.9	
		Energy Consumption in Seed processing	-10	4.04	[98]
			10	-3.8	
		Energy Consumption in Oil Processing	-10	6.42	
			10	-5.71	
	GWP	Diesel Consumption	-10	-2.57	[98]
			10	2.62	
		CO_2 Captivation Ability	-10	7.54	
			10	-7.98	
		Gross Energy Value of Seeds	-10	10.26	
			10	-7.75	
		Energy Input in Seed Cultivation	-10	1.74	
			10	-2.29	
		Seed Yield	-10	+11.41	
			10	−8.46	
Microalgae	Energy ratio	Lipid Content	-10	10	[105]
			10	-10	
		Growth Rate	-10	7	
			10	-7	
		CED in Heat Production	-10	2.8	[201]
			10	-2.7	
		CED in Electricity Production	-10	0.8	
			10	-0.9	
		CED in Fertilizer Production	-10	0.7	
			10	-0.8	
	GWP	Growth Rate	-10	-7	[105]
			10	5	
		Oil Content	-10	2.6	
			10	3.5	
		Water Recycling Rate	-10	2.0	[122]
			10	-2.0	
		Transportation Distance	-10	-1	
			10	1.5	
		Growth Rate	-10	-7	
			10	5	

4.6 Summary

The following are the main results:

- The LCA of alternative fuel, biodiesel production from Karanja, and microalgae has been successfully carried out.
- It is found that the vegetable oils can be successfully converted into biodiesel and the net energy ratio is suitable for the use of vegetable oils, and also for microalgae considering that it doesn't require any land and can be grown on water bodies only.
- The energy ratio of Karanja feedstock 5.67, and the energy ratio of microalgae estimated to be 2.49. This high energy ratio, with a sensitivity of 10%, have positive impact in mitigating the GHG emissions.
- Vegetable oils remained the promising candidate with the lowest GHG emissions values among all processes that emit GHGs. Karanja had less NEV values (NEV: 64.1), whereas microalgae consumed more energy (and NEV: 286.19) while producing a higher yield.
- According to the outcomes of the sensitivity analysis, both emission and energy values are greatly sensitive to biodiesel yield, seed yield, and oil content. The higher yield has the potential to reduce GHG emissions. Different feedstock, however, has contradictory environmental performances.
- Karanja demonstrated effective LCA results compared to microalgae feedstock when data from two feedstocks were compared in terms of GHG emission and life cycle energy balance.

CHAPTER 5
LIFECYCLE ANALYSIS OF IC ENGINE

5.1 Introduction

As the heart of an automobile, the ICEs uses a significant amount of natural resources and produces complicated, precise parts, which have an impact on the environment. The study discovered that the utilisation of recyclable materials in automobile brake systems resulted in reduced air emissions, solid waste, and water emissions, hence offering environmental benefits. However, there is still a lack of ecological assessment of diesel engine parts in India. Previous studies have mostly examined engine fuel and specific parts, leaving decision-makers and Indian authorities without enough information to establish industry standards. The automotive sector mostly uses fossil fuels, such as coal, oil, and natural gas, all of which produce significant amounts of GHGs and have a disastrous impact on climate change [2,204].

To understand the environmental implications and benefits of traditional transportation, it is necessary to investigate the manufacturing processes, usage patterns, and recycling mechanisms of ICEs [205]. This comprehensive analysis may be aided by applying the LCA to the IC Engine.

The LCA of IC Engines is a critical aid in decision-making processes involving the selection of the most appropriate mode of transportation. This is because LCA reveals not only the nature but also the quantity of harmful substances released by these products, whether during the manufacturing phase or consumption[115]. As done in the previous chapter the environmental impacts of ICEs were assessed using the ISO-14040

(International Organisation for Standardisation, 2004) procedure and recommendations, which included four major steps: goal and scope definition, inventory analysis, impact assessment, and result interpretation [147].

5.2 Goal and Scope Determination

The Goal and scope of the present work are intended to thoroughly evaluate and enumerate major environmental influences related to life cycle of diesel engines in India. The analysis covers the diesel engine's life cycle, including key stages, like transportation of raw materials, extraction of raw materials, component production, engine employment, and end-of-life disposal. The major components of the diesel engine are the cylinder head, cylinder block, connection rod, crankshaft, flywheel housing, timing gearbox, and flywheel collectively known as the "seven pieces." These critical components are produced at an engine manufacturing facility in Ghaziabad, India [112]. Data and information from reputable sources, such as the Ecoinvent database and existing literature, are used throughout the LCA process to estimate energy usage and emissions at each stage of the diesel engine's life cycle. Moreover, the research categorizes petroleum, coal, and gas from natural sources as three non-renewable resources that are crucial for meeting the fundamental energy requirements of the engine's life cycle [115].

The primary objective of this research is to give a complete knowledge of the environmental consequences suffered through the diesel engine's entire lifecycle. It hopes to accomplish this by providing critical environmental impact data to decision-makers in the diesel engine manufacturing industry. It also aims to encourage collaboration with relevant Indian government agencies and to promote the widespread adoption of Life Cycle Assessment (LCA) practices within engine associations. The study aims to drive sustainability practices and reduce the overall environmental footprint of diesel engines in India through these efforts, contributing to a more environmentally conscious and responsible future for the industry.

5.2.1 Functional Unit

Various author assumes that an engine is supposed to be fitted with a car or vehicle then the distance travelled decides the life of a car and hence the life of the engine to end with this vehicle. The lifetime of a passenger car is generally taken as 150000km and this distance is taken as the functional unit of LCA [55,85,206–209]. But present work focuses only on engine manufacturing, operation, and disposal. Also, engine is assumed stationary at the time of operation and used for irrigation purposes. So the functional unit of this LCA is taken as "One Diesel Engine" following the study of Liu et al., 2013 [112].

5.2.2 System Boundary

In this LCA the "Cradle to Grave" approach was selected in which the following phases of the system were considered for analysis:

- The production of engine
- The operational phase of the Engine
- Disposal of Engine
- Production of Diesel
- Production of Biodiesel

Figure 5.1 depicts the system boundary of the IC Engine under consideration of this study.

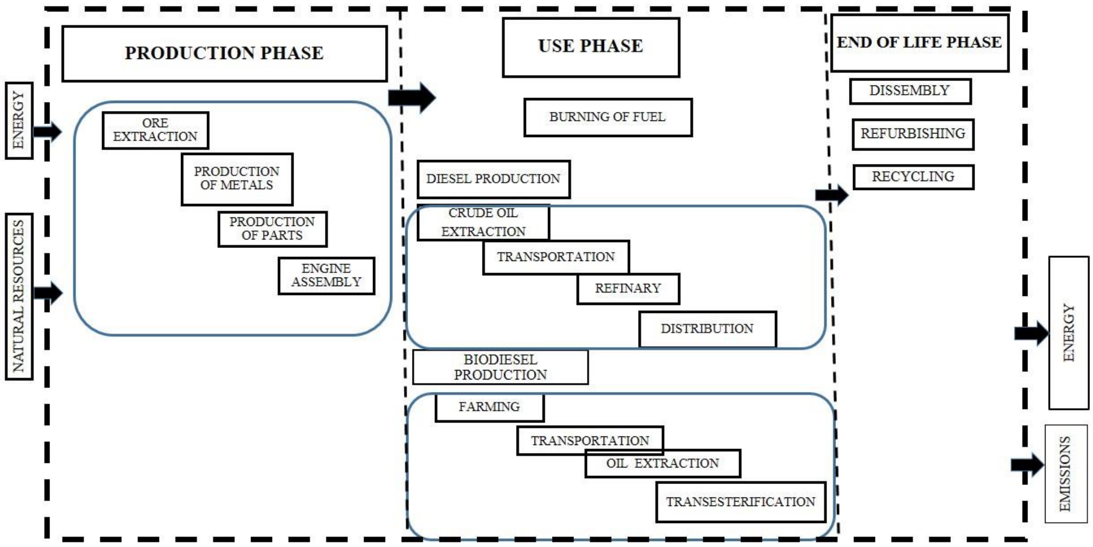

Figure 5.1: System Boundary of IC Engine

5.2.3 Environmental Impact (Impact Categories)

The impact groups for the measurement of environmental impacts (LCIA) are provided by ISO 14040. To make sure that we included most of the key common effects of the dispersion of IC Engine in the automobiles [147]. Major impacts on the environments have already been discussed in previous chapter. Five impact categories were considered for impact assessment: Climate Change (CC), Terrestrial Acidification (TA), Fine particulate matter formation (FPMF), Photochemical Ozone Formation (POF), and Fossil resource scarcity. Similar to how GHGs are the main source of temperature rise or global warming, these impacts are the main driver of environmental changes. Thus, middle level indicators are what these indicators are known as. Only certain environmental problems, such eutrophication, acidification, and climate change, are addressed by midpoint indicators. Endpoint values, on the other hand, show how the environment affects human well-being, ecosystems, and resource scarcity on three larger levels.[85,112,146]

5.3 Life Cycle Inventory Analysis

Life cycle inventory is the important phase of LCA. In this phase, the list of all input and output is prepared. All the items, raw material, energy resources and natural resources required in the whole life from its production to the disposal of the product lies in the input category. While the items produced during the whole life are categorized as output. The life of IC Engine can be divided into three major periods for the life cycle perspective according to the cradle-to-grave concept of ISO 14040/14044 [42,210].

The first stage is known as the manufacturing/production phase, and it begins with the extraction of raw materials and ends with the final construction of the engine, prepared for operation. The second phase is the use phase where the engine consumes fuel and generates mechanical energy for useful work. As the service life of the engine ends due to the deterioration of parts and vintage, the operation of the engine is not beneficial in terms of load, fuel consumption, and environmental emissions, the engine is disposed of at this stage which is called End of Life phase or disposal phase. Ecoinvent and Greet database and literature of reputed journals are used for data requirements [178,211–213]. The main outcome of this phase is the cataloguing of different environmental emissions like GHGs which are used in subsequent phases i.e. LCIA and interpretation as a groundwork. In this work, all three phases of the engine are studied and given below.

5.3.1 Manufacturing Phase of IC Engine

There are huge number of parts made of different materials including metal and non-metal in an IC Engine. These materials are produced from the particular type of ore which are extracted from the mines and passed through various conversion and refining processes. Further to obtain the required type of material with the requisite properties to withstand the forces produced in engine operation, various alloying elements are added. These materials are converted into specific parts of different shapes and sizes with adequate strength as per the design norms using different manufacturing processes.

The required materials to manufacture the parts of an assembly are generally compiled in the form of a Bill of Material for that particular product here which is the IC Engine. A variety of materials is used to manufacture these parts including steel, cast iron, aluminium, copper, plastic, etc. It is impractical to consider all parts of the IC Engine for LCA. So major parts are considered for this LCA and there are seven major parts of the IC Engine which include the Cylinder, Cylinder head, Piston, Crankshaft, and flywheel, which constitute over 98% weight of the total weight of the engine [112]. In the selected engine it was found that steel, aluminium, cast iron, and alloy are mainly used to produce these parts and weighed about 267.00kg which is about 97.6% of the total weight of the engine materials (260.5 kg).

Other components, like rubber and a tiny quantity of polymeric substances, are omitted since the resources and energy used in creating these materials may be believed to be minimal or the emission outcomes can be included with a reasonable proportion.

Smith and Keoleian, (2004) conducted a thorough investigation into the energy consumption associated with the production of diesel engines within an engine manufacturing plant. Their findings revealed that the total energy consumption for manufacturing a diesel engine, including materials procurement, part production, and assembly, was 11,600 MJ [113].

A more practical approach was adopted in another study to evaluate the energy consumption and hence the environmental emission by considering the manufacturing of only critical components. The critical components considered were the Cylinder head, Cylinder block, Connection rod, Crankshaft, Gearbox, as well as Flywheel shell, which are referred to collectively as the "seven pieces." This estimate is carefully carried out by calculating the realistic power needs of every piece of equipment based on its machining time. Furthermore, the energy is used in the manufacture and assembly of other necessary accessories such as bolts, belt pulleys, and water pumps. The research relies on the concept of "experienced specific energy" derived from various manufacturing processes to estimate these energy expenditures [214].

In the present work, it was assumed that the parts of the engine under consideration were produced in Ghaziabad, Delhi National Capital Region (India) and the engine parts are also completed within this plant. For the manufacturing of the IC engine, recyclable materials are also used, but the percentage of recycled material in each material category is unclear, and it also varies over time depending on scrap supplies. As a result, no recycled material is taken into account in the model; instead, only the usage of primary or virgin material was modeled for the baseline. EcoInvent is a database that is commonly used for data requirements in LCA and contains data on the number of materials that constitute each of the parts of an ICE. Due to the lack of India-specific Ecoinvent data, the total weight of each material component was calculated using the worldwide average value. As the EcoInvent database lacks information on the transmission of combustion vehicles, data about the transmission of internal combustion engine vehicles (ICEVs) was gathered from Sullivan, Kelly, & Elgowainy (2018) [215].

The data on embodied energy was acquired from the Indian Construction Materials Database of Embodied Energy and Global Warming Potential, which was released by the *International Finance Corporation of the World Bank* in 2017. This database contains information on the carbon dioxide equivalent emissions that are generated during the manufacturing process of materials including steel, aluminium, and glass [216]. In this research, it was assumed that both the materials and the engine were produced in India. The energy and GHGs emissions associated with the materials were calculated by multiplying the amount of each substance in each component. This aligns with the Make in India program of the Government of India (NITI Aayog and Rocky Mountain Institute, 2017) [217]. Furthermore, the data was acquired from several study publications published in esteemed journals. EcoInvent incorporates the quantity of electrical energy used in the extraction and creation of materials, as well as the components of the engine, and the subsequent assembly of these components to create internal combustion engines.

To determine the amount of GHGs emissions associated with the energy utilized in the automobile manufacturing process, the amount of electrical energy has been multiplied by the carbon footprint of the grid for each year and scenario.

The production steps for the IC Engine are outlined as follows:

- Extraction of Ore
- Refining of Materials
- Production of Material
- Transportation of Material
- Production of Engine Parts
- Engine Assembly

The flow chart of production steps of the IC Engine are shown as in figure 5.2.

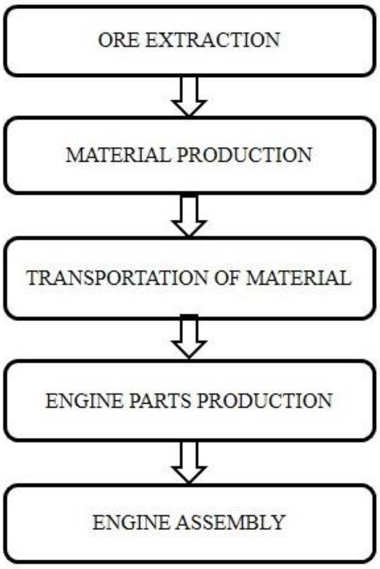

Figure 5.2: Main Steps in IC Engine Production

5.3.1.1 Extraction and Refining of Materials Production

On dismantling the IC engine and further counterchecking from the literature it can be concluded that most of the parts are made of mainly three materials i.e., cast iron, steel, and aluminium [213,218]. Hence the material production part of this study is limited to the production of these materials only. The study focused on the extraction of iron ore for the manufacturing of steel and cast iron, as well as the evaluation of bauxite mining for aluminium production.

Iron Ore Mining

Iron ore is abundant in India. Major iron ore deposits are found in the Precambrian Volcano Sedimentary Braded Iron Formation. The common types of ores are hematite and magnetite, and the total supply of iron ore in 2010 was 28.52 billion tonnes. In India, iron ore mining is divided into five zones: A, B, C, D and E. Zone A includes the Bonai iron ore range in Jharkhand, Orissa, and neighboring areas in eastern India. Zone B includes Chattisgarh, Madhya Pradesh, and Maharashtra's Bailadila, Dallirajhra, Mahamaya, Aridongri, Rowghat, and Surajgarh. Zone C is located in Karnataka's Bellary-Hospet region and contains Hemetite with minor amounts of magnetite, martite, specularite, and goethite, as well as quartz and clay as major impurities. Zone D is the region of Goa and west Maharashtra that contains limonite and clay with branded ferruginous quartzite and phyllite. Zone E is the area of Kudermukh, Bababudan hills, and Kodachari in Karnataka, where thick bands and lenses of hematite and magnetite are extracted, with quartz as the major gangue [219].

There are several methods used in the extraction of iron ores, including, open-pit mining, underground mining, and Drilling integrated with blasting. In the open-pit mining method, rock or minerals are extracted from an open pit or surface quarry. In the case of iron ore, the method involves the removal of overlying soil and rock to expose the ore. Underground mining is used when the iron ore deposit is located deep underground. In this method, tunnels are dug into the earth and the ore is extracted through underground mining. Lastly drilling and blasting method involves drilling holes into the rock and using explosives to break up the rock and extract the ore.

Iron ore obtained from the above methods is separated from other minerals in the ore using magnetic or gravity separation techniques called beneficiation. Lastly, extraction of iron from its ore is done by heating the iron ore with carbon in a blast furnace which produces the pig iron in molten form, which can be further used to produce cast iron or steel as per the requirement [220]. Each of these systems has distinct benefits and drawbacks in relation to expenses, effectiveness, ecological consequences, and security. The choice of technique used is contingent upon variables such as the geographical placement and magnitude of the iron ore reservoir, the calibre and constitution of the ore, and the accessibility to assets and technology.

In terms of environmental impact, the best method for extracting iron ores is open-pit mining, if it is done in an environmentally responsible manner. This is because open-pit mining has a smaller footprint compared to underground mining, and it is less likely to cause significant damage to the surrounding ecosystems. Open-pit mining also has a lower energy requirement, which means less GHGs emissions and less air pollution. Hence in this study, the open-pit mining method is assumed for the mining of iron ore [221]. The steps involved in the ore extraction process for material production are shown in Figure 5.3.

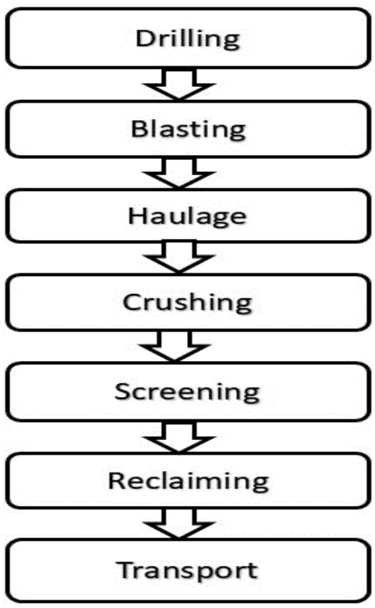

Figure 5.3: Steps of Ore Extraction

The extraction of iron ore involves several processes that are responsible for emitting various types of pollutants into the environment. Main pollutants in iron ore mining are identified as CO_2, SO_2, NO_x, CO, PM, Sulfuric Acid (H_2SO_4): Methane (CH_4), Volatile Organic Compounds (VOCs), and Heavy Metals. GREET database of global type and other research papers are used to compile the data for emissions in the mining of iron ores. The National Mineral Development Corporation, with an output of 35.57 million tonnes in 2017-18, has the distinction of being India's biggest iron ore mining corporation. The 2018 sustainability report of NMDC provides specific information on the amount of fuel and energy used in its mining operations [222]. The Input inventory as per the study of Haque and Norgate (2015) [223] Noragate and Haque (2010) [224], in the mining operation of iron ore, is given in Table 5.1.

Table 5.1: Input for Iron and Bauxite Mining

Name of the Item	Required for Iron ore	Required for Bauxite (Al Ore)	Reference
Diesel (Kg/Ton Ore)	3.4	.93	[223,224]
Electricity (KWh/Ton Ore)	3.8	2.0	
Explosive (Kg/Ton Ore)	.5	0.3	
Water (m3/Ton ore)	0.21	0.3	
Total Energy (MJ/Ton)	175	70	

Aluminium Ore (Bauxite Mining)

Bauxite is the main ore from which aluminium metal is produced and India has a large area for bauxite mining. In India, bauxite mining is primarily carried out in the states of Odisha, Andhra Pradesh, and Gujarat, with Odisha being the leading producer of bauxite in the country. Odisha is a pioneer in bauxite mining. The capacity of bauxite production in India increased in 2019 with 22.3 Mt production as compared with 23.2 Mt in 2018 [225]. The major steps are depicted in Figure 5.4.

Bauxite is typically mined using open-pit mining methods, which begin with the removal of overburden to access and extract the bauxite ore beneath. The extraction process involves the use of heavy machineries such as excavators, trucks, and conveyors, all of which consume fossil diesel and pollute the environment significantly [226].

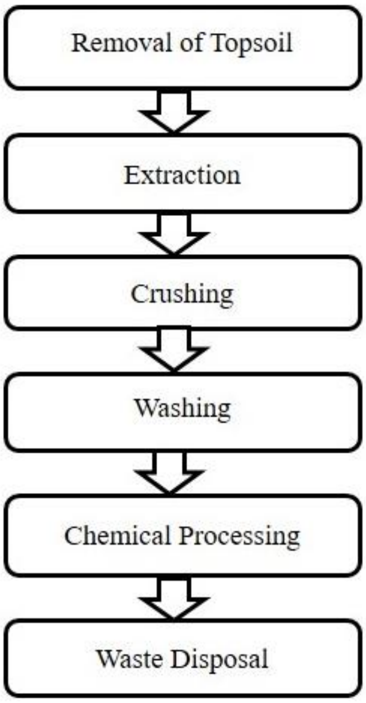

Figure 5.4: Bauxite Mining

To remove impurities, the extraction process is followed by crushing and washing. This process necessitates the use of large amounts of water, which can deplete local water supplies and pollute groundwater with sediment and chemicals used in the washing process. Waste disposal is also an important aspect of bauxite mining. Heavy machinery, such as bulldozers, excavators, and trucks, can cause soil erosion, habitat destruction, and water source disruption. [227]. After the bauxite ore is extracted, it is transported to a processing plant where it is crushed and washed to remove impurities.

This process requires the use of large amounts of water, which can lead to the depletion of local water sources and contamination of groundwater with sediment and chemicals used in the washing process [228]. The crushed and washed bauxite ore is then subjected to chemical processing to extract aluminium oxide, also known as alumina, through a process called the Bayer process. This involves the use of caustic soda (sodium hydroxide) and other chemicals, which can result in the generation of toxic sludge and the release of GHGs such as carbon dioxide [229].

The waste generated during the bauxite mining and processing process, including overburden, sludge, and other waste materials, needs to be disposed of properly, otherwise the contamination of soil, water, and air, can have long-term negative impacts on the environment and local communities [228]. Since 1980, the IAI has regularly performed surveys to assess industrial energy use. Additionally, since the late 1990s, it has gathered important environmental statistics, including information on fluoride emissions, perfluorocarbon emissions, and bauxite residue volumes [227].

Bauxite mining has significant environmental impacts, including deforestation, loss of biodiversity, soil erosion, water pollution, and air pollution, displacement of local communities, and deficient rehabilitation and restoration efforts. In processing and washing of extracted bauxite, large amounts of water are used [230]. The runoff from mining sites can contain toxic substances, such as heavy metals and chemicals used in the mining process, which can contaminate nearby water sources, including rivers, lakes, and groundwater, leading to water pollution. Water pollution can have detrimental effects on aquatic ecosystems, affecting fish and other aquatic organisms, as well as human health if contaminated water is used for drinking or irrigation. The utilization of heavy machinery, such as bulldozers, excavators, and trucks, which emit dust and particulate matter into the air is the major source of air pollution [231].

The dust and particulate matter can settle on vegetation, soil, and water bodies, leading to air pollution. The release of GHGs during the extraction and transportation of bauxite can also contribute to climate change. According to a report prepared by PE Americas, 5246 kg of bauxite is required to produce one tonne of primary aluminium. It yields 1915 kg of alumina, and after electrolysis reduction, approximately 1018 kg of liquid metal is obtained, followed by the preparation of 1000 kg of ingot and the recycling of the remaining metal [228]. The input and output of materials, energy, and emissions for bauxite mining in this study were also derived from the GABi and GRRET report, which used a global average.

Coal Mining

In India, the combustion of coal is responsible for two third emission of total CO_2 emissions in the country. Nonetheless, fugitive emissions from coal mining activities contribute significantly to global GHG emissions. Based on the findings of top-down modelling, it is evident that even with a robust 2°C transition route, these emissions will continue to be substantial until the conclusion of the century, amounting to around 300 Mt-CO2e. Consequently, it is crucial for India, now the second-largest coal producer globally, to engage in accurate and comprehensive assessment and comprehension of mitigation strategies. Surface mining has been the primary method of coal extraction in India, whereas underground mining has seen a gradual decrease to just 6% over the last ten years. The source of this information is the Ministry of Coal, Govt. of India, in the year 2021. The energy consumption and emissions statistics for coal mining are sourced from Coal India Limited, 2017, the biggest global producer of coal. In India, Coal India Limited has a market share of 83% in coal production (Coal India Limited, 2020). The sustainability report released by CIL in 2016-17 states that diesel use is 0.79 litres per tonne of coal or 8.12 kilowatt-hours per tonne of coal. Additionally, the electricity consumption in mine operations is 8.82 kilowatt-hours per tonne of coal. These particular consumption figures are estimated based on the coal output in 2016-17 [232].

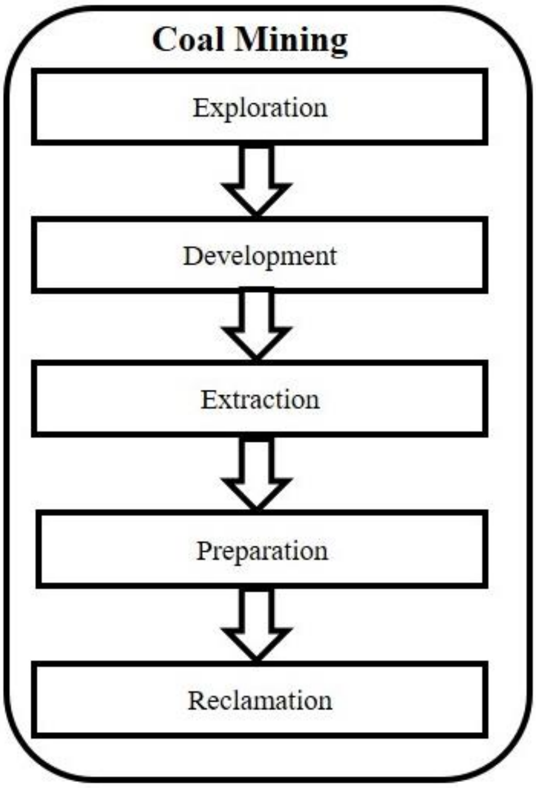

Figure 5.5: Steps of Coal Mining

The Lakhanpur Opencast Project was studied by Khanda, Pal, and Mahananda. It is under the Lakhanpur Area of M/s Mahanadi Coalfields Limited and is situated in the Jharsuguda District of Odisha. The Mine is worked by a Departmental Shovel – Dumper

Combination to remove Overburden with EKG & BEML hydraulic shovels &backkhoes, TATA-1200 hydraulic shovels, and 100 Te, 60 Te & 50 Te Dumpers. Since the system under study is a cradle-to-gate system, the unit processes include drilling, blasting, excavation, loading, and hauling of coal to the mine gate. Major inputs for coal mining are water (69.05 Litters per Te of coal), diesel (1.732 Litre/Ton and it is supplied by a Local Petroleum Refinery), electricity (0.709 KWh/ T of Indian Electricity Mix), and explosive (0.13 Kg/Te of coal) [233].

5.3.2 Production of Engine Parts

It was assumed for the purposes of this research that the engine parts in question were produced in Ghaziabad, in the Delhi National Capital Region (India), and that the engine assembly process took place entirely at this location. The ICEs was made using recyclable materials, but the precise proportion of recycled material in each category was not fixed and changed over time as a result of changes in the availability of scrap. As a result, the model only focused on employing primary or virgin materials as the baseline and ignored recycled resources. Following the study of Liu et al., (2013) [112], the manufacturing of Engine Block, Cylinder Head, Crank Shaft, Connecting Rod, Flywheel, Crank Case, Piston, Camshaft, Inlet/Outlet Manifold were studied for the manufacturing purpose.

Engine Block

The engine block is the main and quite stressed structure that is fitted with several important parts such as crankshaft, camshaft, cylinder heads, pistons, cylinder liners, cross-head, fuel injection pumps, governor, turbo support, etc to form a whole Powerpack. The production sequence of a cast iron engine block is the casting of a rough structure and then performing the machining operations to its exact shape.

Generally, a cupola and induction furnace are used to melt the metal at about 1500°C. Pig iron, steel scrapes, and ferrosilicon are used as the main raw material. For the melting operation about 4GJ/ton of energy is required. The melted metal is held in a holding furnace from where the metal is sent to the molds as per the requirements and production rates. The energy requirement for holding a furnace is about 0.2 GJ per ton of metal. Metal losses are also noticed at the rate of 2% in this stage. Cores are used to provide the internal complex shape of the block, which also consumes energy for the coating and baking. About 0.97 GJ energy per ton of core sand is consumed in core making. Moulds are prepared by machining and used to provide the outer surface of the part, which also consumes energy at the rate of about 0.2 GJ per ton of green sand. Generally, gravity sand casting is used to cast the engine block. After solidification, fettling is used to remove the part, and rough machining is used to remove the risers, gates, runners, and secondary cavities. About 1GJ energy per ton of metal is consumed in this process [114,234–236].

Cylinder Head

The cylinder head is secured to the cylinder block with suds or bolts. The bottom face, which forms part of the combustion chamber, is exposed to severe shock stress and combustion temperature. It is a complicated casting with cored cooling tubes that retain water to cool the cylinder heads. In addition, arrangements are built for the flow of input and exhaust gases. Furthermore, a Nozzle Sleeve inserted in the cylinder head makes room for fuel injection nozzles. The cylinder head casted body also has valve guides and seat inserts. Replaceable worn components in cylinder heads include valve seat inserts incorporating lock rings. The inserts are composed of stellite or weltite. Cylinder head manufacturing includes blank forging followed by machining.

In a study gravity cast with metal molds was applied in which a 5ton capacity induction furnace was used for metal melting at 1580°C. The electricity consumption was 112.75kWh recorded. In machining the cause of environmental pollution is the consumption of electricity and the electricity consumption for the machining of a cylinder head is 189.23 KWh. The "Indian Grid Power Mix" is used to calculate the environmental impacts of the consumed electricity [237,238].

Crankshaft

The engine's crankshaft is possibly the single most expensive component in a diesel engine. It is the medium that converts reciprocating motion into rotational motion. The engine's output is obtained via the crankshaft.

The crankshaft might be built in two sections and welded together, or it could be forged in one piece. Counterweights are given for dynamic balancing of the crankshaft, and they are either bolted or welded. Internal drill holes have been installed to provide lubricating oil to the main bearing along with connecting rod bearing portions, with the same oil being circulated for piston cooling via the connecting rod's internal drill hole. The forging process ensures that the grain remains continuous. As the study was performed in a crankshaft manufacturing industry, for the forging initially the billet is heated in a heating oven (Banyard make) whose cycle time is 15 minutes, and then forged with a hydraulic press of 1000Ton which also takes 15 minutes. The forged crankshaft is machined with a CNC turning machine which takes 70 minutes [239–241].

Connecting Rod

The connecting rod is a part that connects the piston to the crankshaft and serves as a medium for transforming reciprocating motion into rotational motion. Throughout the compression and power strokes of four-stroke engines, the connecting rod experiences a tremendous compressive stress. During the suction stroke, it experiences severe tensile stresses. In the instance of a two-stroke engine, the connecting rod only experiences compressive load. The connecting rod’s length is normally between 4 and 5 times the crank radius. They are I-beams made of fine-grained, totally killed alloy steel forging. Connecting rods feature a fine-drilled hole from the large end to the small end for conveying oil to lubricate the small end bearing and piston pin, as well as to cool the piston. Initially, the billet is heated to forging temperature in the heating oven of Banyard for 15 minutes and processed in a hydraulic press of 250ton whose cycle time is 10 minutes. A pneumatic press of 150T is used for trimming purposes and it takes 5 minutes. CNC turning machine is used for machining operations which are completed in 25 minutes [242–244].

Flywheel

The flywheel accumulates energy from power strokes and smoothly transmits it to the vehicle’s drive train, which connects the engine and gearbox. It transfers this energy in between power surges, resulting in less speed variations and a smoother engine functioning. The flywheel is located at the back of the crankshaft, near the rear main bearing. This is often the longest and largest primary bearing in the engine since it must sustain the total weight of the flywheel. The flywheel of big, low-speed engines is generally composed of cast iron. FG Iron Casting Jolt squeeze sand molding machine of MAKE-DISA 1300 is used to obtain the raw casting of the flywheel. The cycle time is 3 mins. Along with the Shell core shooter machine. Qingdao Antai AT958 is used for the core preparation having a cycle time of 5 mins. After obtaining the casting machining and tooth cutting is done by the CNC turning 2000 of cycle time 40 mins and Gear Shaping SPM of cycle time 90 minutes [245].

Crank Case

The crankcase is a major part of an engine that holds the crankshaft for its rotation. It is made of cast steel generally. It also provides the facility of engine foundation [234,246].

FG Iron Casting Jolt squeeze sand molding machine of DISA 1300 make is used for casting which has a cycle time of 3 mins and Shell core shooter machine Qingdao Antai AT958 make is used for core making having a cycle time of 5 mins. The casted structure is processed for necessary machining operations using a horizontal machining center which takes 60 minutes.

Piston

The piston is an essential component in the diesel engine as it serves as a constituent of the combustion chamber and actively contributes to the power transmission process. The burning of fuel generates a substantial quantity of heat. It is made of aluminum alloy. A die-die-casting machine is used to produce the raw blank and one piece is produced in 15 minutes. The blank is processed using a CNC turning machine which takes 25minutes. Final finishing is performed using cylindrical grinding and Jig grinding consuming 15 minutes and 10 minutes respectively [234,247].

Cam Shaft

The camshaft in diesel engines plays a crucial function in controlling the opening and shutting of the intake and exhaust valves. Additionally, it runs the Fuel Injection Pump to ensure the precise timing of fuel injection into the cylinder. Typically, we provide three cams for each cylinder: two outer cams for the exhaust and intake valves, and one center cam for fuel injection. A bore is created at the midpoint of the shaft to facilitate the lubrication of cam bearings. The cam lobes are lubricated by oil that is supplied through the valve lever actuator via the push rod. It is made up of alloy steel. A raw billet is heated in an oven for 15 minutes and processed for forging operation using the hydraulic press of 1000 tons which takes 10 minutes. CNC turning machine is used for machining operations and it takes 15 minutes after that profile grinding machine performs the final finishing operations in 20 minutes [248].

Inlet/Outlet Manifold

The design of the intake manifold should prioritize minimizing sidewall friction and ensuring a lower temperature to prevent charge re-ignition. Historically, intake manifolds have been constructed from cast iron and aluminum, which are conventional materials for this purpose. Novel composites are suggested to save production expenses and enhance thermal efficiency [249].

There are more components like nuts and bolts, rocker arms, pins, diesel tanks, etc., which are not described in this work. However, the energy consumption and hence the consequence of environmental emissions for these parts manufacturing are assessed through the "experienced specific energy" approach of different manufacturing processes according to the work performed by Gutowski(2006) [214].

Assembly of IC Engine

It was assumed that the engine was produced by assembling the various components in the factory manually. Power-operated tools and equipment are used to perform various assembly operations like nut and bolt tightening, and transportation of heavy parts like crankcases or flywheels from the store to the assembly floor. Electricity consumption is a major cause of environmental pollution in assembling the engine. The energy consumed in the assembly of a six-cylinder diesel engine is provided in a study by Liu et al 2013. So the energy consumption is calculated proportionately [112,250].

5.3.3 Use of the Diesel Engine

It was presumed that an IC Engine is used for 20 hours each day specifically for agricultural irrigation and the fuel consumption for one hour is noted at various time intervals and different loading (also a survey is performed with farmers of ruler area). Further, the diesel fuel utilized for two scenarios one is that in which only pure fossil diesel is consumed and another case is that 20% biodiesel is mixed with the fossil diesel.

In the Case of Pure Fossil Diesel Consumed

Diesel Engine Life 20years= 20*365days = 7300days = 7300*10hrs (Assumed that an engine runs 10hrs/day) =73000hrs

Amount of Diesel consume per hour = 800ml = 0.8L (By Experiment)

Amount of Diesel consumed in 20 years (73000 hours) = 0.8*73000 = 58400L

Mass of Diesel consumption in 20 years (73000 hours) = 0.85*58400L= 49640kg

In this Case, 20% Biodiesel is mixed with Pure Fossil Diesel

Amount of Biodiesel required throughout the life = 58400L *20% = 11680≈12000L

Amount of Diesel required in 20 years (73000 hours) = 58400L -11680L = 46720 ≈47000L

Mass of Diesel consumption in 20 years (73000 hours) = 0.85*47000L = 39950kg

Production of diesel steps of crude oil extraction, transportation of crude oil, and refinery process to obtain diesel suitable for engine combustion purposes were considered in the usage phase, along with the consumption of diesel. Further production of biodiesel obtained from Karanja feedstock was considered because in the previous chapter biodiesel obtained from Karanja feedstock got higher merit in comparison to biodiesel obtained from microalgae in terms of GHGs emission and energy consumption. Also in the production of biodiesel cradle to grave approach LCA was applied to assess the environmental emission, it includes farming of Karanja trees, seed transportation to the oil extraction unit, oil extraction, transesterification, and lastly its consumption in the engine.

5.3.3.1 Production of Diesel Fuel

India, the world's third-largest importer and consumer of oil, imports 84% of its crude oil. Rising oil prices, rising imports, and declining domestic production have resulted in rising crude oil import costs. To combat this, the government is implementing strategies to lower prices of oil prices caused by excessive imports, with total import expenses projected to reach $110 billion. Crude oil extraction in Middle Eastern countries is a complex and highly sophisticated operation that includes several stages, ranging from exploration and drilling to production and refinement. The Middle East is known for its vast oil reserves, and extraction methods have evolved to maximize production efficiency and recovery rates [251,252]. Here is an overview of the crude oil extraction process and methodology in Middle Eastern countries:

Extensive geological surveys and seismic studies are conducted to identify potential oil-bearing rock formations. Once a promising site has been identified, exploratory wells are drilled to confirm the presence of oil and to assess the size and characteristics of the reservoir.

Drilling operations begin after the presence of oil is confirmed. Drilling rigs are a common sight across the desert landscapes of many Middle Eastern countries. Drilling technologies such as directional drilling and horizontal drilling are frequently used to reach oil reservoirs that are deep underground or beneath difficult geological formations. Once a well has reached the desired depth, it is finished with casing and cementing to prevent wellbore instability and ensure that oil does not mix with groundwater. To extract oil from the reservoir, production techniques such as primary, secondary, and tertiary recovery methods are used. Primary recovery typically relies on the reservoir's natural pressure, whereas secondary and tertiary methods involve injecting fluids (e.g., water or gas) to improve oil recovery [77]. The crude oil obtained from the extraction process is transported to the refineries located within the particular country or it is transported to other countries for revenue generation through the ocean tankers.

Crude Oil Extraction

The OPEC accounted for up to 90% of all crude oil imported by India at one point, but this has decreased as a result of Russian oil becoming available at a discount in the days following of Russia's invasion of Ukraine in February 2022 [253]. So in this study, crude extraction process from Middle East countries was considered. For extraction of crude oil, pumping sets, electrical submersible pumps (ESP) gas lifts, and natural lifts are used. Water flooding technology to increase production is applied [77,254].

Gas and oil are the primary sources of energy in Middle Eastern nations, with little dependence on coal. In 2021, gas accounted for 77% of the electricity generated, while oil contributed 18%. The area has a high carbon intensity, with an average of 515gCO_2 per kWh in 2021, in contrast to the world mean of 436gCO_2 per kWh [255].

Crude Oil Transportation

Crude oil is imported from the Middle East Region, which includes Saudi Arabia, Iran, Iraq, and Kuwait. The Average distance of the sea route from the Middle East to India is about 2500km for crude oil transportation. The very large crude carriers can carry between 1.9 million and 3.7 million barrels having dead weight (DWT) of 3 lac tons [256].

The midstream industry encompasses the activities of transporting, storing, and trading natural gas, crude oil, and refined goods. Crude oil, in its raw form, is carried using two main methods: tankers, which navigate maritime routes between different regions, and pipelines, via which the majority of the oil is transported for at least a portion of the journey. After the extraction and separation of oil from natural gas, pipelines are used to convey the products to either another carrier or straight to a refinery.

Heavy fuel oil, which is a residual fuel taken from the bottom of the barrel after the production of more profitable fuels such as petrol and middle distillates, is the most common marine fuel today. It is regarded as an undesirable fuel because it is sludgy with a high sulfur content and highly viscous, necessitating heating to pump through the systems. It is burned in low-speed compression ignition engines, which means that no spark is required to ignite the fuel [257].

The transit from the seaport to the refinery accounted for less than 1% of the overall life cycle assessment (LCA) emissions till the point of exit from the refineries. The refinery location does not matter from the LCA GHG emission perspective [258].

Crude Oil Refining

"The Mathura refinery owned and operated by state-run Indian Oil Corporation (IOCL) in Uttar Pradesh, India has been in production since 1982. The IOCL Mathura refinery had a processing capacity of 8Mtpa (million tonnes per annum). It is located in Mathura, Uttar Pradesh, approximately 154km away from India's capital New Delhi. It has a captive power plant comprising three gas turbines and a heat recovery steam generator (HRSG). The refinery supplies petroleum products primarily to the National Capital Region and North India. The various processing units in the Mathura refinery include an 8Mtpa-capacity atmospheric vacuum unit (AVU), a 1.34Mtpa fluidized catalytic cracking unit (FCCU), a 1Mtpa vis breaking unit (VBU), a 0.466Mtpa continuous catalytic reforming unit (CCRU), a 1.1Mtpa diesel hydro desulphurization unit (DHDS), a 1.2Mtpa once through hydrocracker unit (OHCU), a 1.8Mtpa diesel hydrotreater unit (DHDT). It also houses a bitumen blowing unit (BBU), a gasoline desulphurization unit (Prime-G), apart from sulfur recovery units (SRU), and hydrogen generation units (HGU). This refinery recycle treated sewage water for use, replacing freshwater from the Yamuna River for its Mathura refinery operations since 2018 [259,260].

The 2,660 km-long Salaya-Mathura pipeline (SMPL) transports up to 25Mtpa of crude oil from Salaya near Vadinar, Gujarat, to IOCL refineries at Koyali, Mathura, and Panipat. The 147km-long, 16in-diameter Mathura-Delhi pipeline (MDPL) exports up to 3.7Mtpa of petroleum products from the Mathura refinery to Bijwasan in Delhi. The 56km-long, 16-in-diameter Mathura-Tundla pipeline (MTPL) transports up to 1.2Mtpa of petroleum products from the Mathura refinery to the Tundla terminal, while the 21km-long, 8in-diameter Mathura-Bharatpur pipeline (MBPL) can transport up to 1.2 Mtpa of products from the refinery facility to Bharatpur. The refinery products comprise LPG 519 (5.51%) gasoline 1757 (18.68%), Naptha 236 (2.5%) kerosene 124(1.31%), Aviation Turbine Fuel (ATF) 206(2.19%) Diesel (HSD) 3791(40.3%), Furnace Oil 854 (9.08%), and Bitumin 959 (1.02%) and others [261].

Allocating environmental obligations is crucial given the large number of co-products at this juncture. The ISO 14044:2006 standard indicates that allocation may be prevented by separating the unit process or extending system of product system [77]. As a consequence, the next stage in the hierarchy is to analyze allocation in terms of the physical link between the inputs and the outputs. Mass and resource allocation seem to be feasible alternatives. Another research found that the use of energy and mass-based assignment achieve comparable effects [262]. This research employed secondary data to estimate emissions from flue gas generated by catalyst regeneration in refinery units, as well as emissions via fuel oil combustion using Ecoinvent. Emissions from refinery include gases, liquids, and solid waste. The industrial process generates liquid waste, as do storage tanks, utilities, labs, rain, and household rubbish. Liquid waste is treated utilizing an oil separator/catcher to collect the oil in the sewer and deliver it into the Redistilling Unit, while clean water flows into the Yamuna [77,263].

5.3.4 End-of-Life Disposal

Out-of-service diesel engines will be gathered and returned (via reverse logistics) to the engine production factory in Ghaziabad. Engine components are detached and cleaned followed by inspection to further work on them whether to refurbish the individual part for reassembly or recycling of the part.

It is observed that about 85% of parts of the engine are satisfactorily reused and only refurbishing is required for further use in the engine. These components have more than 90% weight of the total weight of the engine [264].

Energy is consumed in the above operations like separation of parts, washing/cleaning, checking, and refurbishing and again assembling the engine. Other components that are not in a condition of reuse even after the refurbishing process are sent to the recycling purpose. A furnace of 600kw capacity suitable for metal melting is used for recycling the leftover components. Power consumption for melting the cast iron, steel, and aluminium are 560kwh, 600kwh, and 400kwh respectively. Final electricity consumption is estimated by multiplication of the weight of the metal [112]. In Tables 5.2 and 5.3, major emissions and utilization of natural resources for all three phases are listed.

Table 5.2: Emission Inventory of Diesel Engine Life Cycle

Production Phase								Use Phase						End of Life Phase			References
Environmental Emission	Production of Materials (kg)				Material Transport	Engine Manufacturing	Total Emission of Engine Production	Pure Diesel Case			KB20 Biodiesel Case			Components refurbishing	Materials recycling	Total	
	Cast Iron	Steel	Aluminium	Alloy				Production	Combustion	Total Emission in Use Phase for Pure Diesel	Production	Combustion	Total Emission in Use Phase for KB20 Biodiesel				
CO_2	418.74	139.3	294.35	19.32	18.55	1085.93	**1976.19**	18618.51	157014	**175632.51**	15987.83	155420.50	**171408.33**	315.18	28.98	**344.16**	[77,83,97,108,112,138,145,212,214,227,236,245,248,265]
CO	0.09	0.033	0.06	0.32	0.168	0.24	**0.92**	21.62	547.2	**568.2**	67.02	1111.94	**1178.96**	2.78	0.26	**3.04**	
CH_4	1.03	0.31	0.83	0.058	0.0009	3.21	**5.44**	1019.44	2.94	**1022.38**	830.81	7.09	**837.902**	1.12	0.11	**1.23**	
NO_X	0.45	0.18	0.73	0.058	0.11	3.13	**4.66**	31.07	464.37	**495.44**	67.64	412.35	**479.99**	1.22	0.12	**1.34**	
SO_2	0.89	0.37	1.02	0.048	0.05	3.79	**6.16**	131.54	4.97	**136.51**	127.44	0.00	**127.44**	3.18	0.29	**3.47**	
PM	2.52	0.87	0.58	0.12	0.004	14.69	**18.78**	104.08	34.75	**138.83**	105.4	59.10	**164.496**	2.95	0.27	**3.22**	
H_2S	0.0021	0.00062	0.0062	0.0003	0.00005	0.00	**0.01**	0.24	0	**0.24**	0.19	0.00	**0.19**	0.14	0.02	**0.16**	
HCL	9.90E-03	7.30E-03	6.30E-02	2.00E-03	2.50E-04	0.31	**0.39**	1.52E+00	0.00E+00	**1.52E+00**	1.22	0.00	**1.22**	0.08	7.20E-03	**0.0872**	
VOC	0	0	0	0	0.003	0	**0.00**	-	-	-	0	236.38	**236.381**	-	-	-	
BOD	1.09	0.384	0.128	0.01	0.0052	0.01375	**1.64**	366.02	0	**366.02**	293.75	0.00	**293.75**	0.25	0.023	**0.273**	
COD	1.135	0.41	0.194	0.06	0.0075	0.02375	**1.83**	431.27	0	**431.27**	346.12	0.00	**346.12**	0.29	0.027	**0.317**	
NH_4	0.0057	0.0015	0.0023	9.4E-05	0.0037	0.0004875	**0.014**	10.39	0	**10.39**	8.34	0.00	**8.34**	0.003	0.0003	**0.0033**	

Table 5.3: Natural Resources Inventory in Diesel Engine Life Cycle

Natural Resources Utilization																
	Production Phase							**Use Phase**						**End of Life Phase**		
	Production of Materials (kg)				**Material Transport**	**Engine Manufacturing**	**Total**	**Pure Diesel Case**			**KB20 Biodiesel Case**			**Components Refurbishing**	**Materials Recycling**	**Total**
	Cast Iron	**Steel**	**Aluminium**	**Alloy**				**Production**	**Combustion**	**Total**	**Production**	**Combustion**	**Total**			
Crude oil	204.91	57.34	159.54	11.53	2.38	697.2888	**1132.99**	4429.47	0	**4429.47**	3986.523	0	**3986.523**	236.21	15.5101	**251.72**
Coal	8.87	3.02	6.53	0.69	29.57	4.16	**52.84**	62455.42	0	**62455.42**	56209.878	0	**56209.878**	27.36	1.7974	**29.16**
Natural Gas	0.21	0.74	2.15	0.82	0.48	6.2088	**10.61**	30.08	0	**30.08**	27.072	0	**27.072**	2.22	0.1462	**2.37**

Source: [62,112,227,235,247,266–269]

5.4 Life Cycle Impact Assessment (Results and Discussion)

Life cycle Impact assessment (LCIA) is the third and major process of the LCA according to the ISO 14042. ISO 14042 provides detailed guidelines for performing the LCIA. There are various methodologies for this step developed by different institutes and research organizations. The main methodologies include CML, IPCC, Recipe, TRACI, and many more. Some of them provide the guidelines to assess the impact at midlevel while other provides endpoint indicators too. Recipe methodology is suggested and utilized by various researchers as it provides the assessment method for endpoint indicators and it is recognized at the global level. Therefore, the impact evaluation approach used is ReCipe. It assesses indicators at two levels: midpoint as well as endpoint indicators. The midpoint indicators just address individual environmental problems such as climate change, eutrophication, and acidification. In contrast, endpoint indicators demonstrate the overall environmental effect on three broader levels: human well-being, ecosystems, and resource shortages [270].

The environmental emissions in the form of gases liquids and solids obtained as data in the previous step i.e. life cycle inventory are used as input. There are three steps of life cycle assessment i.e. Classification, Characterization, and Normalization, which were followed closely [147]. Five impact categories were considered for impact assessment: CCP, TAP, FPMFP, POFP, and Fossil resource scarcity. This study used science-based conversion factors, known as characterization factors, to change and aggregate the life cycle inventory (LCI) outcomes into representative measures of effects on human well-being, environmental quality, and resource scarcity. Normalization is a technique used to standardize indicator data so that it may be easily compared across different effect categories using a certain reference value [270,271].

The environmental consequences of various processes were meticulously examined, necessitating the use of a logarithmic scale with the python to manage a wide range of data values. CCP is the mid-level impact and is measured in kgCO_2eq. GHGs like CO_2, CH_4, CO, NO_X, etc are responsible for this impact. Notably, the utilization phase of the engine's life cycle had the highest CCP, in both cases ie pure diesel and 20% Karanja biodiesel (KB20) which is 359170.95 kgCO2eq (98.8%) in the case of pure diesel use and 345291.9186 kgCO2eq (98.75%) in case 20% Karanja biodiesel used as fuel. It is due to the energy-intensive production of diesel fuel and emissions during engine operation (CO_2, CH_4, CO, NOx). Using KB20 the CCP impact is reduced by 13789.03kgCO_2eq which is about 3.8%. CCP is also significant during component manufacturing (0.98%) and disposal phase (0.2%), primarily due to electricity generation. Total CCP for the case of pure diesel use and 20% Karanja biodiesel are 363513.60 kgCO_2eq and 349634.61 kgCO2eq respectively.

The Acidification Potential (AP) also has a substantial effect during the usage phase, in both cases. In pure diesel use it was estimated as 347.07kgSO_2eq (97.25%), and in case KB20 it is 328.41kgSO2eq (98.08%). The reduction in AP impact is noticed in the case of biodiesel use at the rate of about 5.50%. AP is driven by SO_2 emissions from diesel fuel production and NO_X emissions during engine operation. Due to higher SO_2 and NOx emissions, aluminium production had a greater AP impact despite its lower mass. Transportation of raw materials and recycling had a lower AP impact.

Fossil resource scarcity impact is driven by namely consumption of crude oil, coal, and natural gas. In the engine life cycle, it is estimated as 58358.5kgOil-eq in case of pure diesel use as fuel while it is 52668.41kgOil-eq in case of biodiesel use as fuel. Again the use phase has the highest value which is about 95.50% and 97.23% in the case of pure diesel and karanja biodiesel respectively. A reduction of about 9.7% of this POFP also is noticed in the case of biodiesel use as fuel.

Photochemical ozone formation (POFP) has a significant impact on the engine life cycle. Its amount was estimated as 501.44kgNO_X-eq in the case of pure diesel use and 485.99kgNO_X-eq in the case of Karanja biodiesel. Raw materials transportation was second and alloy production also had a significant POFP impact due to increased CO emissions.

Fine particulate matter formation is caused by particulate matter present in the environment. When PM2.5 particles are breathed, they can reach the upper airways as well as lungs, leading to adverse health effects in humans. Secondary PM2.5 aerosols are formed in the air from emissions of sulfur dioxide (SO2), ammonia (NH3), and nitrogen oxides (NOx), among other elements (WHO 2003). It has the greatest impact in the use/operation phase of the engine followed by the engine production phase. In use phase 232.92 kgPMeq for pure diesel combustion and 254.25 kgPMeq for KB20 biodiesel combustion. The exceed amount in the case of KB20 biodiesel is due to the more NO_X and PM release in the burning of biodiesel.

In table 5.4, the values of mid-point life cycle impact are compiled for the case of pure diesel use as fuel and in table 5.5 for the case of KB20 (20%) Karanja biodiesel. The environmental impact is also depicted graphically in Figure 5.6 and Figure 5.7 for both cases.

Table 5.4: Mid-Point Life Cycle Impact in case of Pure Diesel Use

Midpoint Life Cycle Impact in case of Pure Diesel Use					
	Impact on the Production Phase of Engine	**Impact in Use Phase for Pure Diesel**	**Emission in Use Phase for KB20 Biodiesel**	**Impact on Disposal Phase**	**Total Life Cycle Impact**
Climate change (GWP)	3551.27	359170.95	345291.9186	791.38	363513.60
Fine particulate matter formation	21.87	232.92	254.25	4.37	259.16
Photochemical ozone formation	4.67	495.44	479.99	1.334	501.44
Terrestrial acidification	44.67	337.55	322.15	3.96	18193.93
Fossil resource scarcity	1180.56	56901.04	51210.94	276.91	58358.51

Table 5.5: Mid-Point Life Cycle Impact in case of KB20 Biodiesel Use

Life Cycle Impact in Case of KB20 Biodiesel Use				
	Emission in the Production Phase of Engine	**Emission in Use Phase for KB20 Biodiesel**	**Emission in the Disposal Phase**	**Total Life Cycle Impact**
Climate change (GWP)	3551.27	345291.9186	791.38	349634.61
Fine particulate matter formation	21.09	254.25	4.37	279.71
Photochemical ozone formation	4.67	479.99	1.334	485.99
Terrestrial acidification	44.67	322.15	3.96	328.41
Fossil resource scarcity (Unit-oil-eq/kg)	1180.56	51210.94	276.91	52668.43

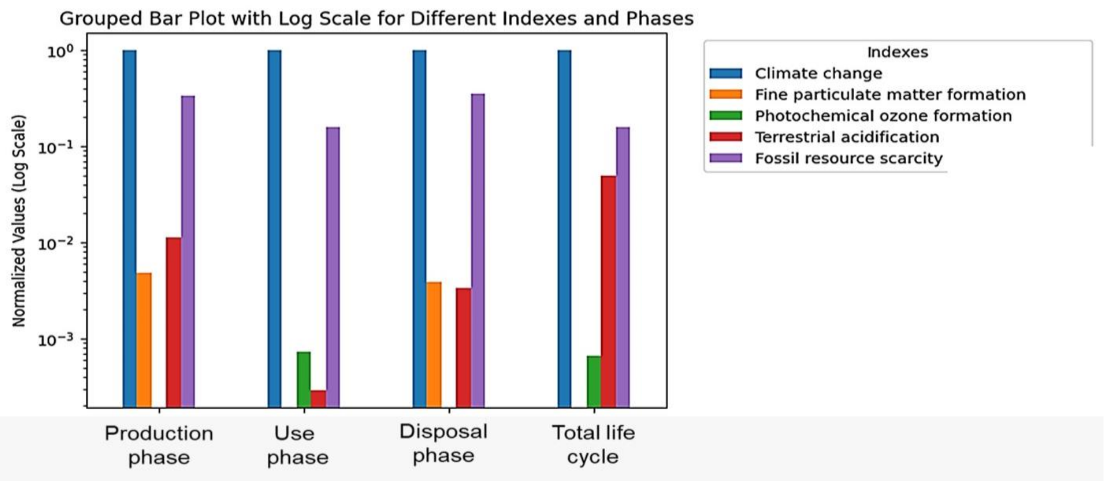

Figure 5.6: Life Cycle Impact in case of Pure Diesel Use

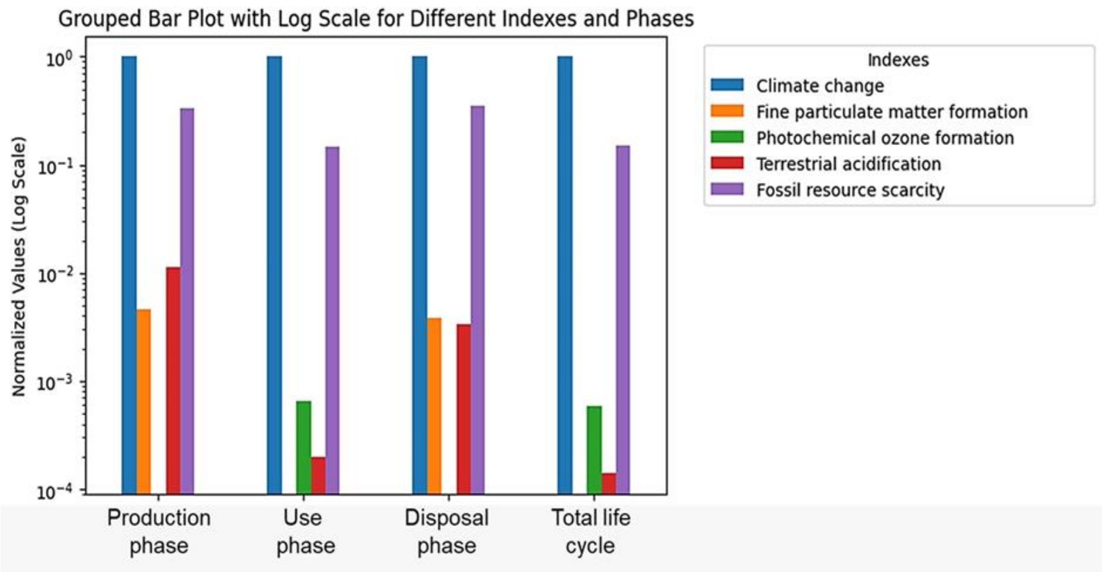

Figure 5.7: Life Cycle Impact in case of KB20 Biodiesel Use

All the midpoint level environmental impacts are converted to the endpoint level impacts according to the Recipe methodology Characterization factor provided in the recipe is used. There are three endpoint-level impacts which include Human health (DALY), ecosystem quality (species.yr), and resource scarcity (dollar). Further, the endpoint-level impacts are converted into a single-point index using the weights of the impact provided in the recipe [129]

There are three perspectives, namely, Individualist, Hierarchist, and Egalitarian for consideration of weights of impacts based on the period. The time horizon for the Egalitarian perspective is explicitly taken as 1,000 years and for Individualists, Hierarchist is 20 and 100 years. In this study Egalitarian perspective is used to cover all environmental impacts [143]. Endpoint Level Life Cycle Impact with single point index of IC Engine is depicted in Table 5.6. Figure 5.8 shows the single point index of the life cycle impact for all three phases of the IC Engine.

Table 5.6: Endpoint Level Life Cycle Impact of IC Engine

End-Level Life Cycle Impact In case of Pure Diesel Use				
	Human Health	**Ecosystem Quality**	**Resource Scarcity**	**Single Index**
Impact on the Production Phase of Engine	2.1374	0.0029	104554.0000	104556.1403
Impact in Use Phase for Pure Diesel	144.3658	2.4403	831361.2300	831508.0361
Impact in Use Phase for KB20 Biodiesel	144.5207	0.5484	748225.11	748370.18
Impact on Disposal Phase	1.0471	0.0016	23347.6125	23348.6612
Total Life Cycle Impact	147.5503	2.4448	959262.1625	959412.1576

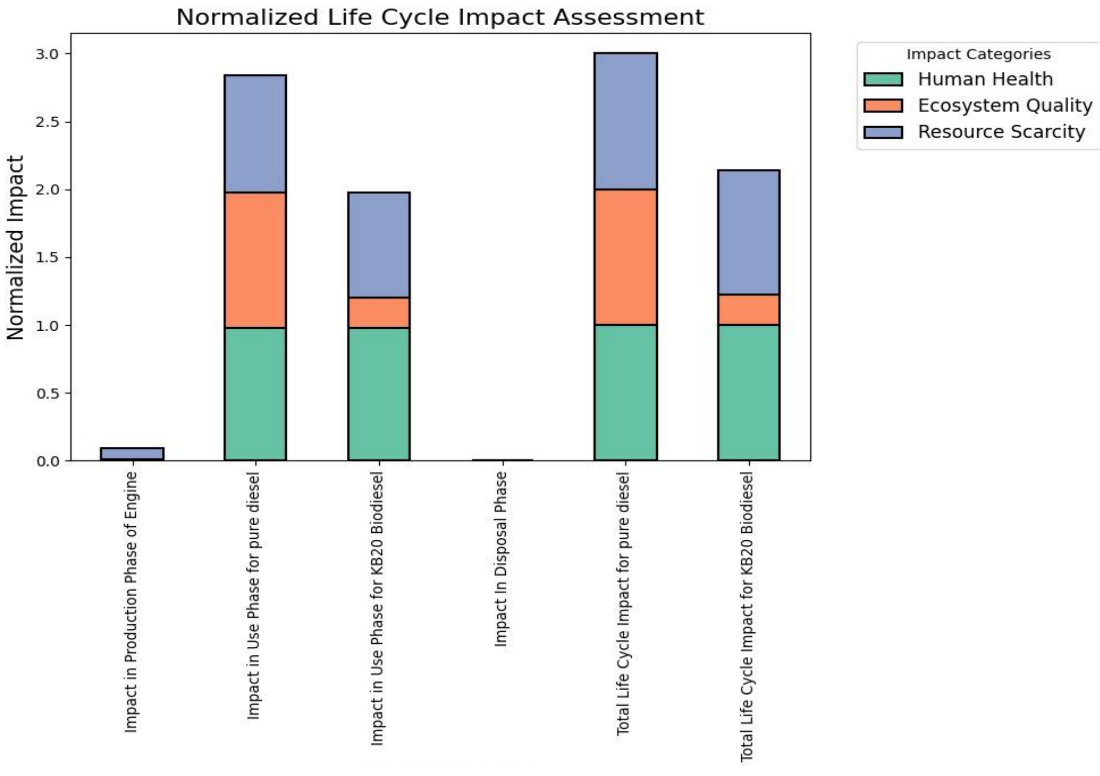

Figure 5.8: Conversion of Endpoint Level Impacts to Single Index

5.5 Summary

The precise environmental effects of a newly designed diesel engine were evaluated. The research carefully investigated the environmental impact of a newly developed diesel engine, with a focus on CCP. CCP has a substantial influence on every stage of the diesel engine's life cycle.

- In this study, a Life Cycle Assessment (LCA) for a generic diesel engine manufactured in India was performed successfully.
- Life cycle inventory has been performed for various stages ie engine production, operation, and disposal.
- The recipe technique is used to examine life cycle impacts. It determines indicators at two tiers: midpoint as well as endpoint indicators. Midpoint indicators concentrate exclusively on specific issues related to the environment, such as climate change, eutrophication, acidification, etc., but endpoint indicators indicate the environmental effect on three higher aggregate levels, which influence the well-being of humans, the ecosystem, and shortages of resources.
- Five significant environmental impacts are selected for life cycle impact assessment, which include, CCP, PCOF, AP, Fine particulate matter formation, and fossil resource scarcity.
- CCP has the highest environmental impact (363513.60kgCO_2eq), followed by Fossil resource Scarcity (58358.51kgOileq), and AP (18193.93kgSO_2eq). POFP and Fine particulate matter formation contribute a significant impact with the amount of 259.16 kgNOX-eq and 501.4492 kgPMeq, in the case of pure diesel usage as fuel.
- In the case of 20% Karanja biodiesel use as fuel the value of Fossil resource Scarcity, CCP and Acidification Potential, POFP and Fine particulate matter formation are 52668.43kgOileq, 349634.61kgCO2eq, 328.41kgSO2eq, 485.99 kgNOX-eq, and 279.7192 kgPMeq.

- The engine's utilization phase represents the most energy-intensive and ecologically destructive part of its life cycle.
- The primary energy demand during the usage part is closely linked to diesel fuel synthesis, whereas CCP, AP, FPMF, and POFP are closely related to engine operation processes.

CHAPTER 6

CONCLUSION

6.1 Conclusions

The following outcomes emerged as significant insights from the conducted research:

For Lifecycle Analysis of Biodiesel

- The LCA of alternative fuel, biodiesel production from Karanja, and microalgae has been successfully carried out.
- It is found that the vegetable oils can be successfully converted into biodiesel and the net energy ratio is suitable for the use of vegetable oils, and also for microalgae considering that it doesn't require any land and can be grown on water bodies only.
- The energy ratio of Karanja feedstock 5.67, and the energy ratio of microalgae estimated to be 2.49. This high energy ratio, with a sensitivity of 10%, have positive impact in mitigating the GHG emissions.
- Vegetable oils remained the promising candidate with the lowest GHG emissions values among all processes that emit GHGs. Karanja had less NEV values (NEV: 64.1), whereas microalgae consumed more energy (and NEV: 286.19) while producing a higher yield.
- According to the outcomes of the sensitivity analysis, both emission and energy values are greatly sensitive to biodiesel yield, seed yield, and oil content. The higher yield has the potential to reduce GHG emissions. Different feedstock, however, has contradictory environmental performances.

- Karanja demonstrated effective LCA results compared to microalgae feedstock when data from two feedstocks were compared in terms of GHG emission and life cycle energy balance.

For the Lifecycle Analysis of IC Engine

- In this study, LCA for a generic diesel engine manufactured in India was performed successfully.
- Life cycle inventory has been performed for various stages ie engine production, operation, and disposal.
- The recipe technique is used to examine life cycle impacts. It determines indicators at two tiers: midpoint as well as endpoint indicators. Midpoint indicators concentrate exclusively on specific issues related to the environment, such as climate change, eutrophication, acidification, etc., but endpoint indicators indicate the environmental effect on three higher aggregate levels, which influence the well-being of humans, the ecosystem, and shortages of resources.
- Five significant environmental impacts are selected for life cycle impact assessment, which include, Climate Change Potential (CCP), Photochemical Ozone Formation Potential (PCOF), Acidification Potential (AP), Fine particulate matter formation, and fossil resource scarcity.
- CCP has the highest environmental impact (363513.60kgCO2eq), followed by Fossil resource Scarcity (58358.51kgOileq), and Acidification Potential (18193.93kgSO_2eq). POFP and Fine particulate matter formation contribute a significant impact with the amount of 259.16 kgNOX-eq and 501.4492 kgPMeq, in the case of pure diesel usage as fuel.

- In the case of 20% karanja biodiesel use as fuel the value of Fossil resource Scarcity, Climate Change Potential and Acidification Potential, Photochemical Ozone Formation Potential (POFP) and Fine particulate matter formation are 52668.43kgOileq, 349634.61kgCO2eq, 328.41kgSO2eq, 485.99 kgNOX-eq, and 279.7192 kgPMeq.
- The engine's utilization phase represents the most energy-intensive and ecologically destructive part of its life cycle.
- The primary energy demand during the usage part is closely linked to diesel fuel synthesis, whereas CCP, AP, FPMF, and POFP are closely related to engine operation processes.

6.2 Key Points for Future Scope

However, there is no denying that humanity will eventually need a variety of energy sources, with biofuels playing a significant part in this supply. Every study leaves open a number of avenues for further investigation into previously uncharted territory. Key points for the future scope of this research has been summarized as follows:

- As we need more sources of biofuel production to meet future energy demands, more researchers can build on the current study by using more biodiesel feedstocks.
- Additionally, researchers can broaden their scope to include more environmental impacts, such as the potential for toxicity, abiotic depletion, and land use and eutrophication.
- In this research the diesel engine of single cylinder is taken for study and assumed to be used as stationary purpose like irrigation. But IC Engine also consume gasoline and CNG as fuel to generate power.

- Hence research work can be extended on IC Engine using gasoline and CNG as fuel.
- Additional investigation can be conducted by using aluminium alloy for the IC engine's cylinder head and cylinder block, which makes the engine lighter but changes the emission values because of the increased aluminium mass.
- More Impact category like eutrophication and ozone depletion can be taken into consideration.

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