CHAPTER 2
REVIEW OF LITERATURE

Hydrocarbon oil-based kerosene/paraffin oil is widely being used as the dielectric fluid for EDM. However, some research studies highlighted that kerosene alters the metallurgical structure and mechanical properties of the tool and work materials. Moreover, it adversely affect the personnel health, operational safety, and environment due to its toxic emissions products, high volatility, fire hazards, and non-biodegradability.

In order to identify research gap in the area, literature review has been grouped into following four subareas,

a) Performance issues of current dielectric fluids and dielectric supply systems
b) Environmental, personnel health & operational safety issues related to EDM
c) Feasibility of using vegetable oils as dielectric fluid
d) Sustainability and other issues for EDM

Past research work carried out by researchers has been reviewed as below.

2.1 Performance Issues of Current Dielectric Fluids and Supply Systems

Valaki and Rathod (31) have reported primary and secondary functions performed by dielectric fluids in EDM process, as listed below.

Primary functions

- To insulate sparking gap between the electrode and workpiece up to breakdown voltage and then breaks down by ionization for a plasma channel generation.
- To flush away eroded particles (debris) produced in the sparking gap during machining
- To restrict spark energy into narrow region for higher energy density
- To reestablish the insulation condition in the sparking gap between the electrode and workpiece by deionization when energy level goes below the dielectric breakdown voltage
**Secondary functions**

- To capture emission products generated because of decomposition of dielectric fluid and vaporized matters of tool and work materials
- To serve as a liquid adsorbing filter for gas and liquid phases when expelled from the gap
- To minimize electromagnetic radiation effect by immersion of the plasma channel
- To assist molten metal globules to detach from the workpiece surface
- To generate an environment for the subsequent discharges to take place uniformly across the sparking gap by minimizing the effect of the magnetic field generated by previous sparks.

In order to perform the above functions efficiently, EDM process has gone through considerable changes in terms of types of dielectric fluids used and modes of dielectric supply. Also, to meet the specific requirements, hydrocarbon oils, water based solutions, synthetic and mineral based oils, gaseous dielectric fluids, water-in-oil (W/O) and oil-in-water (O/W) emulsions have been experimented with wet, powder-mixed, dry, and near dry modes of dielectric supply. Since the introduction of EDM by Lazarenkos in 1943, kerosene is unarguably considered as the preferred dielectric fluid for the process. EDM process removes materials with a complex combination of the thermal, electrical, and mechanical phenomenon (32). Dielectric properties of kerosene deteriorate with continuous usage, which reduces the efficiency of EDM process. The electric spark in oil is more stable, predictable, and uniform than in air (33).

Water was introduced as dielectric fluid with a view to increase MRR. However, it was found that the machining accuracy was poor with distilled water but the surface finish was better compared to kerosene (34). A large amount of heat will be consumed by water due to high specific heat results into low gas
bubble bursting pressure which is insufficient to proper debris removal (35). Kerosene or hydrocarbon oil-based dielectric causes carbon deposition over the machined surfaces. Water as dielectric ensures higher thermal stability and allow much higher power input under critical conditions, resulting into much greater increase in the MRR (36). Carbon-rich hydrocarbon oils and carbon lean distilled water both results into poor surface integrity, wear & tribological properties (28, 37). However, application of water-based dielectric accelerate formation of cracks, electrolysis, and corrosion of the EDMed surface (37). Kerosene produced carbides on the workpiece surface while oxides formed with distilled water. Moreover, larger amount of debris and micro cracks are found in case of distilled water as the dielectric (28). Lower hardness, more micro cracks and thicker heat affected zone obtained with water based dielectrics compared to hydrocarbon based oils (13). Plain water is better in specific conditions but hydrocarbon oils are superior for a wider range of machining conditions. Highly concentrated aqueous glycerine solution offers advantages when working with long pulse durations, high pulse duty factors and discharge currents as compared to hydrocarbon dielectrics (38).

Compressed air as a dielectric medium was used in dry EDM to take benefits of environmental preservation, human health and prevention of fire hazards (39). However, dry EDMed surfaces revealed presence of micro-cracks due to thermal stresses, deposition of spherical particles and poke marks due to entrapped gases on the machined surface (40). The problem during dry EDM is particle evacuation and sticking (42). It has been reported that low stability of arc column, low material removal rate, arcing, poor surface quality as compared to conventional EDM and odor of burning are the challenges in dry EDM process (42). The presence of more amounts of black patches of carbon is observed, due to higher arcing and localized heating of surfaces on dry EDMed surfaces (43). Lower viscosity and thermal conductivity of gas produce a weak cooling effect on the work piece. Due to the lower thermal conductivity of air (0.024W/mK) that of a kerosene (5W/mK), cooling of a workpiece is much reduced in dry EDM. However, Cryogenic cooling of the workpiece resulted in an improvement in dry EDM performance (44).
A mixture of compressed air/gas with water/or other liquids in the form of mist as near dry EDM have been experimented with a view to improving the debris detachment and minimize chances of reattachment with the work and tool material to reduce the chances of dimensional and geometrical changes. Research need in EDM for replacement of the dielectric liquid with dry or semi-dry dielectric fluids having a lower negative impact on the environment (45). Near dry EDM resulted higher material removal rate (MRR), sharper cutting edge, and less debris deposition as compared to dry EDM. However, near dry EDM produce higher material removal rate at low discharge energy and generate a smaller gap distance compared to wet EDM (46). Near-dry EDM exhibits good machining stability and smooth surface finish at low discharge energy. The disposal of used dielectric of near dry EDM is cleaner than that of powder mixed dielectric used for EDM (47). Problems like higher discharge energy requirement in wet EDM and the reattachment of debris to the machined surface in dry EDM can be overcome in near-dry EDM. However, selection of proper dielectric medium and process parameters is a technical barrier in near dry EDM (48). Performance analyses of dry and near dry EDM suggest that for a wide range of machining conditions, liquid dielectric fluids are indispensable (36,46,47).

Water-in-oil (W/O) emulsion could be used as the dielectric fluid of sinking EDM with long pulse duration and large peak current to get higher MRR than kerosene. Moreover, with W/O, less carbon found deposited on the electrode surface, which might have resulted more stable discharge process. W/O is more economical and environmental friendly than kerosene (49).

Decomposition products of hydrocarbon, water, and gaseous based dielectric fluid affect the metallurgical, mechanical, tribological, corrosion resistance properties of the EDM surface.

### 2.2 Environmental Impact, Personnel Health & Operational Safety aspects/ issues of EDM process

EDM process is performed with mainly three modes of dielectric supply like wet, dry and near dry EDM. Wet EDM is performed using liquid dielectrics with
submerged bath, side jet, multi jet, through jet, swiveling jet modes etc. Dry EDM employs high-pressure jet or stream of various gases, a mixture of gases, compressed air or mixture of gas-air. Near dry EDM is practiced with a mixture of liquids and gases in specific proportions.

The phenomenon of ionization and deionization depends on various properties of dielectric fluid like breakdown strength, dielectric constant, viscosity, thermal conductivity, specific heat capacity etc., These properties can be manipulated with type and form in which dielectric fluid is used during the process. Hence, types of dielectric fluid, as well as a form of dielectric supply significantly governs the rate of ionization and deionization, the intensity of pressure & temperature generated in the plasma channel, and the generation of decomposition & emission products. The emission products adversely affect the operator’s health and safety while the sludge and waste generated during the process pollute environment and land.

2.2.1 Environmental Impact of EDM

2.2.1.1 Wet EDM

*Hydrocarbon-based dielectrics*

Manufacturing industries are considered as the main sources of the environmental pollution (50). Compared to other conventional manufacturing process, EDM process is highly energy intensive and environmentally hazardous due to the pyrolysis of the hydrocarbon oil–based dielectric fluids (51). Hence, EDM process has attracted research attention to identify and eliminate the sources of environmental pollution to minimise its adverse impacts. The environmental impact of the manufacturing process is evaluated using factors contributing to the environmental pollutions like emissions from metal working fluids, metallic dust, and use of toxic, combustible or explosive materials (52). Environmental aspects and impacts of EDM process have been reviewed for wet, dry, and near dry modes of dielectric supply as below.

In EDM process, due to a complex combination of the electrical-thermal-mechanical phenomenon, dielectric fluid gets decomposed and intense temperature melts and vaporizes the dielectric fluid and work material. A number
of harmful emanates, aerosols and metallic particles are released into the environment. In order to comply the requirements of ISO 14000, sources of pollutions for a manufacturing process are to be identified and eliminated. In EDM process, a major source of pollution is hydrocarbon based dielectric fluid (13). Also, dielectric vapours, aerosol, and harmful emissions have serious concerns for personnel health and operational safety.

Since the introduction of EDM, kerosene is used as the preferred dielectric fluid in the process. Bommelli (6) reported that hydrocarbon oil-based dielectric fluids emit fumes and vapors containing polycyclic aromatic hydrocarbons (PAH), benzene, vapour of mineral oils, mineral aerosols and various byproducts due to decomposition of oils and its additives. Synthetic dielectric fluids generate various forms of vapors and aerosol products. Due to extremely high temperature and pressure in the sparking gap, composition of the dielectric fluid and its viscosity have a significant influence on the generation of fumes, vapors, and aerosols.

Hydrocarbon based dielectrics release hazardous substances like aliphatic hydrocarbons, aerosols, non-specific aliphatic hydrocarbons, benzene and fine dust (53). The sludge, dielectric waste and deionizing resin need to be disposed of appropriately to prevent land and water pollution (54). In addition, mineral oil based dielectrics emit vapours and aerosols, decomposition products of oil and additives. Its volatile substances and emission products pollute the air and high discharge temperature of the process decomposes the kerosene, causing carbon elements to adhere to the electrode surface. The adhered carbon elements affect normal discharge sequences (55,56). End of life treatment of hydrocarbon-based dielectric causes severe environmental impact. In EDM processes, about 70% of the total energy is consumed by various pumping systems and only 10% by the spark generator system. In addition, dielectric represents 23% of the total environmental impact in EDM process (57). Some technological developments from fully immersed tool-work materials systems to side jetting, using water and gaseous bases dielectrics to minimize end of life treatment as in the case of hydrocarbon oil based dielectrics and ensuring minimum quantity would improve the environmental performance of the process. Process energy, exposure to
aerosol, and dielectric consumption influence the environmental aspect of green EDM. Dielectric consumption leads to environmental and economic impact (58,59). It was reported that used dielectric turns into waste and contribute significantly to the environment as well as economic impact (60). Serious occupational and environmental problems result because of the large amounts of hazardous gases, toxic aerosols, as well as liquid wastes generated during the EDM process.

Billions of liters of dielectric fluids are being used and results into waste. Wastes generated are either disposed of through sewage lines into water bodies, lands or marine beds. Hydrocarbon oils and mineral oil has biodegradability of the order of less than 30% (61). The presence of traces of non-degraded hydrocarbon contaminants is a serious concern for soil health and cause land pollution. Moreover, disposal of 1 liter of waste hydrocarbon oil into the fresh water bodies makes 1 million liters of potable water to non-drinkable (62). Disposal of waste hydrocarbon oil through sewage into the ocean adversely affects the marine ecological system (63).

Biodegradation of hydrocarbons in kerosene simulated soil has been investigated and reported that contamination of kerosene affect soil properties as a reduction in pH, conductivity, total phosphorus and the heterotrophic microbial population. Moreover, an increase in the concentration of heavy metals such as nickel, vanadium and chromium were recorded. It was observed that the rate of microbial growth and hydrocarbon breakdown were pH dependent. Kerosene is a complex mixture of hydrocarbons consisting of paraffin, cycloparaffins, aromatic and olefinic hydrocarbons with carbon numbers predominantly in the C9 to C16 range. The suitable pH range for optimum and efficient biodegradation of kerosene contaminated soil must average between 6.0 and 9.5. PH values above 9.5 will not favour rapid biodegradation and microbial growth. Kerosene reduces the soil pH value to 4.5–5.1 (62).

**Water- based dielectrics**

The distilled water was used as a possible alternative to hydrocarbon based dielectric fluids (34). However, it was in 1983, research attempts were focused on
possible emission products and its impacts on the environment, operator health and safety concerns. During EDM process, dielectric fluid is exposed to intensive oxidation and absorption of workpiece and tool particles. The solid products (pure carbon) and liquid particles (acids, pitch, water etc.) of oxidation and dielectric dissociation are gathered in the filters (63). Roethel et al. (64) investigated the role of five different dielectric fluids in view of their influence on environmental pollution, injurious to operator’s health and process performance. Although wet and dry EDM are well-established processes, some problems associated with wet EDM are electrolysis corrosion of the tool and work materials and existence of corrosion-prone working environment when using water as the dielectric and toxic emissions, contaminated waste and its disposal issues. Electrolysis corrosion of the tool & work materials is a major problem associated with wet EDM. However, water-based dielectrics produces less toxic wastes, toxic emissions, contaminated waste & its disposal issues compared to hydrocarbon-oil based dielectrics. If effective debris removal or filtration system is used, water-based dielectric wastes can be safely released via municipal sewage pipes to cause minimum environmental and land pollution (65). Water-based dielectrics indirectly affects the environment by consuming more energy. They mentioned that 50% of the total energy supplied is consumed by the dielectric system and as water has different values of specific weight, viscosity, dielectric strength, and different ionization mechanisms compared to hydrocarbon based fluids, an indirect adverse environmental impact of water-based dielectric is more than hydrocarbon based fluids (66). Water-based dielectric fluids can be a solution with a view to reducing toxic emissions and improve environmental friendliness compared to hydrocarbon based dielectrics for EDM. They also reported about environmental impact resulting due to waste and emissions generated by oil and water based dielectric media (13).

**Additives and powder-mixed dielectric fluids**

Organic and inorganic chemical compounds are added to the dielectric fluid as additives and fine metallic & non-metallic powders are added into the dielectric media for improving the process performance with a view to increasing MRR, surface integrity, and surface finish. One of the earliest work in this direction carried
out is by (67) where they have studied the feasibility of using water solutions of organic compounds like sugars, polyhydric alcohols, and their polymers. They mentioned that addition of organic acids into water solutions cause problems related to corrosion and conductivity. Thick solutions with high concentrations have a similar environment for the operator as like EDM oils and thin solutions cause little smell in the operator working area. Konig & Jorres (36) have experimented using aqueous solutions by adding organic compounds with large molecular structures such as ethylene glycol, glycerin, polyethylene glycol 200, polyethylene glycol 400, polyethylene glycol 600 and sugar. However, these compounds would be decomposed by the electric sparks producing gases with higher pressure than those produced by the decomposition of pure water. High-pressure gases are likely to react with dielectric and aerosols generated which in turn pollute surrounding environment and also dielectric. Use of powder suspended dielectric fluid in EDM improves surface finish largely. Usage of powder mixed dielectric increases the machining cost, disposal of waste generated causes an environmental concern (54). However, in practical applications, the powder suspended dielectric circulation system is also challenged by separating the machined debris from the useful powders and maintaining a constant powder concentration. Handling and disposal of the waste powder mixed dielectric offers environmental and pollution (68,69).

2.2.1.2 Dry EDM

The dry EDM process utilizes compressed air or gases as dielectric media to substitute hydrocarbon oil-based dielectric fluids to make process environmentally and operator friendly. Air and other gaseous media or mixture of air-gas are used at different pressure and proportion to obtain tailor-made dielectric characteristics in the sparking gap and process performance. However, limited work has been reported related to environmental aspects and impacts of dry EDM. Research work carried out on dry EDM for its environmental aspects and impacts is reviewed as below.
Practical application of the dry EDM process offers many advantages for machine makers and machine end users. Dry EDM permits simplicity of the machine construction, less sophisticated and simple dielectric circulation and cooling system. Hence, design, manufacturing and material costs involved can be reduced (66). Due to the lack of dielectric oils in dry EDM, the presence of organic substances as emission products are minimum which tend to reduce environmental impacts (41). Dry EDM was developed to decrease the pollution caused by the use of liquid dielectric which leads to production of vapour during machining and the cost to manage the waste. The most concerning matters of dry EDM is the inability to recirculation of used gas, tiny particles suspended in the gap and increased gas concentration near the operator working and machining environment. A significant part of the energy (50%) is consumed by liquid dielectrics and its supply system. It can be minimized with dry EDM especially with low energy discharge conditions. Hence, the overall contribution of dry EDM with gaseous dielectrics on the environmental impact is considered low compared to wet EDM particularly with hydrocarbon-based oils (59). However, MRR in dry EDM is comparable to wet EDM under specific conditions. Due to poor debris detachment, surfaces are likely to be rougher. Hence, overall cost of dry EDM is higher than wet EDM.

2.2.1.3 Near dry EDM

Tanimura et al. (70) experimented near dry EDM in 1989, by utilizing the liquid-gas mixture as the dielectric fluid. It is found to be beneficial for the finishing process with good machining stability. Only a small amount of dielectric liquid is necessary to obtain stable machining, if the dielectric liquid is supplied to the spot which is likely to be dried out, heated up, and contaminated with debris. Near dry EDM is also known as Mist EDM causes pollution and difficulty in cleaning and piping required for mist recirculation (71). Disposal of dielectric of near-dry EDM is cleaner than that of powder mixed dielectric EDM (4). Tiny water mist produce severe electrolysis corrosion on the machined surface. Electrolysis products mixed toxic dielectric causes health hazards to the operator and its disposal pollutes the
land. As a result, Tao et al. (4) suggested kerosene mist with compressed air as dielectric for near dry EDM.

2.2.2 Personnel health aspects of EDM

Personnel health in the context of manufacturing activities is related to the impact of emissions from manufacturing operations on directly exposed labor due to chronic exposure, high level of breathing zone concentrates and compliance of regulatory requirements for the maximum permissible emissions values (52). In the manufacturing industry, exposure to hazardous gases, toxic aerosols, and metallic particles for a long time was considered to be a serious occupational health hazard to the operator (72,73).

2.2.2.1 Wet EDM

Industrial personnel's with prolonged direct exposure to cutting fluids in case of conventional machining processes are highly prone to suffer from occupational skin dermatitis. The exposure to oil mist of metal working fluid may contribute to adverse health effects and safety issues, including toxicity, dermatitis, respiratory disorders and cancer (74). In the EDM process, workers are exposed to dielectric fluids of various viscosities, which are strong skin irritants (32).

Hydrocarbon-oil-based dielectric fluids

Dielectrics based on mineral oils generates detrimental products such as polycyclic aromatic in solid and liquid states, oily fog, metal particles and disintegrated parts of oils and additives. Metallic particles cause allergic reactions, asthma, and lung diseases. Hydrocarbon exposure causes health problems like a headache, dizziness, confusion, irritation of the skin, eyes and nose, memory difficulties and stomach discomfort (23). Harmful products such as aromatic hydrocarbons, pitch, and sulphur disintegrate into sulphur dioxide and monoxide, which are injurious to operator's health and may cause benign and malign tumors. Carcinogenic hydrocarbons like benzene and PAHs are expected in case of hydrocarbon-based dielectric fluids. It contains high concentrations of paraffinic and naphthenic petroleum solvents and small amounts of aromatic compounds.
(63). During EDM operation, the operator can easily inhale the vaporized dielectric which may cause an adverse effect on health. Hydrocarbon solvent in the dielectric fluid is probably irritant by exerting its solvent effect primarily on the stratum corneum and upper epidermal cells (23).

The substances found in the emissions of oil based dielectrics are carcinogenic and hazardous to the operator and to the environment as well (13). Evertz (75) mentioned about a report by BIA, Germany, published in 1995, and suggested that from a health perspective, it is recommended to use a minimum dielectric level of 40 mm for EDM process. It is expected that emissions decrease with increasing dielectric levels as more dielectric level above the emission source (processing location), the more substances will be dissolved, precipitated and condensed in the dielectric before actually emitting into the air. A dermatitis or skin irritation is the frequent effect linked to persistent kerosene disclosure. Impact on biodiversity, socio-economic and psycho-health can result due to improper management of kerosene waste (76). Report by Chilcott (77) revealed that toxicity occurs if kerosene is inhaled. Irritability, restlessness, ataxia, drowsiness, convulsions, coma and death can be the effects of acute and chronic exposure. EDM with mineral oils or organic dielectric fluids generate hazardous fumes such as PAH, benzene, vapor of mineral oil, mineral aerosols, and other products are generated by dissociation of oil and its additives. Hydrocarbon-oil based dielectrics produce the same types of vapors and aerosols except PAH and benzene. Due to the vaporization of the workpiece and tool electrodes, inorganic substances such as tungsten carbide, titanium carbide, chromium, nickel, molybdenum, and barium are released and condenses in the air. Emissions of organic materials are generated by the vaporization of the dielectrics (78). Emissions based risk reduction assessment for EDM revealed that tools and workpieces used have a strong influence on aliphatic compounds and metals, but not on volatile organic compounds BTEX and PAHs in air emissions. Increasing the dielectric (mineral oil) level above the processing location decreases BTEX, chromium, nickel and PAH emissions. Aliphatic compounds, in contrast, increase in air emissions. At higher values of peak current (7A) and pulse duration (520 µs), the concentration of
aerosols at breathing zone of the operator was above the permissible exposure limit value for respirable particulates (5 mg/m$^3$). Detailed emission constituent analysis revealed that a major portion of aerosols generated (69%) constitutes metallic particles and presence of about 20 different hydrocarbons present in the aerosols. The size of the spherical aerosol particulates is 20 to 29 nm (24). Dermatitis or skin irritation is the frequent effect linked to persistent kerosene disclosure (25).

Life cycle analysis for EDM process reported that there is a potential risk for EDM operators due to higher than the permitted concentration of aerosols and gaseous emissions near breathing zone and nearby surround (57). Near operator breathing zone, a major proportion of the aerosol (about 69%) constitutes metallic particulates of spherical shape with average sizes ranging from 20 to 29 nm. Analysis of the aerosol produced indicated the presence of about 20 different hydrocarbons with is potential threats to the operators. Gaseous hydrocarbons present in the work atmosphere contained straight chain, branched chain aromatic, alicyclic, and heterocyclic compounds. So, there is risk associated with exposure to gas phase emissions generated from the EDM process (58).

**Water-based dielectric fluids**

EDM process with deionized water and commercial water based dielectrics also generates toxic gases and fumes due to the thermal decomposition (65). Leao & Pashby (13) summarised the research related to substances generated from deionised water and commercial water based dielectrics. It was reported that deionised water produce the lowest number of substances, which are much less hazardous to the operator and the environment. Some of the substances, e.g., benzene, benzopyrene are classified into norms and are submitted to severe prescriptions in the matter of toxicology and limit values of concentration (79). Benzopyrene and benzene are considered as a carcinogenic. Water-based solvents release carbon monoxide, nitrous oxide, ozone, and harmful aerosols (78). Antisepticise action must be taken into consideration when water-based working fluid are to be used in industrial applications (80).

**Additives and powder-mixed dielectric fluids**
Organic dielectric fluids and additive mixed dielectric fluids generate hazardous fumes such as PAH, benzene, the vapor of mineral oil, mineral aerosols and other products due to dissociation of oil and its additives (65). The addition of additives and powders in various proportions have some adverse impacts on personnel health. Aromatic hydrocarbon based additives in dielectric fluids has a serious toxicological effect and is harmful to the operator health (79). Oil based dielectrics with 2% rosin mixed emulsion as dielectric produces explosive mix gases having high explosion possibility. They also reported that harmful gases are not generated with water-based emulsions without rosin additives and resulted in better environmental practices (81).

2.2.2.2 Dry and Near Dry EDM

In dry EDM, dielectric media such as compressed air, inert gases or a mixture of both carries detached debris globules to increase concentration of tiny and micro debris in the operator breathing zone. Inhalation of such contaminated air may cause respirable and lung-related health effects. Also, the odor of burning of the tool and work material with air or gaseous media has some health effects. Near dry EDM using water mist causes severe electrolysis corrosion and results into blackened and rugged work surface. Post EDM cleaning of toxic corrosion products and its handling may be hazardous to the operator (4). Therefore, water mist is not favorable to implement in near dry EDM. Aerosols generated due to the supply of the mixture of liquids and gases at high pressure enhances the aerosol concentrations near operator working area. This is a severe issue concerning the practical application of near dry EDM. To prevent the dispersion of free suspending tiny aerosols, a closed conduit is required. Recirculation of used dielectric mist is also unfriendly to the operator.

2.2.3 Operational safety aspects of EDM

Operational safety is related to the amount of unsafe human interaction and ergonomic design of human interface during a manufacturing process (52).
2.2.3.1 Wet EDM

Main drawbacks of hydrocarbon oils as dielectrics are disturbances in the flushing system, the requirement to install forced ventilation to cope up with the strong odors and health hazards due to the gasses and vapors generated and flammability of dielectric (66). The EDM process has several hazard potentials viz., emission of gasses and aerosols, fire, explosion, depressing effect and electrical hazard. The EDM process utilizes the high amount of energy and dielectrics of low flash and fire points. The risk of fire and explosions in close and non-ventilated machine work area is one of the biggest threats to the EDM operators (53). The possibility of direct exposure to electromagnetic radiation during the dielectric breakdown. The presence of the magnetic field near sparking zone, and electromagnetic radiation due to plasma are one of the indirect health threats to EDM operator (82,83). A technical article by Kern (84) reported that operators working on EDM machine are likely to get affected by various types of hazards like electrical, explosion, fire, chemical and spillage. Improper ventilation for emitting gases results into entrapment of hydrogen gas surround the operator working area. EDM discharges can ignite the mixture with a violent explosion. Fire is a very common hazard noticed in EDM operation when the temperature of the dielectric reaches to its flash point leaving operator at very danger. This can be prevented by maintaining the oil temperature below its flash point using a chilling system and timely maintenance of various safety systems of the machine in proper working conditions. Chemical hazards are another concern in EDM practice resulting due to cleaning solutions used which are mainly phosphoric and muriatic acids and petroleum based solvents cause skin dermatitis. Water filled tanks are highly susceptible to bacterial growth. Operator contact with bacteria affected parts is a serious hazard for EDM operators. Oils are also likely to get contaminated with bacteria’s. So it is recommended to periodically replace the fluid in the tank when it starts odd smelling. Toxicity and flammability of the dielectric affect operational safety considerably and are used for risk assessment analysis of the EDM process. The possibility of fire hazard and explosions due to lower flash points and electromagnetic radiation are serious operational safety-related issues. It was
recommended that due to high volatility and temperature, if possible, dielectrics with a flash point below 65°C should not be used. A flash point above 100°C is preferable (78). The HAZOP study of the EDM process and reported that EDM process is vulnerable to fire and explosion hazards (24). A water-in-oil (W/O) emulsion as dielectric for EDM was more environmentally friendly and safe since the fire hazard can be excluded using this nonflammable working fluid (85,86).

2.2.3.2 Dry and Near Dry EDM

Odors of burning of air and gaseous media are unpleasant to an operator. Very low viscosities of the gaseous dielectric cannot restrict the plasma channel to narrow region. The unrestricted explosion of the plasma channel causes debris from the sparking gap to float freely in the form of a tiny aerosol in the operator working area. Chances of direct exposure to electromagnetic radiation due to unrestricted plasma are one of the serious safety concerns for the operators. High-pressure delivery of liquid-gas mixture into the sparking zone carries expelled debris particles with it. Supplied mixture is to be confined, otherwise, may result into slippery shop floor conditions due to oily mist. Oxygen mixed water-in-oil emulsion is nonflammable and hence it excludes the possibilities of fire hazards in EDM (49). Water based and gaseous based dielectrics can be alternate replacement of hydrocarbon oil based dielectrics in EDM in terms of environmental, personnel health & safety considerations while hydrocarbon oil based dielectrics are found to be superior in terms of process stability and performance. So, to increase sustainability of EDM process, alternate dielectrics having better and comparable performance in all sustainability criterions are to be evaluated.

2.2.4 Drawbacks of EDM Dielectric fluids

From the literature reviewed in this section, it has been found that the dielectric fluids have certain drawbacks which adversely affect the metallurgical structure, surface integrity, environment, health, and safety.

From the reviewed past works, it can be summarized that hydrocarbon, water, and gas based dielectrics have an adverse influence on process...
performance in terms of the environment, social and economic viewpoints. Decomposition products of dielectric causes carburization or decarburization which affects surface hardness; different thermal conductivities result in surface cracks and affect endurance and fatigue strengths due to varying cooling rates. The viscosity of dielectric fluid influences the quantity and quality of emission products generated. Density and dielectric strength of the fluid affect debris evacuation efficiency which in turn affects surface roughness and material removal rate. The composition of the dielectric affects corrosion and other surface characteristics of the material.

Drawbacks of various types of dielectrics are listed as below.

**Hydrocarbon based oils:**
- a) Release of hazardous emission products
- b) Carburization (Carbon deposition on the machined surface)
- c) Toxic and non-biodegradable waste generated
- d) Fire explosion
- e) High specific energy consumption
- f) Electromagnetic radiation

**Water based dielectrics**
- a) Corrosion of EDMed surface
- b) Electrolysis of the dielectric
- c) Decarburization (Carbon depletion from the machined surface)
- d) Micro cracks formation on the EDMed surface

**Dry/gaseous dielectrics**
- a) Poor flushing
- b) Debris detachment
- c) Poor surface finish
- d) Reattachment of debris
- e) Unstable sparking
- f) Poor dimensional and geometrical accuracy

**Mixture of wet and dry dielectrics (Near Dry)**
- a) Release of aerosols
b) High concentration of aerosol in the operator breathing zone

2.3 Review on Vegetable Oil Based Dielectric Fluids

The emergence of the concept of sustainable manufacturing and therefore requirement to comply with ISO 14000 (Environmental Management Standards) have demanded to identify and used green products as alternative to the environmentally hazardous products. To meet these requirements, greener, safer, and environmental friendly solutions are to be searched as an alternative to toxic and hazardous hydrocarbon based dielectric fluids for EDM process. An earlier study reported about the dielectric properties of vegetable oils (87). Vegetable oils, because of its non-fossil origin, could be an appropriate alternative to environmental, safety and health problems, and could have lower end-of-life costs associated in terms of environment, economic and social point of view (88). Some vegetable oils meet the technical requirements of conventional dielectric fluids. Their high biodegradability and non-toxicity are other qualities making these natural oils an interesting raw material for the development of new environmental friendly dielectric fluids (89). Since the mid-1990s, Vegetable oils have been experimented as dielectric or insulating oil for electrical transformers by researchers. Many researchers have worked and reported about the environment, technical and social aspects of using vegetable oils as alternate to conventionally used mineral oils, hydrocarbon oils, and synthetic oils.

2.3.1 Composition of Vegetable Oil

Vegetable oils, also known as tri-glycerides, possess the chemical structure as shown below. Chemical structure comprises of 98% tri-glycerides and small amounts of mono and di-glycerides. Tri-glycerides are esters of three molecules of fatty acids and one of glycerol and contain substantial amounts of oxygen in their structure. The fatty acids vary in their carbon chain length and in the number of double bonds.

Vegetable oil are naturally synthesized by esterification of the tri-alcohol, called glycerol, with three fatty acids. The fatty acids are composed of linear hydrocarbon chains ended by a carboxylic function. These molecules have an
even number of carbon atoms (typically from 8 to 22 in tri-glycerides) and the chain can be saturated or mainly mono-, di- and tri-unsaturated. Fatty acids are represented as like C18:0, where the first number represents the numbers of carbon atoms and last number indicates unsaturated bonds in the molecule. The different crop plants contains oils, which can be characterized by the relative quantities of fatty acids. The nature of the fatty acid components of tri-glycerides plays an important role in determining the physio-chemical properties of bio-oil (88).

2.3.2 Saturated, Mono Unsaturated, Poly Unsaturated Portion

Natural esters are categorized as saturated and single, double and triple unsaturated fatty acids. Saturated fatty acids are chemically stable but of high viscosity. Triple unsaturated fatty acids have a low viscosity, but are very unstable in oxidation. Vegetable oils with a high percentage of single unsaturated fatty acids are proven as useful. Vegetable oils containing a high percentage of unsaturated fatty acids are proven as useful. Vegetable oils containing a high percentage of unsaturated fatty acids, resulting in a lower viscosity and better low-temperature properties. While those with a higher percentage of saturated acids are known to improve oxidative stability. An optimal balance has to be selected between the two types of fatty acids contents in vegetable oils (90).

Vegetable oils possess a tri-glyceride structure. There are three fatty ester linkages in the tri-glyceride molecule which may be completely saturated (no double bonds), mono-unsaturated (one double bond/fatty ester linkage), di-unsaturated (two double bonds/fatty ester linkage) and tri-unsaturated (three double bonds/fatty ester linkage). Fatty acid chain with unsaturation in its fatty acids offers high reactivity with O₂, especially, when it is placed in contact with air/water. Further, the fatty oils with more poly-unsaturation are more prone to oxidation. The relative rate of oxidation for the methyl esters of oleic (18:1), linoleic (18:2), and linolenic (18:3) acids to be 1:12:25 respectively (91).

2.3.3 Sustainability Aspects of Vegetable Oil Based Dielectric Fluids

Advantages of vegetable oil for industrial applications:

- It is safer due to higher flash and fire points than most mineral based fluids.
• Its toxicity to organisms and humans is minimal.
• It is renewable
• Easy to handle and storage
• Lower Green House Gas (GHG) emission compared to mineral oils
• Lower life cycle cost than mineral and synthetic oils
• Generates low amount of combustion emissions (Except NOx), hence better personal health and working environment
• Reduced environmental impact, so in the case of a spill, no hazardous chemicals would have to be cleaned up and they have less toxicity to living organisms.
• Promote agro farming in non-fertile and waste lands thereby uplifting rural employment and economy
• Huge import revenue saving to strengthen national economy
• Reduced dependence on foreign oil import, which gives the country preservation of foreign reserves.
• Enhance economies in communities engaged in agricultural production, since the source is renewable resources.

In the context of sustainable manufacturing philosophy, other than technical performances, total life-cycle costs and end of life costs are critical for the material and process selection criterions. The minimum health and environmental related requirements for applying a liquid as a dielectric fluid are listed below:

• Non-toxicity
• Biodegradability
• Production of only acceptable and low-risk thermal degradation by-products
• Recyclable, reconditionable, and readily disposable
• Not listed as hazardous material
• Thermo-stable

It is reported that about 30 to 40 billion liters of mineral oil are in use as dielectric insulating fluid in transformers operations worldwide (92). Billions of liters of waste dielectric fluids are disposed of annually in either landfill, sewage lines or
riverbeds. It is reported that 1 liter of waste oil can contaminate one million liters of water (93). It is also reported that 1 kg of waste oil might make 5 million liters of water unfit for drinking (94). This has very serious implications on environmental pollution and sustainable living.

The requirement to develop dielectric fluids that are economic, biodegradable, non-toxic and derived from renewable sources are very important for ecological sustainability. In search for an economically viable and renewable raw material for alternative dielectric fluid, natural plant-based oils have potential to use as the dielectric fluid. It may also satisfy affordable cost, health, and ecological considerations. ABB Inc., U.S.A. developed environmentally friendly bio-based dielectric fluid called BIOTEMP fluid. It was the first commercial bio-based dielectric product (89). The fluid shown excellent dielectric characteristics with high-temperature stability, superior flash & fire resistance, excellent compatibility with solid insulating materials and high biodegradability. Then forth, attempts have been reported stating progress made in the search for inflammable and non-toxic insulating fluid. However, the basic challenge in using a natural ester as a dielectric fluid is in synthesizing a fluid with low pour point and high thermo-oxidative stability (95). Vegetable oil based esters have dielectric properties comparable to hydrocarbon and synthetic oils (96). Esterified bio-oils have been used for electrical power transformer due to its superior properties and characteristics than hydrocarbon and mineral based oils (97). Based on its impact on sustainability, vegetable oils are categorized into edible, non-edible and used oil in terms of highest to lowest severity. Recondition and reuse of used vegetable oils may have enormous positive impact on sustainability. Biobased fluids have some potentials to replace hydrocarbon, water and gas based dielectric for EDM process. Economic, social and environmental sustainability can be obtained through the application of natural esters (vegetable oils) for power transformer applications. In terms of economic costs and environmental considerations, soya bean oil and palm kernel oil appear to be viable alternatives to transformer oils. That raw form of both the oils is suitable for low voltage applications while purified forms are suitable for high voltage application (98).
2.3.4 Processing of Vegetable oils

Unfavorable properties of vegetable oils like higher viscosity and poor oxidative stability, higher dissipation factor and pour point can be significantly changed to favorable, if neat vegetable oils are converted to methyl/ethyl esters of vegetable. Esters (Methyl/ Ethyl) of vegetable oils can be produced by esterification followed by transesterification. The oils and fats are filtered and washed to remove water and contaminants. In case of higher percentage of free fatty acids in the raw oils, it can be removed or transformed into esters using special pre-treatment technologies. The pre-treated oils and fats are then mixed with an alcohol (usually methanol) and a catalyst (usually NaOH- Sodium hydroxide). The oil molecules (tri-glycerides) are broken apart and transformed into esters and glycerol, which are to be separated and purified. The edible oils like soybean, sunflower, mustard, palm, cotton seeds, whose acid values are less than 3.0 are transestrified with methanol in the presence of sodium methoxide as catalyst. Non-edible oils like Mahua, Karanja, Jatropha, and Castor oils having acid values more than 3.0 require esterification followed by transesterification. The methyl esters produced by this method are analyzed to ascertain their suitability for various applications.

A raw or crude form of vegetable oil contains free fatty acid (FFA) content and other unsaturated acids, which result into poor oxidative and thermal stability making storage and shelf life of the oil a matter of concern. Esterification followed by transesterification have to be used for the removal of FFA and unsaturated acid contents to convert crude or raw oil in to methyl ester or ethyl ester, which are commonly known as biodiesel. The natural esters comply the IEC standards for the physico-chemical and electrical properties as per the IEC standards for liquid dielectric fluid for the transformer applications.

2.3.5 Suitability of Vegetable Oil Based Dielectric Fluids

There is an increasing trend toward using vegetable oil-based dielectric fluid due to its high sustainability index. It has been reported that vegetable esters based dielectric coolants have most favorable environmental profile compared to
all commercially available non-ester dielectric coolants (99). Vegetable oil-based methyl esters have been successfully tried for power transformer applications under varying voltage conditions and also for other electrical engineering applications (89,100,101). Neutralizing or other processing enhances electro-chemical properties of vegetable oils and makes it acceptable for electric applications and it is possible to develop a highly biodegradable and environment-friendly vegetable oil-based dielectric fluid (92). Vegetable based dielectric fluids are having higher biodegradability (more than 97%) than their conventional counterpart's regular mineral oil (30%) and high temp mineral oils (20%)., elevated flash and fire points, good oxidation stability and endurance during life testing (102). The vegetable oil based esters contain more oxygen and lower calorific value than hydrocarbon diesel. So, it enhances the combustion process and generates lower nitric oxide formation in the exhaust than diesel (103). Vegetable oils are better to mineral oil in terms of dielectric constant and dielectric loss parameter (96). Vegetable plant-based natural oils possess dielectric properties comparable to or even better than hydrocarbon- and mineral oil-based dielectrics (96).

Research reviewed indicate that vegetable oil-based methyl esters have been successfully tried for power transformer applications and other electrical engineering applications. A research study is planned to investigate the technical feasibility of using vegetable oil as a dielectric fluid for electrical discharge machining (EDM) and compare the performance results with conventional dielectrics being used for the process.

*The potential of the bio fluids as a dielectric fluid for EDM is identified due to following facts and (Table 2.1),*

- Higher flash point (96,105)
- Excellent biodegradability (105)
- Higher oxygen content (106)
- Low carbon atom chain (89,106)
- Nontoxic (97,107)
• Higher breakdown voltage (92, 96, 99)
• Higher viscosity (99)
• Lower toxic emissions (108)
• Lower volatility and toxic emissions (108)

In search of an environment friendly dielectric fluid, various vegetable oils and its derivatives have been experimented by researchers. It has been noticed that selection of raw vegetable oil as a substitute to hydrocarbon and mineral based dielectric fluid was skewed demographically. In India, dielectric properties of vegetable oils like castor, jatropha, groundnut, sesame oils and Indian beech oil have been studied (87, 109). Coconut oil was successfully tested for its suitability as a dielectric fluid for power transformers application in Sri Lanka (100). In Malaysia, researches developed palm oil based dielectric fluid for power transformer applications (105, 110). Soybean, Rapeseed, Corn and Sunflower oils have been used to produce commercial grade dielectric fluids in the USA and European countries (61, 89, 102, 111, 112). Attempts were made using Jatropha curcus and castor based oil as dielectric fluid in warmer parts of Asia and African countries (101, 107, 113). However, application of edible vegetable oils like palm, soybean, rapeseed, sunflower, corn, coconut oil etc. as environment friendly dielectric insulating fluid may affect the human food chain and are expensive than hydrocarbon or mineral based oils.

2.3.6 Non-Edible Oils as Dielectric Fluid

Use of edible vegetable oils, known as first generation feed stocks, offer serious concerns due to food versus fuel debate, which might lead to starvation in developing and underdeveloped countries. Non-edible vegetable oils also known as second generation feed stocks like, Castor (Ricinus communis), Jatropha (Jatropha Curcus or Ratanjyot), Karanj (Pongamia Pinnata), Moringa Oliefera, Neem (Azadirachta Indica), Waste Cooking oil etc. have the potential to be used as low cost sustainable source of oils for industrial purposes due to its adaptability in arid and semi-arid conditions, unfertile lands and requirements of less moisture contents. Moreover, it does not compete to the food chain and promote
forestification in non-farm lands (114). Application of non-edible vegetable oils as new generation dielectric fluids, may accelerate the rural growth, forestification, and promote sustainable living by substituting the hydrocarbon and mineral oil-based dielectric fluids.

Jatropha and Castor oils comply with the IEC standards and can be used as candidates for biodegradable insulating fluid. However, castor oil has better insulating characteristics compared to Jatropha oil (115). Chemical and electrical properties of Jatropha oil methyl ester have good agreement with that of the mineral oil based transformer oils. Moreover, significant potential of savings for utilities and remediation procedures is possible due to high biodegradability and nontoxic characteristics (101). Performance analysis of natural esters as transformer liquid insulation using coconut, castor, and sesame oils indicated that castor oil has the best insulation performance when comparing with other natural and mineral liquid insulation materials (116). Results of the physicochemical and electrical properties of Jatropha curcas methyl ester oil (JMEO) as a substitute for mineral oil for high voltage power transformer applications shown that the physicochemical (viscosity, acidity, water content) and electrical (breakdown voltage) properties of JMEO comply with the requirements of IEEE standard C.S7. 147 (117).

WCO methyl ester has the potential to reduce the GHG (Green House Gases) emission for up to 86% compared to soy- based biodiesel which only results in 57% reduction of GHG compared to fossil fuel. The cost of waste cooking oils (WCO) is 2–3 times cheaper than raw vegetable oils. Consequently, the total manufacturing cost of biodiesel can be significantly reduced (118). It is reported that billions of gallons of waste cooking oil are being produced and its post-use disposal is a major concern due to land, water and environmental pollution and its toxic effects. Also, the cost involved in mitigating the pollution caused is also a huge burden from an economic point of view (119). Reuse of waste cooking oil reduces the waste to be disposed of into the sewage systems, contaminating rivers and ground water. One liter of waste cooking oil can contaminate 20,000 liters of water (120). Khan et al. (121) have reported that amongst all bio-oils, waste
vegetable oil (WVO) has the highest impact index of sustainability. Moreover, it is cheapest of all bio-oils. Comparison of biodegradability percentage for vegetable oil, regular mineral oil and high-temperature mineral oil are shown in Fig 2.1.

From the environment, safety and life expectancy at higher working temperature point of view, vegetable oil based natural ester fluids is superior to other types of dielectric fluids for transformer applications(96). Relative comparison of various categories of dielectric fluids for transformer applications as shown in Table 2.1.

![Biodegradability Comparison](image)

**Figure 2.1 Biodegradability Comparison of Vegetable Oil, Regular Mineral Oil, and High Temperature Mineral Oil (102)**

<table>
<thead>
<tr>
<th>Attributes</th>
<th>Mineral oil</th>
<th>Hydro carbon oil</th>
<th>Silicone oil</th>
<th>Natural ester fluid</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fire resistance</td>
<td>Poor</td>
<td>Excellent</td>
<td>Excellent</td>
<td>Excellent</td>
</tr>
<tr>
<td>Environmental impact</td>
<td>Moderate</td>
<td>Moderate</td>
<td>Moderate</td>
<td>Excellent</td>
</tr>
<tr>
<td>Life expectancy at maximum temperature rating</td>
<td>Good</td>
<td>Good</td>
<td>Good</td>
<td>High</td>
</tr>
<tr>
<td>Efficiency</td>
<td>High</td>
<td>High</td>
<td>High</td>
<td>High</td>
</tr>
<tr>
<td>Sound level</td>
<td>Low</td>
<td>Low</td>
<td>Low</td>
<td>Low</td>
</tr>
<tr>
<td>Operating temperature</td>
<td>Low</td>
<td>Low</td>
<td>Low</td>
<td>Low</td>
</tr>
<tr>
<td>Contamination resistance</td>
<td>Excellent</td>
<td>Excellent</td>
<td>Excellent</td>
<td>Excellent</td>
</tr>
<tr>
<td>Overload capacity</td>
<td>Good</td>
<td>Excellent</td>
<td>Excellent</td>
<td>Excellent</td>
</tr>
<tr>
<td>First cost</td>
<td>Low</td>
<td>Low/Moderate</td>
<td>High</td>
<td>Moderate</td>
</tr>
<tr>
<td>Energy costs</td>
<td>Low</td>
<td>Low</td>
<td>Low</td>
<td>Low</td>
</tr>
<tr>
<td>Recycle/Disposal costs</td>
<td>Low</td>
<td>Low</td>
<td>High</td>
<td>Low</td>
</tr>
</tbody>
</table>
One fact has clearly stemmed out from the literature review carried out that vegetable oils possess some properties to use it as dielectric/insulating fluid as the replacement to mineral and synthetic oil. Further processing of vegetable oils makes it as good as mineral and synthetic oil and even on some parameters better than the conventionally used mineral and synthetic fluids. But no work has yet been reported to have investigated about the application of vegetable oils insulating properties as the dielectric medium for the EDM process. As data or knowledge is not available related to its suitability as the dielectric fluid for EDM process, a technical feasibility study has been planned to investigate the feasibility of vegetable oil as dielectric fluid through qualitative and quantitative assessment.

However, application of high oil containing nonedible vegetable oils has high overall sustainability index than edible oils. Based on the literature reviewed, discussions & reviews with experts regarding demographic conditions, sustainability impact, and availability of the feed stocks, negative impact on sustainable food chain dielectric production, impact on rural upliftment, following alternative feed stocks have been identified and selected to be tried out for this study.

a) Jatropha oil (Jatropha Curcus Linn.)

b) Castor oil (Ricinus communis)

c) Waste cooking oil

2.3.6.1 Jatropha oil

Jatropha oil is expelled from Jatropha curcas seeds (Fig. 2.2) which are fast growing seed oil producing plants require little water or fertilizer and can survive in semi or non-fertile soils. Jatropha curcas can be planted in arid, semi-arid and hot regions such as the desert areas of India, western Asia, and African countries. Oil content of the Jatropha seed is 30–40% by weight. Jatropha seed oil has excellent properties, including low acidity, low viscosity compared to castor oil and a better cloud point and pour point when compared to palm oil. Jatropha oil is non-edible as it contains highly poisonous toxalbumin curcin (122). Jatropha seed yield approximately 1590 kg oil/ha with a conversion ratio of Jatropha oil to methyl ester
is 85-95%. Oxidative and thermal stability of neat Jatropha oil is poor due to the presence of free fatty acid (FFA) contents of 8-14%. Transesterification process is used to reduce the FFA content below 1% in the presence of methyl or ethyl alcohol and catalyst to obtain methyl ester. Jatropha plant contributes a reduction of up to 25 tons of CO$_2$ per hectare per year from the atmosphere (over a 20 year period).

![Figure 2.2](image-url) (a) Jatropha Green Shells, (b) Jatropha Seeds

### 2.3.6.2 Castor oil

Castor oil is a vegetable oil obtained by pressing the seeds (Fig. 2.3) of the Castor plant (*Ricinus Communis*). The castor seed contains ricin, a toxic protein making it non-edible. Worldwide castor oil production is accounted to 6, 80,000 tons of which India contributes to over 80% of world's total castor oil production (123). Castor seeds yield 1190 Kg oil per hectre with a methyl ester conversion ratio of 90-95%.

The Indian variety of castor has 40-48% oil content of which 42% can be extracted while the seed cake retains the rest (124). Castor oil is main source of ricinoleic acid, a monounsaturated, (85%) 18-carbon fatty acid. Among all the fatty acids, ricinoleic acid is unique as it has a hydroxyl functional group on the 12$^{th}$ carbon. The presence of hydroxyl group and double bonds in ricinoleic acid (D-12-hydroxyoctadec-cis-9-enoic acid) imparts unique chemical and physical properties for castor oil which make castor oil a vital industrial raw material and stabilizes the oil against oxidation. Besides reducing life-cycle emissions because of its high oil
content (50%), relatively high crop yield and less competition with food crops make it a preferable alternative source amongst other vegetable seed plants. Life cycle analysis of methyl esters produced from castor oil showed that the greenhouse gasses emissions can be reduced up to 90% as compared to hydrocarbon based diesel. Estimated CO₂ absorption level of castor bean plants is 34.6 tons per hectare with 2 growing cycles per year (125). Castor oil is the only vegetable based oil which is soluble in alcohol and does not require the consequent energy requirement for transesterification as like other vegetable oils. Castor oil has a good shelf life compared to other vegetable oils and it does not turn rancid when subjected to excessive heat. A study was reported in Indian context that if 10% of total production of castor seed oil is transestrified into biodiesel, then about 79,782 tons of CO₂ emission can be saved on an annual basis. The CO₂ released during combustion of castor methyl ester can be recycled through next crop production, therefore, no additional burden on the environment (126).

![Figure 2.3 (a) Castor Green Shells, (b) Castor Seeds](image)

**2.3.6.3 Waste Vegetable oil**

Waste vegetable oil (WVO) or waste cooking oil (WCO) or waste frying oil is the oils disposed of after use from household, restaurants, edible oil processing refineries etc. Increasing food consumption has increased the production of a lot of waste cooking oils/fats. The waste oil generated can be used as a less expensive source than edible and non-edible vegetable oils which also minimize
the waste disposal problems. This can be converted into environmental and economic benefit by proper utilization and management of WCO throughout the world.

The Energy Information Administration (EIA) in the United States (USA) estimated that around 100 million gallons of waste cooking oil are produced per day in the USA (127) while the estimated amount of waste cooking oil produced in EU is 7,00,000 -10,00,000 tons of WCO annually (128). The growing awareness about the health threats of reusing cooking oil will increase the annual waste cooking oil generation. There is a demand to identify and develop means to reuse and proper management oil WCO. WCO is a low-cost feedstock for the new generation energy source. The second use of WCO constitutes no or low carbon debt and use of WCO eliminates waste oil treatment processes such as special disposal requirements and illegal WCO landfill problems. The conversion of this amount of WCO into fuel also eliminates the environmental impacts caused by the harmful disposal of these waste oils, such as into drains. Depending upon the quality of oil source, it is composed mainly of saturated short length fatty acid alkyl chains, which was 42–50 wt% of C12:0, 17 wt% C14:0, 10 wt% C16:0 and less than 10 wt% of unsaturated compounds. With proper optimization of alcohol concentration during transesterification, ester yield may reach to 90-92% as reported by researchers.

Since 2002, the European Union (EU) has enforced a ban on feeding WCO mixtures to animals, because of formation of toxic and harmful compounds during frying. Moreover, if the WCO is used as an additive to feeding mixtures for domestic animals, then it could result in the return of harmful compounds back into the food chain through the animal meat (128). Hence, the WCO must be disposed of safely or be used in a way that is not harmful to human beings.

Proper disposal of WCO is also an important waste and environment management concern. As oil is lighter than water and tends to spread into thin and broad membranes which hinder the oxygenation of water. Most of the toxic compounds in the WCO are oxidation products from fatty acids, especially from polyunsaturated fatty acids. These polar compounds are preferentially partitioned...
into the crude glycerol phase during the biodiesel production process, with a further concentration during the glycerol purification step. Thus, the use of WCO as a raw material for biodiesel production instead of its management as a toxic residue will reduce waste treatment costs.

There are various reasons for the search of an alternative fuel that is technically feasible, environmentally acceptable, economically competitive, and readily available. The WVO reduces the cost of waste product removal and treatment. Meanwhile, it can significantly decrease the amount of farmland, which is necessary for oil producing crops. Global warming potential and environmental impact of WCO are shown in Fig. 2.4.

**Figure 2.4 Global warming and Environmental impact of WCO** (128)

The methyl ester of WCO has the potential to reduce the GHG (Green House Gases) emission for up to 86% compared to soy-based biodiesel which only results in 57% reduction of GHG compared to fossil fuel. The price of WCO is 2–3 times cheaper than raw vegetable oils. Consequently, the total manufacturing cost of WCO methyl ester can be significantly reduced (121). It is reported that billions of gallons of WCO are being produced and its post-use disposal is a major concern due to land, water and environmental pollution and its toxic effects. Also, the cost involved in mitigating the pollution generated is also a huge burden from an economic point of view (122). Reuse of WCO reduces the waste to be disposed of into the sewage systems, contaminating rivers and ground water.
But no work has been reported to have tried WCO as a possible dielectric fluid. Based on availability, economic and environmental advantages it offers, its feasibility as a dielectric fluid for EDM process is to be assessed. Fatty acid components of the selected vegetable oils are listed in Table 2.5.

Table 2.2 Fatty Acid Components of Selected Vegetable Oils

<table>
<thead>
<tr>
<th>Fatty Acid component</th>
<th>Jatropha oil</th>
<th>Castor oil</th>
<th>Waste Vegetable oil</th>
</tr>
</thead>
<tbody>
<tr>
<td>C6:0</td>
<td>0</td>
<td>0</td>
<td>0.08</td>
</tr>
<tr>
<td>C8:0</td>
<td>0</td>
<td>0</td>
<td>6.64</td>
</tr>
<tr>
<td>C10:0</td>
<td>0</td>
<td>0</td>
<td>5.38</td>
</tr>
<tr>
<td>C12:0</td>
<td>0</td>
<td>0</td>
<td>42.30</td>
</tr>
<tr>
<td>C14:0</td>
<td>0.15</td>
<td>0</td>
<td>16.77</td>
</tr>
<tr>
<td>C15:0</td>
<td>0</td>
<td>0</td>
<td>0.00</td>
</tr>
<tr>
<td>C16:0</td>
<td>14.42</td>
<td>1.38</td>
<td>11.59</td>
</tr>
<tr>
<td>C16:1</td>
<td>0.69</td>
<td>0</td>
<td>0.24</td>
</tr>
<tr>
<td>C17:0</td>
<td>0.08</td>
<td>0</td>
<td>0.00</td>
</tr>
<tr>
<td>C18:0</td>
<td>5.82</td>
<td>1.11</td>
<td>4.16</td>
</tr>
<tr>
<td>C18:1</td>
<td>42.81</td>
<td>3.35</td>
<td>9.97 (88.07*)</td>
</tr>
<tr>
<td>C18:2</td>
<td>35.30</td>
<td>4.84</td>
<td>1.82</td>
</tr>
<tr>
<td>C18:3</td>
<td>0.23</td>
<td>0.56</td>
<td>0.03</td>
</tr>
<tr>
<td>C20:0</td>
<td>0.09</td>
<td>0.25</td>
<td>0.11</td>
</tr>
<tr>
<td>C20:1</td>
<td>0.10</td>
<td>0.42</td>
<td>0.11</td>
</tr>
<tr>
<td>C22:0</td>
<td>0.14</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>C22:1</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>C24:0</td>
<td>1.47</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

* C18:1 OH Ricinoleic acid

2.4 Review for Sustainable Manufacturing Practices in EDM Process

Sustainability of any manufacturing process can be improved by minimizing environmental impact, manufacturing cost, and energy consumption while improving personnel health, operational safety, and waste management practices of the process. However, EDM process offers some environmental, economic and social concerns like poor material removal rate, electrode wear, high specific energy consumption, deteriorated surface characteristics, hazardous emissions near operator breathing zone, the possibility of fire explosion, toxic waste, and sludge generation etc.
Die sink EDM consume high amount of energy compared to conventional processes for the same amount of material removal. This indirectly affects the environment. The energy consumed for the erosion of the material is usually less than 20% of the total input of electrical energy. On the other hand, the energy consumed by the dielectric system may represent 50% of the total input of electrical energy, especially when low values of peak current are used (66). The waste mass from the dielectric was affected by the specific heat capacity of the fluid. The specific heat capacity of water is 1.5 times higher than kerosene and thus, the amount lost through evaporation is lower (54). Though the operating cost per part in EDM is lower by 42%, total operating cost of machining with commercial water-based dielectric was 36% higher than with hydrocarbon oil. It is due to cost due to equipment depreciation, electrical energy, dielectric losses, and filtering aids (13). Optimization of EDM processes can favor the minimum consumption of precious raw materials, energy and critical chemicals. This results in a positive impact on their environmental and economic performances with social benefits to improve the quality of life (26). Dielectric which turns into waste after certain cycles contributes environment and economic impact. Kerosene waste generated by EDM industry contributes to alarming pollution condition. To make EDM a green process, alternate dielectric fluids are required to be developed (59).

2.5 Research Gap

Based on the literature review carried out, following research gaps have been observed:

- Very little work have been reported that addressed sustainability and sustainable manufacturing practices of the EDM process
- No research work has been reported to have defined key performance indicators for improving sustainability of EDM process
- No research has been reported to have investigated potential of vegetable oil based dielectric fluids for EDM process
- A research gap exist to investigate the operational and technical feasibility of non-edible oils as alternate bio dielectric fluid for EDM process