ECO-FRIENDLY DIELECTRIC MEDIUMS FOR SUSTAINABLE EDM: A COMPREHENSIVE REVIEW

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ABSTRACT: *Electro Discharge Machining (EDM) is a non-traditional machining technology that uses heat energy during the removal of material from the workpiece. During the EDM, the melting and vaporization of the material occur due to the continuous electron flow from the cathode (negative) to the anode (positive). The dielectric fluid is perhaps the most vital element in Electro Discharge Machining. It's been demonstrated that dielectric fluids have a significant influence on machining characteristics like tool wear, material removal, and electrode material surface roughness. In industry, the most often utilized dielectric fluid in EDM is hydrocarbon-based oil. The degradation of these hydrocarbon oils emits carcinogenic harmful pollutants such as polycyclic aromatic hydrocarbons, carbon dioxide, benzene, and carbon mono-oxide, along with other things. To make the EDM process more sustainable, a wide range of dielectric fluids (based on gas, water, and emulsions) have been employed. The use of vegetable oils as a dielectric medium in EDM has yielded promising results. This study provides a complete overview of the dielectric fluids used in EDM to make the whole process more sustainable. Finally, a sustainability study of eco-friendly dielectrics has been described, which can render the process more environmentally friendly and safer.*

KEYWORDS: *Electrical discharge machining; Properties of dielectrics; Eco-friendly dielectrics; Vegetable oil; Sustainability index*

1 INTRODUCTION

Electric discharge machining seems to be the most frequently used non-conventional material removal method, accounting for more than 7% of total machine tool sales globally [1]–[4]. High-frequency electric sparks induce the dielectric media to decompose, resulting in extreme temperatures on the order of 8000 K to 12,000 K, which melt and evaporate the work material [5]–[7]. The process's unique feature is that the material is removed exactly and precisely at an extraordinarily high temperature [8], [9]. On difficult-to-cut materials, controlled material erosion allows for the creation of dimensionally and geometrically precise profiles [10], [11]. EDM is primarily utilized to create punches, dies, cutting tools, moulds, and steel roll surface texturing [12]–[14]. However, with advances of other variations of the technique, its applications are anticipated to be stretched to surface alloying and texturing, and fabrication of elements for medical, electronics, surgical, optical, automotive, jewellery, and aerospace sectors [15]. In terms of productivity, economy, and component quality, the dielectric fluid is crucial [15]–[17]. During the EDM process, the dielectric fluid serves a variety of purposes. The function is divided into major and subordinate functions based on its relevance in EDM physics and material removal. EDM is one of the most demanding machining methods due to the complicated collection of dielectric fluid characteristics and process physics [18], [19]. Understanding the influence of various dielectric fluid parameters on process behaviour is critical for defining and evaluating the EDM process's long-term sustainability [20]–[22]. EDM discharges solid metallic elements, aerosols, and poisonous fumes during the process of ionisation and deionisation of dielectric fluid, all of which are dangerous to the operator and the environment. Aside from that, electromagnetic radiation, fire, toxic emissions, and other health risks might occur throughout the machining [23], [24]. Furthermore, the application of green dielectric fluid as a substitute to conventional fluids is among the research topics suggested for improving the sustainability of the EDM process. Vegetable oil has the greatest sustainability rating of all the dielectric fluids since it is a plant-based naturally occurring substance. Vegetable oils that have been refined and transesterified have dielectric characteristics comparable to those applied in conventional EDM [25], [26]. As a result, they may be used to replace traditional dielectric in the EDM technique. Vegetable oil reconditioning and reusing would have a significant influence on the sustainability rating. In terms of sustainability, vegetable oil-based dielectric fluids provide substantial advantages [27]–[29]. As a result, its implementation in industrial operations is anticipated to enhance process sustainability indices. A variety of additives have also been mixed with the dielectric fluid to improve its thermo-physical characteristics and also the overall sustainability of EDM. Several types of additives that are blended with the dielectric medium in powder form are silicon carbide, copper, graphite, titanium, etc. [30], [31]. Different optimal mixtures of these additives boost MRR while reducing tool consumption and improving surface integrity when working with a low current level. Aluminium dust added to kerosene results in efficient machining with modest input current and pulse on time [32]. Furthermore, the use of glycol, waste vegetable oils, water–oil emulsion, and other materials have been documented, which yielded positive results during experimental runs. However, no evidence of these alternative dielectrics being used in industry has been found so far. Furthermore, according to a few studies, these oils promote a poor rate of heat dissipation and may be the cause of heat-affected surfaces (HAZ) [33]. Hence, this review article provides a comprehensive analysis of the current literature, which discusses various aspects of eco-friendly dielectric mediums.

2 OBJECTIVE & METHODOLOGY

The following are the summary of the document's objectives: (a) A collection of research publications relevant to the topic. (b) Identifying the specific regions where the environmentally sustainable dielectric medium has been developed and implemented. (c) Report the advantages of an eco-friendly dielectric medium in EDM operation. (d) Critical analysis of sustainable EDM technology. (e) Additionally, the authors reported the future directives for sustainable EDM. Because of the numerous advantages obtained from the usage of an eco-friendly dielectric medium in EDM operation, the amount of research articles on eco-friendly dielectric mediums has increased during the last few years (**Fig. 1**). As a result, an effort has been made to locate all necessary publications demonstrating the usage of environment-friendly dielectric fluid in EDM. A thorough assessment of the literature in the field of EDM was conducted in order to compile this manuscript. Typically, literature reviews are conducted using one of three commonly used databases: Web of Science, Scopus, and Science Direct. In the initial search, all research publications published from the inception of ecofriendly dielectric media up to December 2021 were evaluated. We discovered 300 research publications that offer reasonable proof of the current research after an intensive review of gathered databases. The research evidence included in these documents is being examined for further investigation. Because of the present focus on ecology and environmental safety, the eco-friendly lubricants/dielectrics applied in machining have gotten a lot of attention. A critical review of the literature suggested that hydrocarbon and additive-based dielectric mediums are widely used in EDM. Nonetheless, there have been few attempts to use the sustainable dielectric medium. Therefore, it has become very important to evaluate the sustainability of Eco-friendly dielectric mediums.

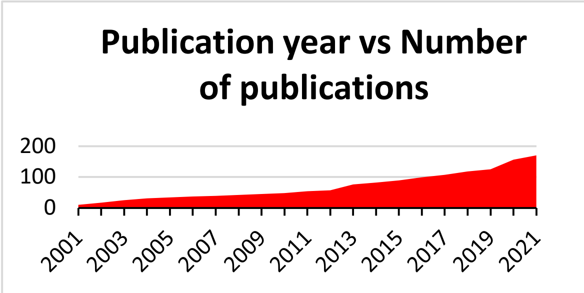


Fig. 1 An increasing trend of research on eco-friendly dielectric mediums

3 PERFORMANCE OF DIELECTRICS

3.1 Water-based dielectric medium

Water-based dielectrics were originally investigated as an alternative to hydrocarbon oil in 1981, and they are still employed to achieve superior MRR. All of the previous assessments determined that faster machining rates were achieved along with the development of cracks in the workpiece, which is undesirable in today's environment [34]–[36]. Deionized water outperformed hydrocarbon-based dielectrics in various EDM processes due to its improved flow rate, low viscosity, and higher thermal conductivity. Furthermore, deionized water decreases the carbon content acquired in the gap, resulting in a smaller heat-affected zone, and also produces less amount of recast layer [37]. At first, Kuneida et al. [38], [39] presented a water dielectric blended with pure oxygen to increase MRR, followed by a research of several dielectrics used in micro-EDM during the process of micro-hole drilling into Ti-6Al-4V alloy. According to comparisons of machining parameters in the case of tap water and deionized water, electrode wear was minor or non-existent with the copper tool of negative polarity. Owing to disassociation with the release of oxygen and hydrogen, the MRR can be considerably improved by the combination of water and organic compounds in contrast with hydrocarbon oils. Which results in oxidation of the workpiece material [38], [40]. Additionally, the process reaction force is restricted, the gap is likewise reduced compared to traditional EDM, and the electrolysis phenomena in deionized water cause the least corrosion. The legitimacy of the addition of organic molecules such as sucrose, dextrose, polyethylene glycol400, and polyethylene glycol600 was investigated by Leao and Pashby [15]. A similar experiment with the addition of urea into the water in the case of the titanium workpiece has demonstrated the creation of a hard layer after the EDM process in case of high duty factors, high open-circuit voltages, and long duration cycles. The use of deionized water in the WEDM context results in poor carbon adhesion onto the surface of the electrode, while the carbon element develops dendritic structures into the work piece's surface. One more significant aspect is the development of surface fractures as a result of thermal stresses induced onto the machined surface. The use of deionized water with a low resistivity lowered the surface roughness index for the lapping phenomena in the EDM technique [41]. Due to the deionization concept, tool wear compensation is taken into consideration for higher accuracy. With a copper tool of negative polarity, a mixture of tap water and deionized water was later used, resulting in a slight amount of electrode wear [42]. It was also discovered that using tap water to machine titanium-based alloys resulted in a considerable increase in MRR and improved tool wear conditions [43], [44]. The main defect in this medium is that it's not long-term sustainable. According to Modica et al. [45], EDMed surfaces in kerosene have lower surface roughness, while E365 and E206 machined in deionized water and hydrocarbon oil have more surface craters when compared to other dielectrics (**Fig. 2**).

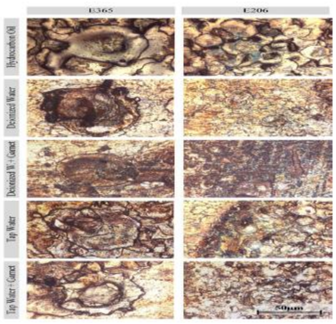


Fig. 2 Microscopic views of the crater in different dielectric mediums (Copyright reserved) [45]

3.2 Additive based dielectric medium

To improve machinability, several additives are added with hydrocarbon oils and EDM oils to regulate the characteristics of the dielectric fluid [46], [47]. For instance, Carbon nanotubes are often substantially tougher than steel and also have far higher thermal and electrical conductivities than copper. Owing to the accessibility in powder form of highly conductive materials, they diminish the breakdown strength of dielectrics when applied, like other powder additives. Once combined with the medium, they provide a more stable MRR than typical hydrocarbon dielectrics. When it comes to the carbon nanotube-mixed fluidized media, it has a lower tool wear rate [48]. In the case of machining without carbon additions, the fluctuation of MRR is observed with changes in process parameters. However, with carbon additives, nearly a constant MRR may be produced without any substantial fluctuation. In terms of tool wear, carbon additives produce acceptable results when compared to traditional EDM. While injected into a dielectric medium, copper is a very conductive material. It speeds up pulse propagation and also reduces dielectric strength. Nevertheless, the inclusion of copper is unlikely to enhance the material removal rate but may improve the microhardness of the machined surface [49], [50]. Tripathy et al. [51] assessed silicon carbide powder concentration, surface morphology, recast layer development, and other variables during the electro-discharge machining of H11 steel. The results show that the inclusion of carbide additives within the allowed range decreases dielectric strength, resulting in greater removal of debris particles and a considerable enhancement in surface integrity.

Aluminum additions can also help increase EDM oil's dielectric properties. Micro-hole drilling on tungsten carbide using a copper-tungsten electrode boosted MRR and surface integrity when aluminum dust was introduced to the EDM fluid [52]. The inclusion of aluminum powder additives to EDM oil resulted in a greater aspect ratio while micromachining with copper–tungsten electrodes. The machining time is lowered when EDM is operated with micro-tools. The machining rate improved when Al_2O_3 powder grains were introduced to the EDM fluid [53]. Jabbaripour et al. [54] studied the behaviour of powder-mixed dielectric liquid during machining of titanium aluminates, with different additives such as SiC, Al, C (graphite), Cr, and Fe. Aluminum was found to be the best additive for machining titanium aluminates because it provides higher surface integrity than other additives (**Fig. 3**). Graphite has a significant influence on machining performance. It has the potential to increase MRR by 60% and minimise tool wear by 15%. Once deionized water is being utilised as a dielectric fluid, graphite powder is typically appropriate. Surface roughness and tool wear rate are considerably diminished when graphite particles are blended with the dielectric during Inconel machining with a copper electrode [49], [55]. When machining is conducted at ton = 25 µs,

Titanium is present in TiO and TiC forms and is commonly used as a paraffin or kerosene oil additive. Although there is a possibility of micro-particle accumulation inside the spark gap, it improves the MRR during machining. To prevent this, a high-pressure flushing force needs to be applied to the drilled hole [56][51]. On the other hand, the density of the charged atoms within the ionised column enhanced with the inclusion of tungsten powder, resulting in more effective localised heating, and also observed an increment in MRR with superior surface roughness properties [57]. Kumar et al. [58] investigated the die steel's surface properties and micro-hardness which is treated with the tungsten mixed dielectric liquid. It was discovered that tungsten had a mechanism of effective material transfer via the ionised channel, which might lead to significant changes in machined surface properties. These powder components also have an impact on machining results concerning surface integrity, MRR, and tool wear.

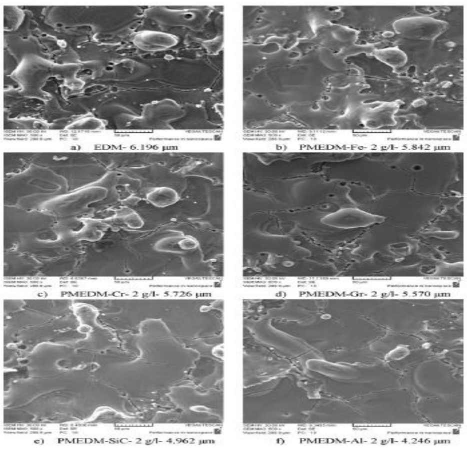
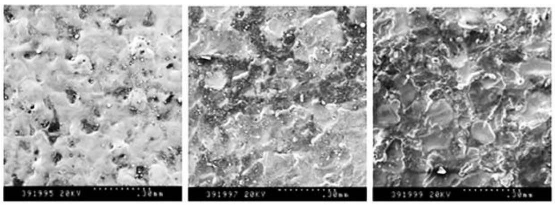


Fig. 3 SEM images of machined samples in powder mixed dielectric mediums (Copyright reserved) [54]

3.3 Gaseous dielectric medium

In Dry EDM, gaseous dielectric fluid is applied rather than liquid dielectric fluid. However, in the case of Near-Dry EDM, a gas-liquid mixture is used as the two-phase dielectric fluid, which has the advantage of allowing the liquid concentration and dielectric fluid characteristics to achieve desirable performance responses. The pipe transports high-pressure air/gas. The role of the gas is to take away debris from the spark gap while also cooling down the inter-electrode gap. The technology was designed to reduce pollution-induced with the help of dielectric fluid, which produces vapour while machining and increases the expense of waste management [59], [60]. Kunieda et al. [39] discovered that the working of EDM utilising gas (air and O_2) could be superior to that of a dielectric fluid under certain conditions, such as the application of a tubular electrode with a very thin wall, high-speed gas flow, rotation/planetary motion, and negative polarity. The material removal rate attained with air and EDM oil was lower than that of oxygen. The most significant benefit of EDM with gas is the extremely low degree of electrode wear, which has been observed to be unbiased of pulse length. Ultrasonic vibrations of the workpiece can increase the MRR of EDM with gas by assisting the rinsing of molten metal from the craters. Pattabhiraman et al. [61] studied the spray-EDM (spray-based Electric Discharge Machining) with atomized dielectric in case of Sustainable Manufacturing. Spray EDM is the process of applying dielectric to the cutting region in the form of micrometer-sized droplets. In contrast with the traditional dry and wet EDM methods, the purpose of a thin coating of dielectric lowered the amount of material utilised throughout the process while also improving machining performance. In comparison to traditional wet-EDM and dry-EDM procedures, the spray-EDM technique has 37 % of greater discharge energy. The quantity of material eradicated in the case of the spray EDM method was 78% larger than the wet-EDM processes. The flowing liquid layer has superior heat removal capabilities. Due to this, the tool wear rate in spray-EDM was much lower than that in the case of dry EDM and equivalent to that seen in traditional wet-EDM. Dhakar and Dvivedi [62] also stated that the MRR using a dielectric medium of air-water seemed to be 3.29 mm^3/min at the identical parameter selection. Finally, the researchers claimed that the combination of air and glycerine as a dielectric medium provides nearly three times better MRR than an air-water dielectric medium. About a decade ago, Liqing et al. [63] noticed deeper craters on the workpiece surface EDMed with oxygen as compared to other gases. On the other hand, recast layers were formed on the surface machined with argon gas (**Fig. 4**).



(a) (b) (c)

Fig. 4 SEM images of machined surfaces in gaseous dielectric mediums: (a) In argon (b) In nitrogen (c) In Oxygen (Copyright reserved) [63]

3.4 Emulsions based dielectric medium

The effect of emulsion as dielectric fluids has been investigated by several researchers during the past decade. The most typical method for producing an emulsion is to combine water and oil in order to make use of both liquid qualities. Emulsion seems to be more efficient, inexpensive, and ecologically friendly than kerosene, although it is less stable [64], [65]. An emulsion for die-sinking EDM was researched by Liu et al [66]. Triethanolamine oleate and sodium petroleum sulfonate make up the anionic compound emulsifier (ACE). Emulsion-1 consisted of distilled water, emulsified oil, ACE, and machine oil. Emulsion-2 contains distilled water, emulsified oil, ACE, machine oil, and OP-10. The main factor for this is the OP-10 molecule being able to access the ACE-created saturated adsorption film. It can promote adsorption and lower the Van Der Waals force among hydrophobic groups, resulting in a very modest reduction in surface tension when OP-10 is increased. As compared with kerosene, both emulsion combinations employed in EDM have a higher MRR, a larger discharge gap, lower surface roughness, and a better working environment. Emulsion-1 has a lower electrode wear ratio than kerosene. Emulsion-2 has a greater electrode wear ratio than kerosene. In contrast with emulsion-1, the emulsion-2 applied in EDM has a higher MRR, a smaller discharge gap, lower surface roughness, and a higher electrode wear ratio. The findings of the experiments demonstrate that the tool electrode is negatively polarized when employing emulsion-1 and emulsion-2 as machining fluids in EDM. Zhang et al. [67] investigated die-sinking EDM by using a special dielectric fluid i.e. oxygen mixed water-in-oil emulsion. The emulsion and oxygen have been mixed before being pumped inside the gap through the flushing hole in the core of the copper electrode. The water droplets in the emulsion had an average diameter of 8–10m. The effectiveness of material removal was observed to be much increased when oxygen was added to the emulsion. The machined surface has a recast layer, which was substantially thinner with the oxygen aided EDM because the melted material was efficiently eliminated. Zhang et al. [43] performed the EDM operation of mild steel 8407 with the help of a steel needle and five distinct dielectrics: deionized water, air, oxygen, kerosene, and water-oil emulsion and observed the effect of different dielectrics on work material properties. The sole variable considered over a wide range of 52 to 840 s was pulse on time. Even under identical experimental conditions, it was discovered that the geometric shape of the craters developed in various dielectrics differed dramatically. Due to the remarkably high viscosity of the water-oil emulsion, high pressure may be maintained for a significantly longer duration than in deionized water and kerosene. Finally, it was proposed that due to the elevated pressure at the discharge point, water in oil could remove more material. In comparison to kerosene, Dong et al. found that water-oil nanoemulsion produces a machined surface with fewer cracks and pores, as well as a cross-section with a smaller HAZ and recast layer as shown in **Fig. 5.**

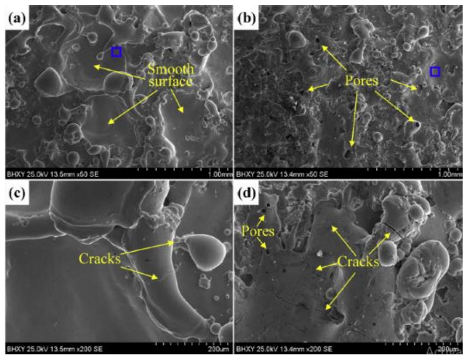


Fig. 5 SEM micrographs of EDMed surfaces: (a, c) water in oil nano-emulsion medium (b, d) Kerosene medium (Copyright reserved) [68]

3.5 Vegetable oil-based dielectric medium

The dielectric characteristics of vegetable oil-based esters are comparable to synthetic and hydrocarbon oils [69]. In comparison to hydrocarbon oils, vegetable oils produce no emissions and are environmentally safe and efficient. In contrast with hydrocarbon oils, the application of bio-based oils in EDM has resulted in higher electrode wear rates, higher material removal rates, and improved surface roughness [70], [71]. Valaki and Rathod [32] studied the possibility of using waste vegetable oil as a bio dielectric fluid in EDM. To evaluate machining responses under kerosene and esterified waste vegetable oil medium, the cold-worked plastic mould steel was machined by using a 99.73 % carbon electrode. The findings of the present study indicated that waste vegetable oil dielectrics can be employed as a replacement of hydrocarbon-based dielectric fluids for example kerosene in terms of operational feasibility. The trends of response metrics obtained with waste vegetable oil, such are comparable to those observed with kerosene. Valaki and Rathod [72] evaluated the viability of EDM using two vegetable oil-based green dielectric fluids, Jatropha oil, and waste vegetable oil. In order to assess the performance of aforesaid vegetable oils, and kerosene with respect to material removal rate, electrode wear rates, and relative wear ratio, a comparative analyses were conducted. Under the impact of current, it was discovered that the material removal rate produced with Jatropha oil and waste vegetable oil improved by 38% and 165%, respectively. Furthermore, Jatropha oil and waste vegetable oil had higher electrode wear rates than kerosene, i.e. 100% and 275% respectively. However, under the impact of pulse length, Jatropha oil and waste vegetable oil had 30% higher and 7% lower relative wear ratio, respectively. Mali and Kumar [69] looked into the viability of using Waste Vegetable Oil obtained from Pongamia Pinnata and Blended Used Vegetable Oil made from leftover edible vegetable oil, which act as a dielectric for a long-term EDM process. Copper tool electrode was used to process the Inconel 718 workpiece. When compared to conventional hydrocarbon oil, waste vegetable oil has a 32 % more material removal rate while Blended Used Vegetable Oil has a 10% lower material removal rate. When machining with waste vegetable oil, the electrode wear rate is 40% greater than with conventional hydrocarbon oil, but Blended Used Vegetable Oil produces an 8% lower electrode wear rate. Valaki et al. [70] investigated the viability of a bio dielectric fluid based on Jatropha Curcas oil for sustainable EDM. Under the effect of process factors such as current, pulse on time, gap voltage, and pulse off time, jatropha produced a greater material removal rate and reduced surface roughness than kerosene. The possibility of sunflower and canola biodiesels as a replacement of dielectric fluids in case of sustainable EDM was reported by Singh et al [73]. In EDM, Sadagopan and Mouliprasanth [71] investigated the effects of several kinds of dielectrics. Aluminum alloy 6063 was machined by using biodiesel, kerosene, and transformer oil employing a copper tool electrode. Palm styrene was used to make biodiesel, which has a reduced viscosity and a greater flashpoint. The material removal rate of biodiesel as a dielectric is much greater than that of kerosene and transformer oil, whereas the electrode wear rate of biodiesel is somewhat lower than that of kerosene and transformer oil. It was proposed that peak current, preceded by pulse on time, had the greatest influence on electrode wear rate and material removal rate. According to Das et al. [33], all vegetable oil-based dielectrics have a higher rate of material removal but reduced surface roughness compared to kerosene. However, when it comes to material removal rate and surface roughness, the results of jatropha and canola stand out. According to the findings, the neem oil has 18 and 40 % higher over and tapper cut compared to kerosene. It's because the produced crater has a smaller axial and radial extension. Canola, on either side, exhibits 12% reduced surface roughness for the similar reason. However, due to the poor heat removal rate, increased viscosity, and lower flowability of the vegetable oil based dielectrics, the produced surfaces are more susceptible to HAZ and thermal fractures (**Fig. 6**).

The subsurface physics is well described by Das et al. [74] Vegetable oils contain a larger amount of oxygen, which aids in the melting–vaporizing cycle being completed faster. As a result, these mediums may melt and evaporate a greater volume of materials than traditional dielectrics. However, dielectric constant and higher viscosity, enable greater energy confinement, which contributes to the development of uniform craters with larger radial extensions. The craters' recurrent overlapping covers most of the irregularities, indentations, and discontinuities, resulting in superior surface integrities and reduced roughness. According to studies, energy concentration is higher at the cathode than at the anode. Hence, regardless of dielectrics, the EDM process at the negative polarity of the electrode deliberates a lot more energy at the electrode as compared with the workpiece, which results in higher tool wear [75], [76]. As a result, positive electrode polarity is chosen in the vast majority of situations. Furthermore, at positive tool polarity, these types of vegetable oils and Water-oil emulsions break down and discharge carbon particles, which stick to the electrodes and produce less tool wear. The increased viscosity of these emulsions imposes a significant constraint on channel creation and generates a bigger impulse on the workpiece, resulting in larger craters and a higher material removal rate than kerosene [77]. Physical parameters such as viscosity, oxidation rate, and thermal conductivity make significant contributions to micro-hardness. The increased oxidation rate aids rapid melting and high viscosity, while the thermal conductivity guarantees good heat dissipation and flushing, and the surface is comparably harder than kerosene [68].

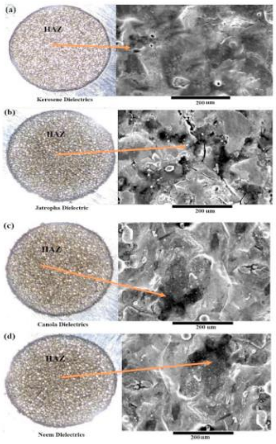


Fig. 6 A comparative study between kerosene and vegetable oil-based dielectrics in terms of HAZ and machined surface topology (Copyright reserved) [33]

4 SUSTAINABILITY EVALUATION OF DIELECTRIC MEDIUMS

The novel dielectric medium intends to minimise the effects of aerosol emissions and should restrict the production of sludge, which could retain fine alloy particles and nitrides and may produce undesirable consequences such as skin damage and eye irritation if environmental awareness is not taken into account [78]. Polycyclic aromatics, such as benzpyrene, should not be formed in the dielectric because they are carcinogenic. Particularly in the tool and die producing manufacturing divisions, EDM has a greater electromagnetic radiation impact, which directly contradicts the sustainable aspects furnished by the government and contributes waste discharge to the environment [79]. Another issue with the EDM process is its high energy consumption. In the current scenario, roughly half of the energy is used for machining and the rest is being used for dielectric flushing and cooling operations during machining [80]. Only a few studies have looked into the viability of various dielectrics. This revealed an enormous gap in customising the new dielectric while adhering to safety regulations, which is directly related to sustainable EDM regeneration. Das et al. [74] investigated the technological, social, and environmental issues of developing a sustainable dielectric medium. The technical aspects are measured by micro-morphology, micro-hardness, tool wear rate, surface roughness, material removal rate, surface integrity, etc. On the other hand, gas evolution, biodegradability, noxious odour, and impacts on operator health are social and environmental factors. This study considers all potential of future dielectrics and compares them to conventional EDM oil and kerosene. The comparison shows emulsion seems to have the highest sustainability index among all of these dielectrics. Nevertheless, vegetable oils have a lower index as compared with urea and deionized water. Furthermore, when it comes to machining performance, vegetable oils are preferable since they provide more efficient machining operations than urea and deionized water while having no negative impact on society or the environment. However, because of the high cost of extraction and transesterification method, vegetable oils are more expensive than other dielectrics [72], [81].

5 DISCOURSE ANALYSIS

The observations of the literature are carefully reviewed in order to identify potential future difficulties that may develop when such vegetable oils are evaluated for industrial use. Dry EDM is shown to be environmentally friendly, although it produces less material removal rate and inferior surface characteristics when contrasted with other mediums [97]. Dry machining, on the other hand, requires a large, airtight setup that includes a mixing chamber, pipelines, compressors, air strainers, and an MQL machine for optimum flushing [98], [99]. Aside from them, mixing two or more fluids (with the same or different phases) is necessary, and occasionally cryogenic conditions must be retained if the efficiency increases. Although dry or near-dry EDM is environment friendly, they also have an economic problem i.e. the increased cost of machining, which has a direct or indirect impact on sustainability [100], [101]. However, no such arrangements are required for water-in-oil emulsion and vegetable oils because they can be easily refilled by just substituting the conventionally used oils in the EDM tank. As a result, this section focuses solely on the difficulties that may develop when using these types of dielectric mediums. Although the high viscosity and density of vegetable oil-based dielectric are beneficial for surface integrity and machining rate, they may exhibit certain intrinsic behaviour when used in long-term industrial applications. The high viscosity causes difficulties against flushing, and this insufficient flushing can induce clotting of the debris particles, shortening the tool-workpiece gap and lowering surface energy [80]. Furthermore, the settlement of these particles can cause small spikes and unevenness, as well as unanticipated allotropy migration on the upper layer. According to the literature, the density, viscosity, and specific heat of any fluid during flushing are the primary characteristics that determine heat dissipation. A fluid with lower viscosity and high specific heat can dissipate heat more effectively. However, because these alternative dielectrics have 3-4 times higher viscosity and lower specific heat than kerosene, they may produce heat-affected zones on the processed surface [35]. The systematic replacement of the whole conventional dielectric medium is not possible due to these inevitable situations that may appear during real-life machining. A deterministic mixing method may be used to overcome these obstacles and achieve an appropriate balance between machining performance and sustainability. This will open up new research avenues in which vegetable oils are blended with kerosene in a stoichiometric proportion, ensuring both machining and sustainability. This method is already being used in the biodiesel industry, and most of these vegetable oils have demonstrated outstanding pollution management and engine performance. In terms of dielectric behaviour, several vegetable oils have previously been studied and shown to be suitable for being used as alternative dielectrics in high-voltic capacitors and transformers. In this context, the use of a blending technique can provide appropriate results while also promoting the usability of vegetable oils as a role of alternative dielectrics for industrial applications [83].

6 CONCLUSIONS AND FUTURE SCOPES

The following conclusions can be drawn from previously published literature: **(a)** Dry EDM makes use of a variety of gases. However, oxygen and air are the most common gaseous dielectrics employed in machining. **(b)** Dielectrics based on the water were the first to be employed as a substitute for EDM oil. These dielectrics performed well during machining. Water-based dielectrics are also employed in the biomedical and aerospace instrumentation industries for various sorts of coatings. **(c)** The use of an additive-based dielectric medium for surface coating and improving EDM machining performance is also a very effective approach. However, the powder materials can react with the dielectric in some cases, resulting in harmful solid waste and odours. **(d)** When it comes to machining performance, vegetable oils are preferable as a dielectric medium since they provide more efficient machining operations than alternative dielectrics while having no negative impact on society or the environment. **(e)** Few studies show that the high viscosity of vegetable oil causes difficulties against flushing, and this insufficient flushing can induce clotting of the debris particles, shortening the tool-workpiece gap and lowering surface energy.

To render EDM activities more sustainable, the following areas have now been suggested for further investigation: (a) it is necessary to do a systematic and scientific inquiry that anticipates and analyses the operator risk such as fire, explosions, the pollutants released, and the toxicity level of wastes. (b) To anticipate and describe the products of emission and the toxicity of the released waste, a scientific model must be constructed. (c) A scientific technique is necessary to define the conditions of dielectric fluid during the EDM method, which will assist in decision-making in the case of dielectric fluid's life span. (d) Research needs to be done to optimise pumping system components to decrease energy consumption. (e) Life cycle assessment (LCA) analysis is required, which will serves as a foundation for determining the suitable dielectric medium for EDM.

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