Sustainable Electrical Discharge Machining: A Review of Energy, Dielectric, Electrode and Process Strategies for Greener Manufacturing

Prof. Aniket Salve, Prof. Satish Chinchanikar, Aditya Basarkar, Ayush Baldota, Parth Bhat, Prathmesh Bodkhe, Shantanu Bhagat
Department of Mechanical Engineering, Vishwakarma Institute Of Technology, Pune, India

Abstract—Electrical discharge machining (EDM) is indispensable for shaping hard, conductive and geometrically complex components in the aerospace, die and mould, biomedical and automotive sectors. However, the process is energy intensive, consumes hydrocarbon dielectric fluids, wears away electrodes and generates fumes, sludge and waste fluid. As manufacturers face tighter environmental targets, sustainability has become a central research theme in EDM. This paper reviews the literature on sustainable EDM and organises it into six areas: quantification of the energy and environmental footprint, parameter and energy optimisation, bio-based and waste-derived dielectrics, water-based and powder-mixed dielectrics, dry and near-dry machining, and electrode and tool strategies. The role of modelling and multi-criteria decision-making in balancing productivity with environmental performance is also discussed. The review shows that vegetable-oil and water-based dielectrics, nano-additives and dry or near-dry operation can each reduce environmental burden, but each brings trade-offs in stability, removal rate, surface integrity or cost. Gaps remain in standardised life-cycle assessment, long-term dielectric ageing data, industrial-scale validation and integrated sustainability metrics. Priorities for future work are outlined.

Index Terms—bio-dielectrics, dry EDM, energy consumption, green manufacturing, life cycle assessment, optimization, powder-mixed EDM, sustainable EDM.

I. Introduction

Electrical discharge machining removes material through a series of controlled sparks between a tool electrode and a conductive workpiece immersed in, or flushed with, a dielectric medium. Because removal does not depend on the hardness of the workpiece, EDM is widely used for superalloys, titanium alloys, hardened tool steels, stainless steels and advanced ceramics and composites. This capability has made the process a standard part of modern manufacturing, including micro-scale and wire-cut variants.

The same features that make EDM versatile also give it a notable environmental footprint. Early industrial assessments, such as the study of Malaysian industries by [1] , highlighted the need to move EDM practice toward green manufacturing. Subsequent work has treated EDM as a process whose electricity demand, dielectric use, tool consumption and waste streams should be measured and reduced [2], [3], [4] .

Research on sustainable EDM has grown quickly in recent years, and several reviews now cover parts of the field. [5] reviewed green and sustainable EDM broadly, [6] examined research scope in eco-friendly EDM, [7] focused on eco-friendly dielectric media, and [8] surveyed advances in modelling, optimisation and sustainability. [9] placed EDM within the wider context of sustainable non-conventional machining. The present review complements these by organising recent experimental and modelling studies around the main levers available to an EDM practitioner: reducing energy, replacing or modifying the dielectric, eliminating the liquid altogether, and improving the electrode.

The remainder of the paper is organised as follows. Section II summarises the fundamentals of EDM and the sustainability framework adopted in this review. Section III describes how the environmental footprint of EDM is characterised. Section IV reviews sustainable strategies in turn, and Section V provides a cross-cutting analysis by workpiece material, trade-offs, economics and digitalisation. Section VI compares the strategies in a summary table, Section VII discusses challenges and research gaps, Section VIII outlines future directions, and Section IX concludes.

The motivation for sustainable EDM goes beyond compliance. Energy and consumable costs make up a meaningful part of the operating cost of EDM, so measures that reduce them can improve competitiveness as well as environmental performance. Customers in aerospace, medical and automotive supply chains

increasingly ask suppliers to document environmental performance, and mould and die makers that rely heavily on EDM face the same pressure. At the same time, workers and local communities are more sensitive to occupational and waste-related issues. These drivers explain why research output on green EDM has accelerated, with many of the studies reviewed here appearing in the past three years, including several in 2025 and 2026.

A. Scope and review approach

This review is built on a curated corpus of roughly fifty publications spanning 2011 to 2026. The corpus includes peer-reviewed journal articles, conference proceedings, earlier review papers and a small number of preprints and reports. The studies were grouped by the sustainability lever they investigate, namely energy and process parameters, dielectric fluid, absence of liquid dielectric, electrode and tooling, and modelling or decision-making. Where a study spans more than one lever, it is discussed under its principal contribution and cross-referenced elsewhere. Rather than ranking individual papers, the aim is to identify patterns, agreements, contradictions and gaps across them.

Because experimental conditions differ widely between studies in workpiece material, electrode material, polarity, pulse settings, dielectric volume and measurement method, absolute numerical values from different papers are not directly comparable. The discussion therefore concentrates on qualitative trends, mechanisms and the sustainability indicators used, and readers are directed to the original sources for quantitative results.

B. Contribution of this review

Earlier reviews of sustainable EDM have largely concentrated on a single theme, most often alternative dielectrics. The contribution of the present paper is threefold. First, it frames sustainable EDM through several linked dimensions, namely energy, dielectric, tooling, emissions and economics, so that the interaction between them becomes visible. Second, it brings together recent work from 2023 to 2026 on engineered water-based media, nano-enhanced bio-dielectrics, additive-manufactured electrodes and neural-network-based sustainability modelling, which earlier reviews could not cover. Third, it identifies concrete research gaps relating to standardised assessment, dielectric ageing, fume characterisation and industrial validation.

II. Fundamentals of EDM and the Sustainability Framework

A. Principle of the process

In EDM, a pulsed voltage is applied across a small gap between a tool electrode and a workpiece. When the field strength is sufficient, the dielectric in the gap breaks down and a plasma channel forms. The channel grows during the pulse-on period, and the intense local heating melts and partly vaporises a minute volume of workpiece material. At the end of the pulse the channel collapses, the dielectric flushes the molten material away as small debris particles, and the gap is de-ionised ready for the next discharge. Many thousands of such discharges per second erode a shape in the workpiece that mirrors the tool.

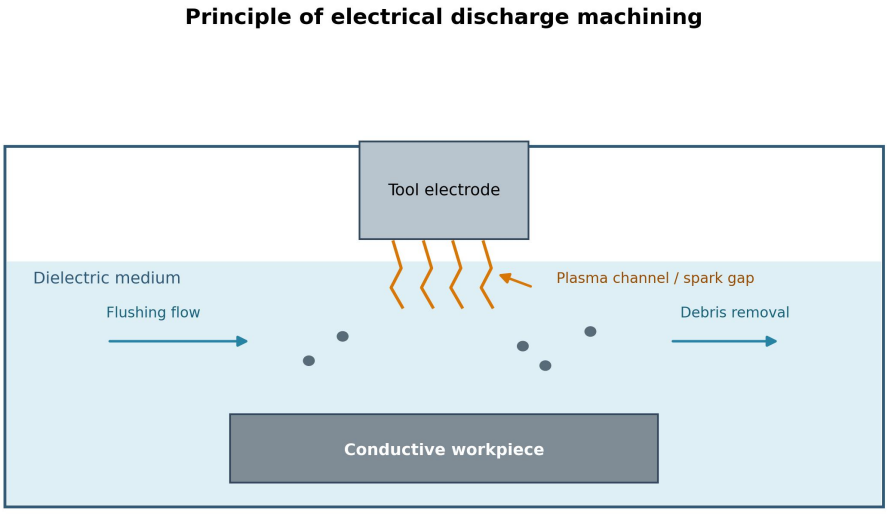


Fig. 1. Schematic representation of the EDM discharge gap, material removal and dielectric flushing. Source: Authors' own illustration.

The dielectric is therefore much more than a coolant. It insulates the gap until breakdown, constrains and shapes the plasma channel, quenches the molten material, and transports debris out of the gap. Its electrical strength, viscosity, thermal conductivity, specific heat, flash point and chemical composition all influence discharge stability, removal rate, tool wear and the character of the machined surface. This is the technical reason why replacing the dielectric, which is the focus of a large share of the sustainability literature, is never a simple substitution and must be assessed against process performance as well as environmental benefit [5], [7]

The resulting surface typically carries a recast layer, a heat-affected zone and micro-cracks whose severity depends on discharge energy and the dielectric used. The surface integrity of components machined with alternative dielectrics is therefore a central question in the literature, as shown by studies that report surface integrity together with dielectric choice [10] or that consider dimensional accuracy and micromachining errors [11] .

B. Process variants

Several EDM variants appear in the reviewed literature, each with its own sustainability profile. Die-sinking EDM uses a shaped electrode that is plunged into the workpiece, and it accounts for much of the dielectric studies reviewed here. Wire EDM uses a continuously fed thin wire and is studied for energy optimisation [12] and near-dry operation [13] . Micro-EDM scales the process down for micro-components [14], [15] . EDM milling uses simple rotating electrodes to generate complex shapes and has been used in both dry [16], [17] and arc-assisted forms [18]. Rotary tool and rotary workpiece arrangements improve flushing and have been combined with bio-dielectrics [19] . Upward-sinking configurations have been used with engineered water-based media [20] .

C. Dimensions of sustainability in machining

Sustainable manufacturing is commonly considered through environmental, economic and social dimensions. The environmental dimension covers energy use, resource consumption, emissions and waste. The economic dimension covers machining time, tool and consumable cost and the cost of waste handling. The social dimension covers operator health and safety, including exposure to fumes and aerosols and the fire risk of flammable fluids. Much of the EDM literature addresses the environmental and economic dimensions, while the social dimension is considered mainly indirectly, through the use of less toxic or non-flammable media. A balanced assessment should consider all three, and the studies of [21] and [22] are examples that explicitly combine environmental and economic evaluation.

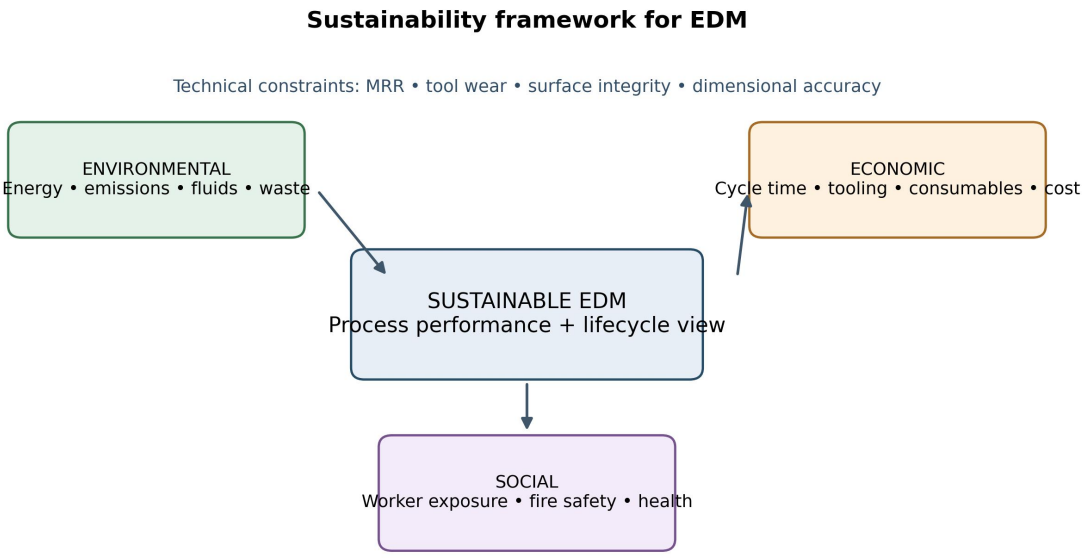


Fig. 2. Environmental, economic and social dimensions used to frame sustainable EDM. Source: Authors' own illustration.

D. Performance and sustainability indicators

Studies typically report a set of technical responses, namely material removal rate, tool wear rate, surface roughness, recast layer thickness and overcut or dimensional accuracy. Sustainability studies add indicators such as specific energy consumption, which relates electrical energy to the volume of material removed, dielectric consumption, carbon dioxide equivalent emissions and cost per part. The way these indicators are defined and normalised affects the conclusions. For example, a dielectric that lowers removal rate may appear environmentally attractive per hour of operation but less so per part produced, because machining time and thus electricity use increase. Reporting indicators per unit of material removed or per finished feature is therefore preferable, and it is a recurring recommendation across the energy-focused studies [3], [23] .

Multi-criteria decision-making methods such as grey relational analysis, TOPSIS and MOORA convert several indicators into a single ranking [24], [25]. These methods require weights for each criterion, and the selection of weights is a subjective choice that should be reported clearly. Neural network models, in turn, predict responses from inputs and have been applied to sustainability indicators [26] . The reviewed papers collectively show that no single indicator is adequate, which motivates the integrated analyses discussed in Section V.

III. Environmental and Energy Footprint of EDM

A. Energy consumption

Electricity is generally the dominant environmental input in EDM, since the process converts electrical energy into thermal energy at the discharge gap while auxiliary systems such as pumps, filtration and cooling add further load. [3] characterised the energy efficiency of EDM and showed that energy use needs to be understood at the level of both the discharge process and the supporting machine subsystems. [12] examined process-level energy optimisation in wire EDM of Inconel and titanium superalloys, demonstrating that parameter choice has a direct effect on energy per unit of material removed.

More recent studies tie energy to electrode choice and economics. [21] assessed electrode materials in EDM of SS316L in terms of energy consumption, electrode wear, dielectric consumption, greenhouse gas emissions and economic viability, [23] analysed the balance between productivity and sustainability by examining energy consumption together with electrode degradation [22] combined machining performance with economic and environmental analyses and multi-criteria optimisation for SS310 alloy. Together these works show a shift from single-response optimisation toward joint treatment of performance, energy and cost.

Energy characterisation in EDM is complicated by the pulsed nature of the process. Instantaneous power during a discharge is high, but the duty cycle is low, so the average power drawn from the supply depends on pulse settings, and the fraction of discharges that are productive varies with gap conditions. Not all supplied energy leads to material removal: some is lost as heat to the dielectric, the electrode and the workpiece, some is consumed in ineffective arcing or short-circuit pulses, and some is dissipated in the generator itself. Understanding this partition is the basis for efficiency improvements, and it explains why different studies report very different energy intensities for apparently similar operations. Energy-aware comparison of alternative dielectrics therefore needs measurements at the machine level, for the same part and the same accuracy requirement, rather than comparison of removal rates alone.

B. Life cycle inventory and process-level assessment

Meaningful comparison of green alternatives requires reliable inventory data. [2] addressed this by ascertaining life cycle inventory data for EDM, and [27] reported process-level environmental performance when machining aluminium (3003) and AISI P20 steel. [14] considered sustainability in micro-EDM of micro-components, where the very small removal volumes change the balance between process energy and the energy embedded in electrodes and consumables. These studies provide the foundations on which later dielectric and electrode comparisons are built, although the number of published inventories is still small relative to the range of EDM configurations in use.

A life cycle perspective extends the assessment upstream and downstream of machining. Upstream impacts include the production of dielectric fluids, electrodes, wire and additives, as well as the generation of electricity. Downstream impacts include the treatment of spent fluid, filters and debris. For bio-based fluids, the agricultural phase, including land use and fertiliser use, can contribute to the overall footprint, which means that biodegradability at end of life does not automatically translate into lower life cycle impact. For water-based media, the energy and chemicals involved in water treatment must be counted. These considerations show why inventory work such as that of [2] and process-level comparisons such as [27] remain essential, and why claims about green dielectrics should be supported by quantified analysis rather than by qualitative argument alone.

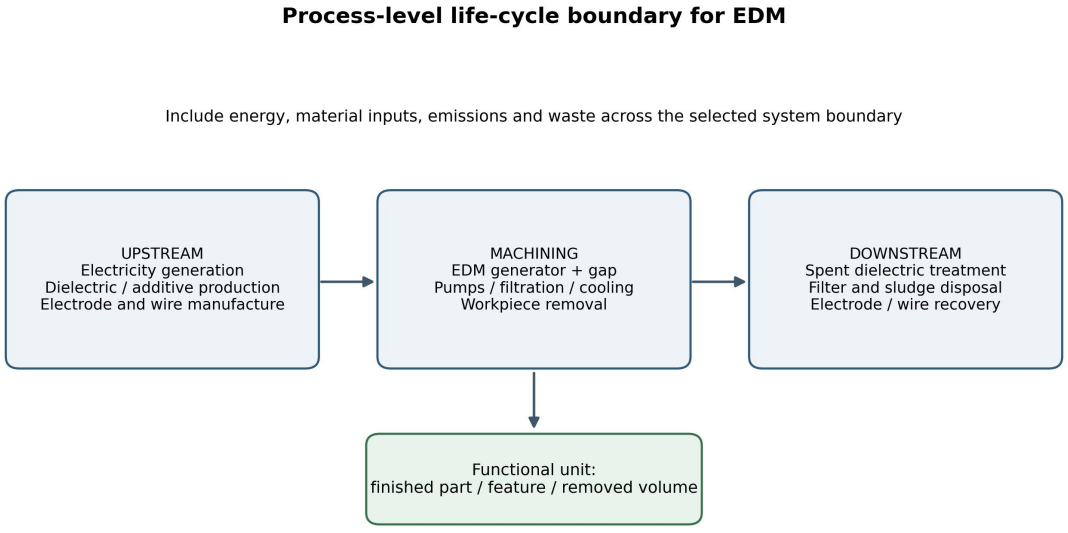


Fig. 3. Illustrative system boundary for assessing the life-cycle inputs and outputs of an EDM operation. Source: Authors' own illustration.

C. Dielectric, electrode and emission burdens

Conventional hydrocarbon dielectrics are consumed through evaporation, contamination and periodic replacement, and they release vapours and aerosols during sparking. Spent dielectric and debris-laden filters must also be disposed of. Electrode wear represents a further burden because tool material is consumed and

must be manufactured. Reducing these burdens is the motivation behind the dielectric and electrode strategies reviewed in Section IV.

D. Operator health, fumes and fire safety

Beyond resource use, EDM influences the working environment. The sparking of hydrocarbon dielectrics produces vapours and aerosols, and the heated oil can emit smoke that requires extraction. Hydrocarbon oils are also flammable, so fire prevention measures such as level monitoring and fire suppression are standard practice. These issues are a major driver of interest in water-based media, which are non-flammable, and in bio-dielectrics, which are often considered less hazardous. However, the literature on fume composition from alternative dielectrics is much thinner than the literature on their machining performance. Vegetable oils, for example, may decompose differently from mineral oils during sparking, and their emissions deserve explicit measurement. The spectrographic work of [25] on vegetable oils points to the value of characterising fluids in detail, although it addresses fluid properties rather than operator exposure.

E. Linking footprint measures to improvement options

The footprint categories above map naturally onto the strategies reviewed in the next section. Energy demand is addressed mainly through parameter optimisation and by raising efficiency per part. Dielectric consumption and disposal are addressed through bio-based, waste-derived, water-based and dry or near-dry approaches. Electrode consumption is addressed through tool material selection, treatment and additive manufacturing. Emissions, including fumes and carbon dioxide equivalent, depend on all of these and on the electricity mix of the machining site, which means that the same machining strategy can have a different carbon footprint in different regions. Studies reporting carbon emissions, such as that on waste cooking oil by [28] and the electrode assessment of [21] , therefore provide results that are strictly valid for the grid and boundary assumptions they adopt.

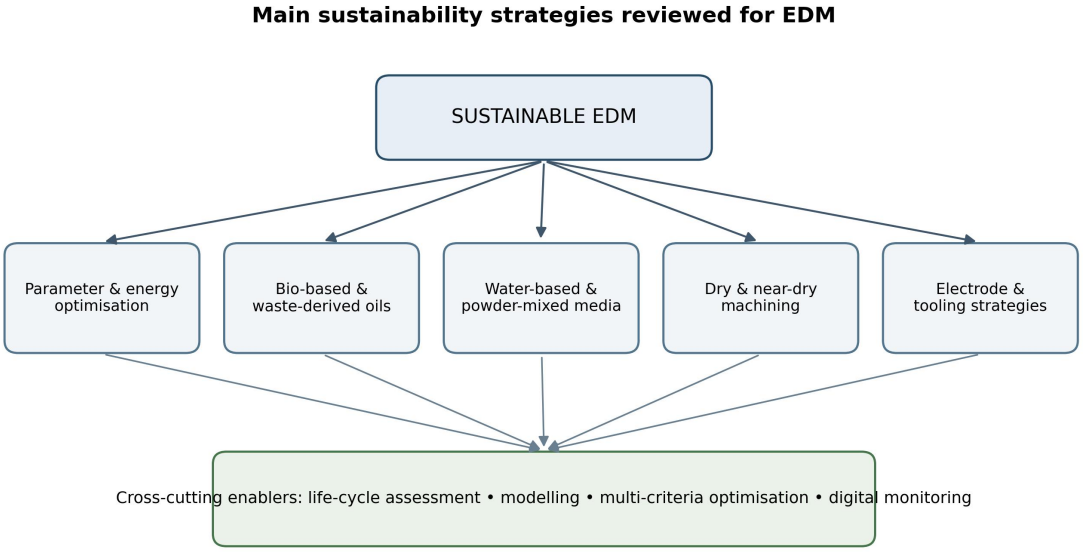


Fig. 4. Main sustainability strategies and cross-cutting assessment tools discussed in this review. Source: Authors' own illustration.

IV. Sustainable Strategies in EDM

A. Process parameter and energy optimisation

The simplest route to a greener process is to operate the existing machine more efficiently. Pulse current, pulse-on time, voltage and duty cycle together determine removal rate, wear and specific energy. [3], [12] provide evidence that these settings can be tuned for lower energy use. Jagadish et al. [29] proposed a hybrid decision-making approach for green die-sinking EDM, illustrating how several environmental and

performance criteria can be handled in a single optimisation. Because these strategies require no new fluids or hardware, they are attractive for industrial adoption, but their gains are limited by the underlying physics of the discharge and are specific to material and machine.

Parameter selection also interacts with surface integrity. Higher discharge energy raises removal rate and, up to a point, lowers energy per volume removed, but it also deepens the recast layer, increases crater size and may worsen tool wear. A sustainable parameter set is therefore not simply the one with the highest removal rate but the one that meets the surface and accuracy requirements of the part with the lowest overall resource use. This is why optimisation studies that combine energy, wear and quality in one objective are more informative than single-response studies [22], [29] .

The distinction between process energy and machine-level energy is also important. Part of the electricity drawn by an EDM machine is consumed by auxiliary equipment that operates regardless of the discharge settings, such as pumps, filtration units and control electronics. Reducing machining time therefore reduces both process and auxiliary energy, while measures that reduce only discharge power may leave much of the overall energy use unchanged. [3] illustrate the value of separating these contributions, and later energy studies on electrodes and dielectrics build on the same logic [21], [23] . Practical measures such as switching off auxiliary units during idle periods, right-sizing dielectric tanks and scheduling jobs to reduce set-up time are rarely studied in the academic literature but could yield savings independent of the discharge process.

B. Bio-based and waste-derived dielectrics

Vegetable oils are among the most studied alternatives to mineral and synthetic dielectric oils, because they are renewable and biodegradable. [30] investigated the technical feasibility of Jatropha curcas oil as a bio-dielectric, and [31] assessed the operational feasibility of waste vegetable oil. [32] studied neem oil as a dielectric, and [10] more recently combined neem oil with a 3D-printed SS316L electrode for machining Ti-6Al-4V, linking dielectric choice to additive manufacturing of tools. [33] examined sunflower oil in mist form, which connects bio-dielectrics with the near-dry approach discussed in Section IV-D.

Several studies address the fluid properties that determine whether such oils can replace conventional dielectrics in practice. [34] experimentally investigated the stability of vegetable oils used as dielectric fluids, and [35] reported a case study on their use in EDM. [25] combined spectrographic analysis and particle image velocimetry with TOPSIS and MOORA evaluation to judge the technical feasibility of vegetable oils. [36] optimised process parameters and performance when machining Inconel 718 in renewable dielectrics, and [37] compared different dielectrics for Waspaloy.

Circularity has also been explored. [28] examined the circular use of waste cooking oil as a dielectric and linked it to lower carbon emissions. [11] analysed micromachining errors in Inconel 600 with several biodegradable dielectrics, and [38] studied the role of biodegradable dielectrics in tool wear and dimensional accuracy in copper-mixed die-sinking EDM. [39], [40] investigated eco-friendly dielectrics for AISI 2507 super duplex stainless steel, including multi-response optimisation by grey relational analysis. Overall, bio-dielectrics show that machining with renewable fluids is feasible, but outcomes vary with oil type, workpiece material and parameters, and issues such as viscosity, oxidation and fume generation need continued attention.

The suitability of a vegetable oil depends on its composition. Oils differ in their fatty acid profile, and a higher degree of unsaturation generally increases susceptibility to oxidation and polymerisation, which raises viscosity and acidity during use. Viscosity affects flushing: a more viscous fluid can hinder debris removal from small gaps, while excessively low viscosity may reduce the insulating effect needed for stable discharges. Flash point, dielectric strength and thermal conductivity also vary between oils and relative to mineral dielectrics. The stability study of [34] is valuable because it addresses these ageing aspects directly, and its focus is a reminder that short machining trials may not reveal problems that appear after prolonged use.

The machining outcomes reported for bio-dielectrics are mixed and depend on material and parameters. Several studies find that vegetable oils can deliver machining performance comparable to conventional fluids in some responses, while others find lower removal rates or higher tool wear in particular conditions, which is reflected in the range of materials, oils and optimisation methods used across the literature [32], [35], [36],

[37] . Surface integrity also varies, because the carbon released by the breakdown of oil molecules can be incorporated into the recast layer and alter its hardness and composition. This effect is well known for hydrocarbon dielectrics in general and should be examined for each bio-oil and workpiece combination.

Waste-derived dielectrics add a circular-economy aspect. Using waste cooking oil as a dielectric diverts a waste stream and avoids the production of virgin dielectric [28], [31]. The challenge is the variability of waste oil, since its composition depends on the original oil and on the degree of prior heating. Pre-treatment, filtration and quality control are therefore necessary before waste oil can be used reliably. A full life cycle comparison must also account for collection, treatment and eventual disposal of the used fluid, which no study in the reviewed corpus appears to address fully. Such an assessment would build on the inventory approach of [2] .

The combination of bio-dielectrics with other measures shows how sustainability levers interact[38], [41] use copper-mixed biodegradable dielectrics, [42] disperse copper nanoparticles in vegetable oil, and [15] use a nano-abrasive zirconium oxide-enhanced biodegradable dielectric in micro-EDM. In each case the bio-oil provides the environmental benefit, while the additive seeks to compensate for performance limitations. The trend suggests that bio-dielectrics may be most effective as base fluids in engineered systems rather than as direct substitutes in unmodified form.

C. Water-based, powder-mixed and nano-enhanced dielectrics

Water is an obvious green alternative to hydrocarbon oils. [43] studied green EDM in tap water for Ti-6Al-4V and optimised the parameters. [18] researched green dielectric fluids for high-efficiency electrical discharge assisted arc milling. Newer water-based concepts include a green microdroplet dielectric [44] and green foam water for upward-sinking EDM, whose mechanisms were analysed by [20] . [45] integrated nano hydrogen and oxygen bubbles to improve machining performance in a sustainable way. These works illustrate a trend toward engineered water-based media rather than plain water.

Powder additives modify the discharge gap and can improve removal rate and surface quality, which in turn reduces the energy and time needed per part. [24] optimised powder-mixed EDM of Ti6Al4V with alumina and silicon carbide in deionised water using grey relational analysis. [46] enhanced powder-mixed EDM performance with a green dielectric fluid, and [47] analysed graphene-based dielectrics for Ti-6Al-4V. [48] used alumina-mixed deionised water and modelled the process with artificial neural networks in support of net-zero goals. Copper nanoparticles dispersed in vegetable oil were examined by [42] for Ti-6Al-4V, and [15] combined nano zirconium oxide with a biodegradable dielectric in micro-EDM of aluminium nitride. [49] compared process and environmental performance for a SiC-PEG dielectric. Powder-mixed systems therefore offer a way to compensate for the lower performance that some green base fluids show, although powder settling, circulation and filtration remain practical concerns.

Water-based dielectrics have attractive features. Water has high thermal conductivity and specific heat, is non-flammable and non-toxic, and can be treated and disposed of more easily than oil. It also generates no hydrocarbon fumes. However, water has lower electrical resistivity than hydrocarbon oil unless it is deionised, and conventional EDM in water can involve electrolytic effects, corrosion of the workpiece or machine components, and different discharge channel behaviour. These issues explain why the literature has moved from plain tap water [43] toward engineered water-based media such as microdroplet systems [44] , foam water [20] and water containing nano bubbles [45] . Each of these seeks to retain the environmental benefits of water while managing its discharge behaviour.

The mechanisms behind powder-mixed EDM are widely discussed in the literature. Suspended particles are thought to lower the effective dielectric strength of the gap and to widen and disperse the discharge channel, so that the discharge energy is spread over a larger area. This tends to improve discharge stability and can produce smoother surfaces with a more uniform recast layer, and in some cases to raise removal rate. The nature of the powder matters: conductive powders such as copper or graphene, abrasive or semiconducting powders such as alumina or silicon carbide, and polymer-modified systems such as SiC in polyethylene glycol

each act differently [24], [46], [47], [49] . The concentration, particle size and dispersion stability are decisive, and too much powder can cause short circuits or arcing.

From a sustainability viewpoint, powder additives raise a double-edged question. On one side, they can reduce machining time and energy per part and may improve surface quality so that secondary finishing is reduced. On the other side, they introduce additional materials whose production, recovery and disposal must be considered, and nano-sized powders raise questions about worker exposure and environmental fate. The studies by [41], [48] which use ANN modelling to support net-zero targets, show the intention to quantify these benefits, but a comprehensive accounting that includes powder life cycle impacts remains to be done.

Practical aspects of powder handling also deserve attention. Powders settle, so the system requires agitation or circulation, which adds energy demand and can interfere with filtration. Powder-laden fluid may also require specially designed tanks to limit the quantity of dielectric needed. In industry, these practical constraints often determine whether a powder-mixed process is adopted, regardless of its benefit in laboratory trials.

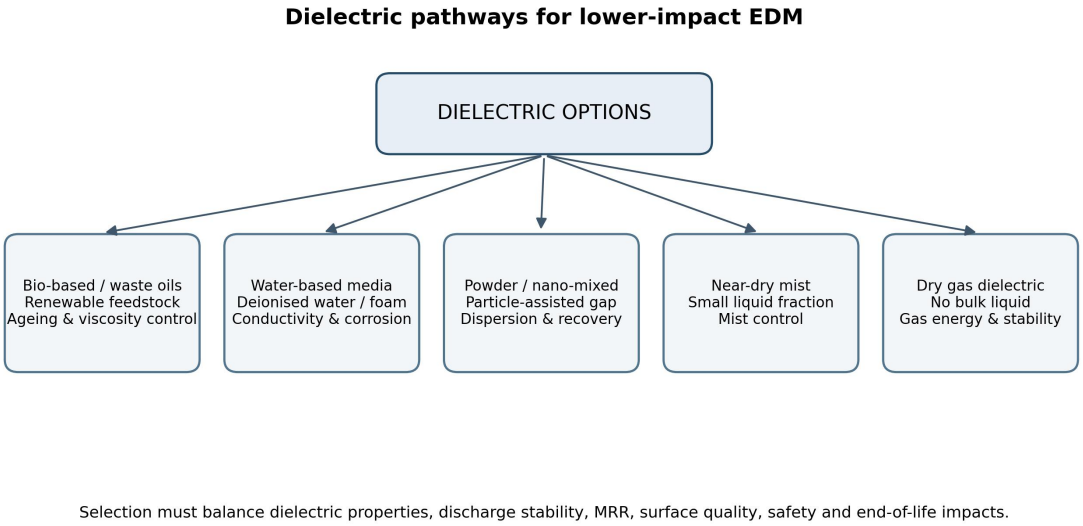


Fig. 5. Dielectric pathways considered in sustainable EDM and the principal process issues associated with each. Source: Authors' own illustration.

D. Dry and near-dry EDM

Dry EDM replaces the liquid dielectric with a gas, usually air, and removes the need for liquid disposal. The method was studied systematically by [50] , who examined how the anode material influences breakdown behaviour, and [51] , who showed the influence of an oxidising gas on process stability. [16] optimised dry EDM milling, and [52] analysed the discharge gap and relative discharge ratio in dry EDM. Later work has extended dry EDM to difficult materials: [53] modelled process parameters for SiSiC ceramic composite, [54] applied big data analytics to optimise dry EDM of stainless steel, and [17] investigated dry EDM milling with workpiece cooling for Inconel 625.

Near-dry EDM uses a mist of liquid in a gas stream, trading some of the cleanliness of fully dry operation for better stability. [13] studied helium-mist near-dry wire-cut EDM of M2 high-speed steel, while [33] used sunflower oil mist. These approaches greatly reduce dielectric volume, yet typically operate at lower removal rates and with narrower process windows than liquid-immersed EDM, so they suit finishing or specialised operations more readily than bulk roughing.

The physical basis of dry EDM differs from that of liquid EDM. In a gas, breakdown occurs at a smaller gap and the plasma channel is less constrained, with less cooling and flushing of debris. The removal

mechanism and the debris behaviour therefore change, and process stability depends strongly on the gas, its flow and the electrode design. [50] found that the choice of anode material influences breakdown behaviour, which is relevant because polarity and electrode material are used to control stability in dry EDM, and [51] showed that an oxidising gas affects stability, in keeping with the idea that the gas chemistry plays an active role in the discharge rather than acting merely as an insulator.

Tool electrodes in dry EDM are often thin-walled tubes through which gas is delivered, and this geometry supports milling-type kinematics in which the tool rotates and moves along a path [16] . Workpiece cooling has been explored as a way to limit thermal effects when machining difficult materials such as Inconel 625 [17] , while the discharge gap and relative discharge ratio have been analysed to describe how efficiently discharges are used [52] . Ceramic composites and stainless steels have been studied with modelling and optimisation, including data-driven approaches [53], [54] . These examples show that dry EDM is moving from basic feasibility studies to application in specific difficult-to-machine materials.

The sustainability advantages of dry EDM are clear in terms of dielectric consumption and waste, but the overall balance depends on the effect on productivity and the supply of compressed gas, which has its own energy cost. If lower removal rate leads to considerably longer machining time, the energy per part may increase. Gases such as oxygen can improve removal but raise tool wear and safety questions, while inert gases such as helium, as used in near-dry wire EDM by [13] , have supply cost implications. The environmental case for dry and near-dry EDM is therefore strongest for finishing, small-feature or specialised operations where dielectric handling is a major burden, and weaker for high-volume roughing where productivity dominates.

E. Electrode materials and tool strategies

Electrode wear influences accuracy, material waste and the energy embedded in tooling. [21] compared electrode materials against energy, wear, dielectric use, emissions and cost, and [23] linked electrode degradation to energy and productivity. [19] combined bio-dielectrics with treated tools in rotary tool, rotary workpiece EDM of an aluminium hybrid composite, and[10] used 3D-printed SS316L electrodes with neem oil. [38] reported that dielectric choice affects tool wear, showing that dielectric and electrode strategies interact and should be assessed together.

Electrode choice has several sustainability implications. Tool wear changes the machined geometry and may require multiple electrodes or electrode redressing, which consumes material and time. The electrode material itself carries an embedded environmental burden, for example the energy and emissions of producing copper, graphite or other tool materials, and its end-of-life handling. Studies that include electrode wear in a sustainability assessment, as in [21], [23] , therefore capture an aspect that single-response parameter studies miss.

Two newer tooling directions appear in the reviewed corpus. The first is surface or bulk treatment of tools to improve wear behaviour, as applied by [19] in rotary tool rotary workpiece EDM. The second is additive manufacturing of electrodes, as used by [10] , which allows complex geometries, internal channels for flushing, and potentially lower material waste than subtractive electrode fabrication. A full assessment would compare the energy and materials needed to print an electrode with those of conventional electrode manufacture, and with the benefit in machining performance. The studies demonstrate technical feasibility, but the system-level sustainability benefit is not yet quantified.

Electrode polarity and material also strongly influence dry EDM, where the anode material affects the breakdown process [50] , and powder-mixed or bio-dielectric EDM, where material transfer from the electrode or powder can modify the machined surface [38] . This reinforces the point made earlier that dielectric, electrode and parameter decisions should be considered jointly.

F. Modelling and multi-criteria optimisation

Because green EDM involves competing objectives, optimisation and modelling are central. Grey relational analysis has been applied in several studies [24], [40] , and TOPSIS and MOORA were used by [25] . Artificial

neural networks have been used to model sustainable EDM with alumina-mixed water [48] , copper-mixed biodegradable dielectrics [41] , and sustainability metrics more broadly [26] . [22], [29] combined economic and environmental criteria in optimisation. [54] illustrated the potential of big data analytics. Collectively, these studies move EDM optimisation from maximising removal rate toward explicit sustainability objectives, though most models are trained on small experimental datasets for a single material and machine.

The use of artificial intelligence and statistical methods is growing because sustainable EDM involves many variables and conflicting objectives. Regression and response surface methods remain common, but neural networks are increasingly used where relationships are nonlinear [26], [41], [48] . Multi-criteria decision-making techniques such as grey relational analysis, TOPSIS and MOORA offer transparent ways to rank alternatives [24], [25], [40] . The hybrid decision-making approach proposed by [29] illustrates a trend toward combining weighting and ranking techniques to obtain more robust solutions.

Several limitations of current modelling practice are visible. The experiments used to train models are usually few in number, taken from a single machine and designed for exploration rather than for model building, which limits generalisation. The choice of objective weights in multi-criteria methods is often subjective and may change the ranking. Many models predict technical responses rather than direct environmental outputs, so sustainability is inferred rather than modelled explicitly, although the work of [26] on sustainability metrics is a step toward direct modelling. Finally, models are rarely validated on different machines, materials or industrial settings, and uncertainty is seldom reported. Addressing these points would raise the credibility and usefulness of modelling work.

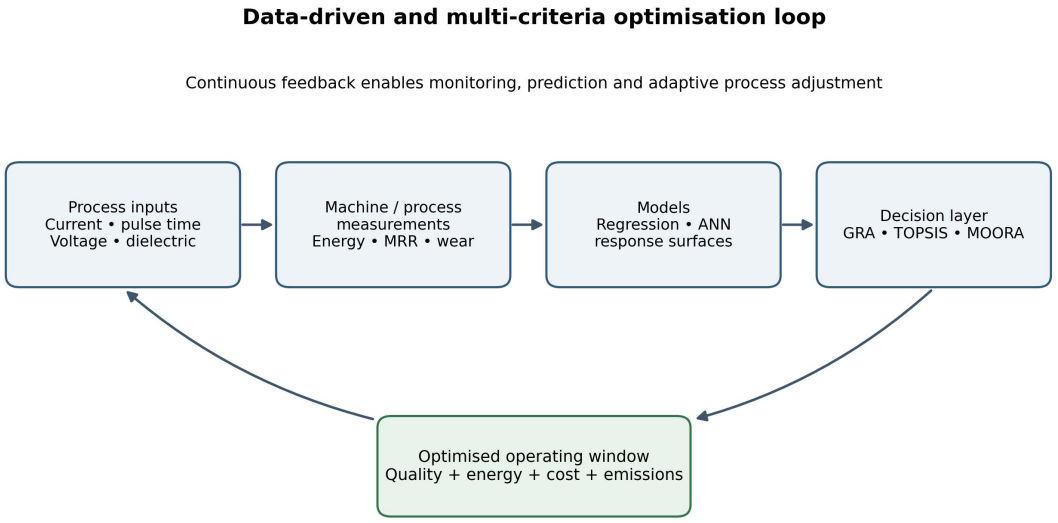


Fig. 6. Conceptual data and decision workflow for multi-response optimisation of sustainable EDM. Source: Authors' own illustration.

G. Micro-EDM and wire EDM

Sustainability considerations differ for micro-EDM and wire EDM. In micro-EDM the volumes of dielectric and removed material are small, but electrode fabrication and dimensional accuracy become critical [11], [14], [15] . In wire EDM the continuous consumption of wire and the dielectric flow are key issues, and studies have addressed process energy [12] and near-dry operation [13] . Evidence for green strategies in these variants is thinner than for die-sinking EDM and deserves more attention.

Micro-EDM places special emphasis on electrode wear and accuracy, because the electrodes are small and wear changes the geometry of the features quickly. Biodegradable dielectrics have been examined for micromachining accuracy [11] , and nano-additives have been used in micro-EDM of ceramics [15] . The very small volume of dielectric used suggests that fluid consumption is not the main environmental issue in micro-EDM, whereas electrode manufacture, machine energy use over long cycle times and cleanliness

requirements may be more important. Modica et al. [12] considered these aspects in their treatment of sustainable micro-manufacturing.

Wire EDM consumes a wire that is generally discarded after one pass, and it uses a dielectric, normally deionised water, which is cleaner than hydrocarbon oils but requires filtration and resin treatment. The energy optimisation work on Inconel and titanium superalloys [12] and the near-dry approach with helium mist [13] show that both process energy and dielectric handling can be targeted. Wire recycling, wire material selection and strategies for reducing the number of cutting passes are additional levers that are described in practice but appear less often in the academic sustainability literature of this corpus.

V. Cross-Cutting Analysis

A. Trends by workpiece material

The reviewed studies are concentrated on a limited set of difficult-to-machine materials, and this concentration shapes the evidence base. Ti-6Al-4V is a frequent test material and has been machined in tap water [43] , graphene-based dielectrics [47] , alumina and silicon carbide powder in deionised water [24] , copper nanoparticle-dispersed vegetable oil [42] and neem oil with a 3D-printed electrode [10] . Titanium alloys are attractive test cases because they are important in aerospace and biomedical applications and are costly to machine, so improvements have clear industrial value. Their low thermal conductivity and tendency to form carbides in hydrocarbon fluids, however, mean that results may not transfer to other materials.

Nickel-based superalloys such as Inconel 600, 625, 718 and Waspaloy are the second major group. Studies have used biodegradable and Cu-mixed dielectrics [11], [38], [41] , renewable dielectrics [36], alternative dielectrics for Waspaloy [37] and dry EDM with workpiece cooling [16] . The high strength and low thermal conductivity of these alloys lead to high tool wear and heat concentration, so improvements in flushing and discharge stability may be especially valuable.

Stainless steels form a third group, including SS316L [21] , SS310 [22] and super duplex AISI 2507 [39], [40] , as well as stainless steel in dry EDM [54] . These studies often incorporate energy, economic and environmental analyses and so illustrate the most integrated treatments in the literature. Ceramics and composites, such as SiSiC [53] , aluminium nitride [15] and aluminium hybrid composites [19] , represent a smaller but growing group, where the conductivity of the workpiece and abrasive reinforcement add complications. The imbalance in coverage means that general conclusions about green dielectrics should be drawn cautiously and that tool steels, aluminium, copper alloys and more diverse composites deserve further study.

B. Performance versus sustainability trade-offs

A recurring theme is that no sustainable option dominates conventional EDM on every criterion. Bio-dielectrics reduce toxicity and improve renewability but may offer less oxidative stability and higher viscosity. Water-based media remove hydrocarbons and fire risk but need management of conductivity and corrosion. Powder additives improve discharge behaviour but add materials and handling complexity. Dry and near-dry methods eliminate or reduce liquid but can lower productivity. Tooling strategies can reduce wear but may increase manufacturing burden. The correct choice depends on the priorities of the user. A job shop with low-volume, high-value parts may accept lower removal rate in exchange for cleaner operation and lower fluid handling cost, whereas a high-volume producer may prioritise productivity and adopt incremental measures such as parameter optimisation and fluid recycling.

This reasoning supports the use of multi-criteria and scenario-based assessment instead of single-criterion ranking. It also suggests that a hierarchy of measures is sensible: first, optimise parameters and avoid waste of energy and fluid; second, adopt cleaner dielectric options where technically compatible; third, consider more demanding changes such as dry EDM or specialised tooling when the application justifies them. The evidence from the reviewed studies supports this staged approach, since the first step requires no new equipment and the latter steps demand additional process development.

The evidence also suggests that the benefit of a measure depends on how it is benchmarked. When a green dielectric is compared with a conventional dielectric under identical electrical settings, differences in removal rate and wear are easy to see but may mask the possibility that each fluid has a different optimum. A fairer comparison optimises each fluid separately, as is done in several of the multi-response studies reviewed [25], [36], [40]], and then compares the best achievable outcomes in terms of energy, cost and quality. This distinction is often overlooked and may account for part of the contradictory findings reported across the literature.

Finally, sustainability claims should be assessed with attention to system boundaries. A study may show that a dielectric lowers emissions during machining, while the production of that dielectric or of its additive's offsets part of the gain. Similarly, a lower tool wear rate achieved with a costly electrode material may not reduce the overall footprint if the electrode itself is energy intensive to make. Boundary-aware analysis, as attempted by [21], [23] , is therefore the standard to which future work should aspire.

C. Economic considerations

Economic viability decides whether sustainable practices spread. The studies of [21] and [22] explicitly include cost, which is valuable because environmental benefit that carries an unacceptable cost penalty is unlikely to be adopted widely. Cost elements include electricity, dielectric purchase and disposal, electrode material, machining time and labour, and the capital cost of any modification. Bio-based and waste-derived oils could reduce disposal costs and, in the case of waste oil, fluid purchase cost, but they may require more frequent replacement if stability is poor. Powder additives and engineered water systems add material and equipment cost. Dry EDM reduces dielectric cost but needs gas supply and may increase machining time.

Regulatory pressure and customer requirements are increasingly relevant. Manufacturers may be required to report energy use and emissions, and original equipment manufacturers may specify environmental standards for suppliers. Such drivers raise the value of the carbon and energy accounting approaches reviewed here [23], [28] The early industry study by Abbas et al. [1] is a reminder that awareness and practical guidance within companies are as important as technical development, and that adoption depends on training, supply of suitable fluids and confidence in process reliability.

D. Digitalisation and data-driven sustainability

Data-driven approaches may enable more sustainable EDM beyond offline optimisation. [54] used big data analytics for dry EDM, indicating how large process datasets can be exploited, and neural networks have been used to link process variables to sustainability metrics [26], [48] . Real-time monitoring of discharge characteristics, such as the proportion of normal, arc and short-circuit pulses, together with energy metering could allow adaptive control that avoids unproductive discharges and wasted energy. Monitoring of dielectric condition, including conductivity, viscosity and contamination, would also support timely fluid replacement and extend fluid life. Although these ideas are largely absent from current experimental work, they are natural extensions that would connect laboratory sustainability studies to modern digital manufacturing practice.

VI. Comparative Summary of Strategies

Table I summarises the main strategies, representative studies, their sustainability benefits and their limitations. The strategies are not mutually exclusive; many recent studies combine them, for example bio-dielectrics with nanoparticles or additive-manufactured electrodes.

TABLE I
SUMMARY OF SUSTAINABLE EDM STRATEGIES

Strategy	Representative studies	Main sustainability benefit	Key limitations
Parameter and energy optimisation	[3], [12], [22], [23]	Lower specific energy consumption and cost per part	Results depend on machine, material and discharge settings

Strategy	Representative studies	Main sustainability benefit	Key limitations
Vegetable-oil and waste-oil dielectrics	[28], [31], [32], [35]	Biodegradable, renewable, lower toxicity; waste-oil reuse	Oxidative stability, viscosity, smoke and long-term ageing
Water-based and tap-water dielectrics	[18], [20], [43], [44]	Removes hydrocarbon fluids; low cost; easy disposal	Electrolysis, corrosion, lower stability if poorly controlled
Powder-mixed and nano-additive dielectrics	[42], [46], [47], [48]	Higher material removal rate and better surface quality, which lowers energy per part	Powder settling, agglomeration, filtration and powder cost
Dry and near-dry EDM	[13], [16], [33], [50], [51]	Eliminates or minimises liquid dielectric; cleaner fumes handling	Lower removal rate, process instability, gas supply
Electrode and tool strategies	[19], [21], [30]	Reduced wear and material waste; additive-manufactured and treated tools	Tool cost, fabrication energy, limited industrial data
Modelling and multi-criteria optimisation	[25], [26], [29], [41]	Predicts and balances performance, energy and emissions	Models are narrow in scope and need larger validated datasets

VII. Challenges and Research Gaps

- Standardised assessment: studies use different system boundaries, functional units and indicators, which makes results hard to compare. More life cycle inventories of the type begun by Gamage et al. [2] are needed, covering dielectric production and disposal as well as machining.
- Dielectric ageing and reuse: most bio-dielectric studies run short experiments. Long-term oxidation, contamination, viscosity change and filtration behaviour, as raised by Radu et al] [34] , need systematic study to judge real replacement intervals.
- Fume and emission characterisation: the health and emission profiles of vegetable oils, water-based media and mists are less thoroughly characterised than their machining performance.
- Productivity trade-offs: dry, near-dry and some water-based approaches often reduce removal rate, so their net energy and cost benefit per part must be demonstrated, not assumed.
- Nano-additive handling: agglomeration, settling, recovery and the environmental fate of nanoparticles are rarely addressed, even though additives are used to improve the sustainability of the process.
- Material and machine coverage: much of the work concentrates on Ti-6Al-4V, Inconel alloys and stainless steels in die-sinking mode. Ceramics, composites, wire EDM and micro-EDM are less covered.
- Model generalisation: neural network and multi-criteria models are generally built on limited datasets and are seldom validated on other machines or at industrial scale.
- Literature quality and consistency: a number of sources in this field are preprints, conference papers or reports with limited peer review, so conclusions should be weighed accordingly.

These gaps should be considered alongside the limitations of the present review. The corpus is restricted to the supplied set of references and therefore may not include all relevant work, particularly studies in languages other than English or in industrial reports. Several included sources are preprints or documents with incomplete publication details, and the assessment of their findings relies on the information given in titles and available descriptions. The qualitative approach adopted here also means that no formal meta-analysis of quantitative results has been attempted, which would in any case be hindered by differences in experimental conditions between studies. Readers should therefore regard the conclusions as indicative of research directions rather than as definitive performance rankings.

VIII. Future Directions

Several directions appear promising. First, integrated sustainability frameworks that combine energy, dielectric, tooling, emissions and cost in one metric would help practitioners compare options on equal terms, building on the multi-criteria approaches already reported [22], [26], [29] Second, hybrid systems that combine bio-based or engineered water-based dielectrics with carefully chosen additives and treated or additive-manufactured electrodes deserve systematic evaluation [11], [15], [42] . Third, data-driven and big-data methods, including machine learning and digital monitoring, could enable adaptive control that minimises energy in real time [48], [54] . Fourth, circular strategies such as reuse of waste oils and recovery of debris and powders should be studied for scalability [28] . Finally, industrial case studies and open datasets would help move green EDM from the laboratory to the shop floor, extending the early industry-oriented perspective of Abbas et al. [1] .

A further direction concerns standardisation and open reporting. Common system boundaries, functional units and indicator sets would allow results from different laboratories to be combined and compared, and would make meta-analysis possible. Reporting of experimental conditions, including dielectric volume, flushing method, electrode dimensions and electricity measurement approach, should be complete enough to permit reproduction. Collaboration between universities and industry, including shop-floor trials with realistic parts and production schedules, would address the gap between laboratory and industrial evidence. Finally, education and guidelines aimed at EDM practitioners, building on the practical focus of early work such as [1], [4] , could help turn research results into everyday practice.

IX. Conclusion

Sustainable EDM has progressed from basic energy and inventory studies to a wide range of dielectric, electrode and process innovations supported by increasingly sophisticated modelling. Bio-based and waste-derived oils offer renewable alternatives to hydrocarbon dielectrics; water-based and nano-enhanced media can improve performance while avoiding oils; dry and near-dry EDM greatly reduce liquid use; and electrode and parameter strategies cut wear and energy. None of these options is superior in every respect, and the best choice depends on workpiece material, geometry, accuracy requirements and production scale. The main need now is for standardised, comprehensive and industrially validated assessments that treat energy, emissions, economics and part quality together, so that sustainable EDM can be adopted with confidence.

In practical terms, the review supports a staged route for practitioners. Optimising energy use and parameters, and managing fluids well, are low-risk steps that can be taken immediately. The adoption of vegetable-oil, waste-oil or engineered water-based dielectrics offers further benefits where fluid properties, filtration and operator practices are suitably managed. Dry and near-dry operation and advanced tooling are best targeted at applications in which their specific advantages outweigh productivity penalties. For researchers, the most valuable contributions will be those that combine technical performance with quantified environmental and economic indicators, report conditions fully, and test findings beyond a single machine or material. If these priorities are met, EDM can continue to serve demanding applications while moving closer to the goals of sustainable manufacturing.

References

[1] N. M. Abbas, N. Yusoff, and R. M. Wahab, “Electrical discharge machining (EDM): Practices in Malaysian industries and possible change towards green manufacturing,” in *Procedia Engineering*, Elsevier Ltd, 2012, pp. 1684–1688. doi: 10.1016/j.proeng.2012.07.368.

[2] J. R. Gamage, A. K. M. Desilva, C. Harrison, and D. Harrison, “Ascertaining Life Cycle Inventory Data for Electrical Discharge Machining,” in *Procedia CIRP*, Elsevier B.V., 2016, pp. 908–913. doi: 10.1016/j.procir.2015.12.091.

[3] W. Li and S. Kara, “Characterising energy efficiency of Electrical Discharge Machining (EDM) processes,” in *Procedia CIRP*, Elsevier B.V., 2015, pp. 263–268. doi: 10.1016/j.procir.2015.01.039.

[4] J. Singh and R. K. Sharma, "Green EDM Strategies to Minimize Environmental Impact and Improve Process Efficiency," *Journal for Manufacturing Science and Production*, vol. 16, no. 4, Feb. 2017, doi: 10.1515/jmsp-2016-0034.
[5] U. Arif, I. Ali Khan, and F. Hasan, "Green and sustainable electric discharge machining: a review," 2022, *Taylor and Francis Ltd.* doi: 10.1080/2374068X.2022.2108599.
[6] S. ViswanthV, "A Review of Research Scope on Sustainable and Eco-Friendly Electrical Discharge Machining (E-EDM)," 2018. [Online]. Available: www.sciencedirect.comwww.materialstoday.com/proceedings2214-7853
[7] S. Das and J. Deb Barma, "ECO-FRIENDLY DIELECTRIC MEDIUMS FOR SUSTAINABLE EDM: A COMPREHENSIVE REVIEW."
[8] M. T. Ulhakim *et al.*, "Electrical discharge machining: Recent advances and future trends in modeling, optimization, and sustainability," Jul. 01, 2025, *KeAi Publishing Communications Ltd.* doi: 10.1016/j.ijlmm.2025.03.006.
[9] K. Gupta and M. Kumar Gupta, "Developments in Non-Conventional Machining For Sustainable Production-A State of Art Review."
[10] S. Barik, B. K. Nanda, S. B. Mishra, M. P. Satpathy, and S. T. Debebe, "Performance and surface integrity studies in electric discharge machining on Ti-6Al-4 V using neem oil dielectric and 3D Printed SS316L electrode," *Sci. Rep.*, vol. 16, no. 1, Dec. 2026, doi: 10.1038/s41598-026-51103-y.
[11] K. Ishfaq, M. A. Maqsood, S. Anwar, A. Alfaify, and A. W. Zia, "Analyzing micromachining errors in EDM of Inconel 600 using various biodegradable dielectrics," *Journal of the Brazilian Society of Mechanical Sciences and Engineering*, vol. 44, no. 6, Jun. 2022, doi: 10.1007/s40430-022-03560-5.
[12] J. R. Gamage, A. K. M. DeSilva, D. Chantzis, and M. Antar, "Sustainable machining: Process energy optimisation of wire electrodischarge machining of Inconel and titanium superalloys," *J. Clean. Prod.*, vol. 164, pp. 642–651, Oct. 2017, doi: 10.1016/j.jclepro.2017.06.186.
[13] B. Sampath, M. Sureshkumar, T. Yuvaraj, and D. Velmurugan, "Experimental investigations on eco-friendly helium-mist near-dry wire-cut edm of m2-hss material," in *Materials Research Proceedings*, Association of American Publishers, 2021, pp. 175–180. doi: 10.21741/9781644901618-22.
[14] F. Modica, V. Marrocco, G. Copani, and I. Fassi, "Sustainable micro-manufacturing of micro-components via micro electrical discharge machining," *Sustainability*, vol. 3, no. 12, pp. 2456–2469, 2011, doi: 10.3390/su3122456.
[15] M. Ravi, G. Thangavel, M. Raja, T. G. Sakthivel, N. Ashok, and A. Bhowmik, "Intelligent optimization of micro-electrical discharge machining of aluminum nitride ceramics using nano abrasive zirconium oxide-enhanced biodegradable dielectric," *Sci. Rep.*, vol. 16, no. 1, Dec. 2026, doi: 10.1038/s41598-026-51911-2.
[16] G. Skrabalak, J. Kozak, and M. Zybura, "Optimization of dry EDM milling process," in *Procedia CIRP*, Elsevier B.V., 2013, pp. 332–337. doi: 10.1016/j.procir.2013.03.027.
[17] A. Żyra, "Influence of machining conditions on dry EDM with workpiece cooling of Inconel 625 alloy in the milling kinematics," *International Journal of Advanced Manufacturing Technology*, vol. 134, no. 5–6, pp. 2921–2937, Sep. 2024, doi: 10.1007/s00170-024-14275-3.
[18] X. Wu, Y. Liu, L. Qi, Y. Han, and M. Li, "Research on green dielectric fluids of high-efficient electrical discharge assisted arc milling," in *Procedia CIRP*, Elsevier B.V., 2022, pp. 196–201. doi: 10.1016/j.procir.2022.09.145.
[19] U. Arif, I. Ali Khan, and F. Hasan, "Enhanced machining of Al 10%SiCmicro 1%SiCnano hybrid composite using rotary tool rotary workpiece EDM with bio dielectrics and treated tools," *Sci. Rep.*, vol. 14, no. 1, Dec. 2024, doi: 10.1038/s41598-024-71713-8.
[20] P. Zhang *et al.*, "Mechanisms of green foam water on the sustainability of upward sinking electrical discharge machining," *Chinese Journal of Mechanical Engineering*, p. 100270, Mar. 2026, doi: 10.1016/j.cjme.2026.100270.
[21] M. A. Ali *et al.*, "Assessment of electrode materials in EDM of SS316L: energy consumption, electrode wear, dielectric consumption, GHG emissions, and economic viability for sustainable development," *Sci. Rep.*, vol. 15, no. 1, Dec. 2025, doi: 10.1038/s41598-025-24430-9.

[22] A. Hannan *et al.*, "Machining performance, economic and environmental analyses and multi-criteria optimization of electric discharge machining for SS310 alloy," *Sci. Rep.*, vol. 14, no. 1, Dec. 2024, doi: 10.1038/s41598-024-79338-7.
[23] S. K. Maurya, G. Campatelli, M. Veracini, M. Arcioni, and D. Clori, "Balancing Productivity and Sustainability in EDM: A Comprehensive Analysis of Energy Consumption and Electrode Degradation," *Machines*, vol. 13, no. 6, Jun. 2025, doi: 10.3390/machines13060469.
[24] A. Y. Joshi and A. Y. Joshi, "Multi response optimization of PMEDM of Ti6Al4V using Al2O3 and SiC powder added de-ionized water as dielectric medium using grey relational analysis," *SN Appl. Sci.*, vol. 3, no. 7, Jul. 2021, doi: 10.1007/s42452-021-04712-3.
[25] S. R. Jana, J. Shiek, and M. Ponnusamy, "Green dielectric exploration: spectrographic analysis and technical feasibility of vegetable oils in EDM via PIV, TOPSIS, and MOORA evaluation methods," *Discover Applied Sciences*, vol. 6, no. 10, Oct. 2024, doi: 10.1007/s42452-024-06157-w.
[26] M. Sana, M. Asad, M. U. Farooq, M. Tlija, and R. Haber, "Sustainability metrics targeted optimization and electric discharge process modelling by neural networks," *Sci. Rep.*, vol. 15, no. 1, Dec. 2025, doi: 10.1038/s41598-024-78883-5.
[27] J. R. Gamage, A. K. M. Desilva, C. S. Harrison, and D. K. Harrison, "Process level environmental performance of electrodischarge machining of aluminium (3003) and steel (AISI P20)."
[28] K. Ishfaq, M. Sana, M. U. Waseem, S. Anwar, and A. W. Zia, "Circular usage of waste cooking oil towards green electrical discharge machining process with lower carbon emissions," *International Journal of Advanced Manufacturing Technology*, vol. 131, no. 9–10, pp. 5133–5153, Apr. 2024, doi: 10.1007/s00170-024-13322-3.
[29] Jagadish, D. Zindani, A. Selvam, G. G. Tejani, and A. J. Santhosh, "Optimization of process parameter for green die sinking electrical discharge machining: a novel hybrid decision-making approach," *Sci. Rep.*, vol. 15, no. 1, Dec. 2025, doi: 10.1038/s41598-025-92713-2.
[30] J. B. Valaki, P. P. Rathod, and C. D. Sankhavara, "Investigations on technical feasibility of Jatropha curcas oil based bio dielectric fluid for sustainable electric discharge machining (EDM)," *J. Manuf. Process.*, vol. 22, pp. 151–160, Apr. 2016, doi: 10.1016/j.jmapro.2016.03.004.
[31] J. B. Valaki and P. P. Rathod, "Assessment of operational feasibility of waste vegetable oil based bio-dielectric fluid for sustainable electric discharge machining (EDM)," *International Journal of Advanced Manufacturing Technology*, vol. 87, no. 5–8, pp. 1509–1518, Nov. 2016, doi: 10.1007/s00170-015-7169-0.
[32] S. Das, S. Paul, and B. Doloi, "Investigation of the Machining Performance of Neem Oil as a Dielectric Medium of EDM: A Sustainable Approach," in *IOP Conference Series: Materials Science and Engineering*, IOP Publishing Ltd, Nov. 2019. doi: 10.1088/1757-899X/653/1/012017.
[33] S. BOOPATHI, A. S. Alqahtani, A. Mubarakali, and P. Panchatcharam, "Sustainable developments in near-dry electrical discharge machining process using sunflower oil-mist dielectric fluid," Dec. 05, 2022. doi: 10.21203/rs.3.rs-2293160/v1.
[34] M. C. Radu, R. Tampu, V. Nedeff, O. I. Patriciu, C. Schnakovszky, and E. Herghelegiu, "Experimental investigation of stability of vegetable oils used as dielectric fluids for electrical discharge machining," *Processes*, vol. 8, no. 9, Sep. 2020, doi: 10.3390/PR8091187.
[35] M. C. Radu *et al.*, "Use of vegetable oils as dielectric fluids for electrical discharge machining. A case study," *Heliyon*, vol. 10, no. 11, Jun. 2024, doi: 10.1016/j.heliyon.2024.e31772.
[36] W. Ming *et al.*, "Optimization of process parameters and performance for machining Inconel 718 in renewable dielectrics," *Alexandria Engineering Journal*, vol. 79, pp. 164–179, Sep. 2023, doi: 10.1016/j.aej.2023.07.075.
[37] P. Priyanka, V. Jayakumar, P. K. Giridharan, and S. M. Muthu, "Sustainable machining and optimization of machining parameters utilizing different dielectrics in EDM machining of Waspaloy," *Sci. Rep.*, vol. 15, no. 1, Dec. 2025, doi: 10.1038/s41598-025-18356-5.
[38] K. Ishfaq, M. Sana, M. Rehman, S. Anwar, A. Y. Alfaify, and A. W. Zia, "Role of biodegradable dielectrics toward tool wear and dimensional accuracy in Cu-mixed die sinking EDM of Inconel 600 for sustainable

machining," *Journal of the Brazilian Society of Mechanical Sciences and Engineering*, vol. 45, no. 4, Apr. 2023, doi: 10.1007/s40430-023-04126-9.

[39] V. S. Viswanth, R. Ramanujam, and G. Rajyalakshmi, "Improving productivity with eco-friendly dielectrics in sustainable EDM machining of AISI 2507 super duplex stainless steel."

[40] S. Viswanthvaleti and R. Radhakrishnan, "MULTI-RESPONSE OPTIMIZATION OF PROCESS PARAMETERS OF GREEN ELECTRICAL DISCHARGE MACHINING ON AISI 2507 SUPER DUPLEX STAINLESS STEEL USING GREY RELATIONAL ANALYSIS (GRA)." [Online]. Available: www.tjprc.org

[41] K. Ishfaq, M. Sana, W. M. Ashraf, and V. Dua, "Sustainable EDM of Inconel 600 in Cu-mixed biodegradable dielectrics: Modelling and optimizing the process by artificial neural network for supporting net-zero from industry," *J. Clean. Prod.*, vol. 421, p. 138388, Oct. 2023, doi: 10.1016/J.JCLEPRO.2023.138388.

[42] N. M. Anh *et al.*, "Environmentally sustainable EDM of Ti-6Al-4V alloy employing copper nanoparticle-dispersed vegetable oil dielectrics," *Results in Engineering*, vol. 28, Dec. 2025, doi: 10.1016/j.rineng.2025.108038.

[43] L. Tang and Y. T. Du, "Experimental study on green electrical discharge machining in tap water of Ti-6Al-4V and parameters optimization," *International Journal of Advanced Manufacturing Technology*, vol. 70, no. 1–4, pp. 469–475, Jan. 2014, doi: 10.1007/s00170-013-5274-5.

[44] R. Bian *et al.*, "High-performance and sustainable electrical discharge machining with green microdroplet dielectric," *Journal of Materials Research and Technology*, vol. 37, pp. 2989–2999, Jul. 2025, doi: 10.1016/j.jmrt.2025.06.229.

[45] C. L. Kuo, C. T. Chen, and C. C. Ho, "Enhancing electrical discharge machining performance through nano H_2/O_2 bubble integration: A sustainable and optimized approach," *Micro and Nano Engineering*, vol. 28, Sep. 2025, doi: 10.1016/j.mne.2025.100306.

[46] R. Bajaj, A. R. Dixit, and A. K. Tiwari, "Machining performance enhancement of powder mixed electric discharge machining using Green dielectric fluid," *Journal of the Brazilian Society of Mechanical Sciences and Engineering*, vol. 42, no. 10, Oct. 2020, doi: 10.1007/s40430-020-02597-8.

[47] K. Ishfaq, M. Asad, S. Anwar, C. I. Pruncu, M. Saleh, and S. Ahmad, "A comprehensive analysis of the effect of graphene-based dielectric for sustainable electric discharge machining of Ti-6Al-4V," *Materials*, vol. 14, no. 1, pp. 1–24, Jan. 2021, doi: 10.3390/ma14010023.

[48] M. Sana, M. Asad, M. U. Farooq, S. Anwar, and M. Talha, "Sustainable electric discharge machining using alumina-mixed deionized water as dielectric: Process modelling by artificial neural networks underpinning net-zero from industry," *J. Clean. Prod.*, vol. 441, Feb. 2024, doi: 10.1016/j.jclepro.2024.140926.

[49] T. Tiwari, A. K. Singh, and C. S. Rakurty, "Manufacturing Letters Assessing Process and Environmental Performance of SiC-PEG Dielectric EDM: A Comparative Study," 2025. [Online]. Available: www.sciencedirect.com

[50] R. Roth, H. Balzer, F. Kuster, and K. Wegener, "Influence of the anode material on the breakdown behavior in dry electrical discharge machining," in *Procedia CIRP*, 2012, pp. 639–644. doi: 10.1016/j.procir.2012.04.113.

[51] R. Roth, F. Kuster, and K. Wegener, "Influence of oxidizing gas on the stability of dry electrical discharge machining process," in *Procedia CIRP*, Elsevier B.V., 2013, pp. 338–343. doi: 10.1016/j.procir.2013.03.029.

[52] L. Liqing and W. Yunhang, "Discharge gap and relative discharge ratio in dry electrical discharge machining," in *Procedia CIRP*, Elsevier B.V., 2020, pp. 482–487. doi: 10.1016/j.procir.2020.03.145.

[53] H. Farooq and R. A. Pasha, "Investigation of process parameters for modeling of ceramic composite SiSiC IN dry EDM (DEDM) cutting," *Heliyon*, vol. 10, no. 17, Sep. 2024, doi: 10.1016/j.heliyon.2024.e36459.

[54] S. Fattahi and A. S. Ullah, "Optimization of Dry Electrical Discharge Machining of Stainless Steel using Big Data Analytics," in *Procedia CIRP*, Elsevier B.V., 2022, pp. 316–321. doi: 10.1016/j.procir.2022.09.004.