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REVIEW ARTICLE

Electrochemical discharge machining for micro fabrication of insulating brittle material: State of the art and future directions

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Abstract - Electrically non-conductive advanced engineering materials, such as glass, ceramics, quartz, and composites, pose significant challenges for conventional machining methods. Electrochemical discharge machining (ECDM) emerges as a notable hybrid non-conventional technique specifically tailored for brittle, hard-to-machine, nonconducting materials. This technique achieves a delicate balance between thermal energy and chemical interactions. Variations of ECDM have been developed to enable the fabrication of complex miniature profiles. However, prevalent issues such as unstable electrolyte conditions and inadequate flushing within the machining zone compromise the process accuracy and repeatability, thereby undermining the industrial viability, sustainability, and stability of the ECDM process. To address these limitations, researchers have developed hybrid ECDM variants. Despite this advancement, challenges persist, particularly in maintaining high surface integrity and robust process stability. This review aims to provide a comprehensive overview of recent developments in the mechanism underlying ECDM and its variants. It examines the influence of process parameters and triplex hybridisation on the performance matrices. Additionally, the review outlines potential research directions across various aspects of ECDM, highlighting areas for further exploration.

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1. Introduction

Advanced insulating brittle materials, including advanced ceramics, glasses, and composites, exhibit high electrical resistivity, exceptional thermal stability, and considerable chemical inertness [1]. These materials retain structural integrity and insulating properties at elevated temperatures, in corrosive environments, and under demanding mechanical conditions, making them vital in Micro Electro Mechanical System (MEMS), aerospace, energy, biomedical, and semiconductor industries [2]. However, their strong ionic and covalent bonds result in inherent fragility, posing significant engineering challenges that require specialised micro-machining and toughening techniques [3]. Conventional approaches, such as micro-drilling, are ineffective for these materials due to their hardness, brittleness, susceptibility to chatter, and frequent tool failure during processing [4-8]. To overcome the limitations of conventional machining, non-conventional or lithography-based machining techniques are typically employed to achieve precise shapes, dimensional accuracy, and high surface integrity, irrespective of the chemical and mechanical properties of advanced materials [8-10]. For small batch production, non-conventional machining processes are favoured over lithographic methods [11]. Non-conventional machining utilises various energy sources, including thermal energy in laser beam machining (LBM) and electrical discharge machining (EDM), mechanical energy in ultrasonic machining (USM), and chemical energy in electrochemical machining (ECM) or hybrid processes such as electrochemical discharge machining. ECDM has a significant advantage over alternative non-conventional machining techniques for brittle and insulating materials. The ECDM process can machine both conductive and non-conductive substrates [12].

Table 1 provides an overview of the performance indicators of various non-conventional machining techniques. However, EDM and ECM are bound to conductive materials [13-14]. ECDM achieved higher sustainability indices (approximately 0.70–0.85) and minimum feature sizes (approximately 15 µm) than conventional USM, using safer, water-based electrolytes that cause less environmental harm [15-17]. By bridging thermal and chemical processing, ECDM allows micromachining of non-conductive materials at a high material removal rate (MRR) in the range of 2-20 mm^3/min (higher than USM [18]), improved accuracy of ±20-40 µm, and a fine surface finish (Ra ≈ 0.4-2.5 µm). It also offers a lower heat-affected zone (HAZ) than LBM [19]. Given this, ECDM is especially suitable for micromachining glass, ceramics, and composite materials, when other techniques are strongly limited by heat or electrical issues [20-26]. To further enhance ECDM micromachining productivity, the discharge energy was varied, leading to variants of ECDM. Various machining operations, such as the production of complex and intricate micro dies [27], micro profiles [28-29], machining of cylindrical parts [30], dressing of micro-grinding tools [31], slicing of glass rods [32], and deep drilling [33], were performed by using these variants, namely, electrochemical discharge-drilling, grinding, turning, and milling. The ECDM process has achieved significant milestones since its inception. However, several limitations of ECDM variants have been reported by researchers, including poor geometrical accuracy, low aspect-ratio structures, low MRR, poor surface integrity, the presence of an existing HAZ and a recast layer, and non-repeatability of operations due to unstable spark generation [21]. Table 2 presents the historical background and development of the ECDM process over the years. This timeline illustrates the continuous evaluation of ECDM, characterised by innovative research and technological advancement that have significantly expanded its application and improved its precision.

Table 1. Comprehensive comparison of non-conventional machining processes

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Process	ECDM [12]	EDM [13]	ECM [14]	USM [18]	LBM [19]
MRR (mm^3/min)	2-25	10-100	1500-15000	5-50	0.1-50
Tolerance (µm)	±20-40	±10-50	±50-100	±7-25	±10-25
Min. feature Size (µm)	15-40	10-50	50-100	20-100	1-10
SR (Ra, µm)	0.4-3.5	0.2-12.5	0.1-1.2	0.2-1.6	0.5-5.0
Energy efficiency (J/mm^3)	Low (Hybrid)	Low (10^3-10^5)	Moderate (10^2-10^3)	High (10^1-10^2)	Very low (10^4-10^6)
Material applicability	Glass, ceramics, composites	Carbides, alloys, metals	Steel, aerospace alloys	Glass, ceramics	Metals, plastics
Sustainability index	High (0.70-0.85)	Low (0.45-0.60)	Medium (0.65-0.75)	High (0.80-0.90)	Medium (0.50-0.65)

MRR: Material removal rate, SR: Surface roughness, ECDM: Electrochemical discharge machining, EDM: Electrical discharge machining, ECM: Electrochemical machining, USM: Ultrasonic machining, LBM: Laser beam machining.

Table 2. Background and historical development in the ECDM process

Year	Author	Development in the ECDM process
1968	Kurafuji [20]	First introduction of "Electrical Discharge Drilling" of glass.
1973	Cook et al. [26]	Highlighting ECDM's unique applicability to a broad range of non-conducting materials.
1985	Crichton and McGeough [25]	Study of discharge mechanism in ECDM.
1991	Tandon et al. [23]	Expanding ECDM applications and their similarities with "Electrochemical Arc Machining".
1996	Basak and Ghosh [34]	Introduction of a theoretical model linking electrochemical discharge phenomena to machining processes.
2001	Yang et al. [35]	Understanding of the material erosion mechanism in ECDM as "High-Temperature Etching Process".
2005	Wüthrich and Bleuler [36]	First comprehensive review based on ECDM explaining electrical discharge, thermal, and chemical machining.
2006	Kim et al. [37]	Study on the effect of pulse voltage on the heat-affected zone.
	Yang et al. [38]	Use of abrasive-mixed electrolytes to reduce discharge energy and surface roughness (SR).
2008	Wüthrich and Jana [39]	Extension of ECDM applications in micro and nanomachining.
2009	Doan Cao et al. [40]	Expanding the ECDM application by machining a 3D microstructure.
2010	Cheng et al. [41]	Introduction of magnetic-field-assisted ECDM improves process control and efficiency.
2011	Yang et al. [42]	Introduction of spherical tool electrodes for high aspect ratio drilling, reducing entrance diameter and machining time.
2013	Liu et al. [43]	Introduction of grinding-assisted ECDM enhances the process's capabilities.
2017	Rattan and Mulik [44]	Introduction of magnetic field-assisted travelling wire-ECDM, enhancing MRR (0.19 mg/min).
2018	Mehrabi et al. [45]	Study on ultrasonic-assisted ECDM, improving machining performance.
2020	Singh et al. [46]	Investigation on laser-assisted ECDM to improve machining precision and material erosion.
2022	Gupta et al. [47]	Comprehensive review of various process variants and hybridisation of ECDM milling and dressing.
2023	Bahar et al. [48]	The use of electrolyte stirring and tool rotation in micro-ECDM improves surface finish (by 91%) and MRR (by 220%).
2024	Kong et al. [49]	Experimental study on porous-electrode ECDM process, achieving more efficient processing than the solid-electrode tool.
2025	Tiwari et al. [50]	Study on the influence of disk-shaped at higher machining depth, improving ECDM process efficiency.

To overcome the issues associated with conventional ECDM variants, another triplex hybrid ECDM variant is under development. These triplex hybrid methods have the potential to improve machining efficiency, including performance and productivity [41]. The current study presents a critical review of the evaluation of the ECDM process, its variants, and hybrid variants. It concludes with recommendations for future research potential and trends for the ECDM methodology.

2. Materials and Methods

2.1 Advanced Engineering Material

Industrial demand for advanced engineering materials suitable for the fabrication of complex miniature products is growing exponentially. Applications for these materials include, but are not limited to, various sectors such as aerospace, automotive, energy, biomedical, electrical, electronics, telecommunications, defence, and MEMS. Such materials possess unique properties superior to those of traditional materials, including increased strength and hardness at high temperature, improved chemical and wear resistance, and lower electrical conductivity. Micromachining on these materials is thus a crucial process for achieving product efficiency and determining its industrial acceptance [12]. Figure 1 illustrates the trend of research activity in the field of advanced engineering materials, as reviewed in the current report. The materials studied include glass (optical, Pyrex, borosilicate) [20, 24, 29], quartz (SiO_2), ceramics (alumina, zirconia) [28, 51], silicon wafer, composites (metal matrix composite, ceramic matrix composite, polymer matrix composite) [23], besides hard metals (tungsten, stainless steel, Inconel) and polymers (fibre-reinforced polymer, e-glass fibre reinforced polymer). According to the observed research trend, glass, quartz, and ceramics account for most of the research activity in the ECDM process. In contrast, composites, hard metals, and polymers receive fewer research interests.

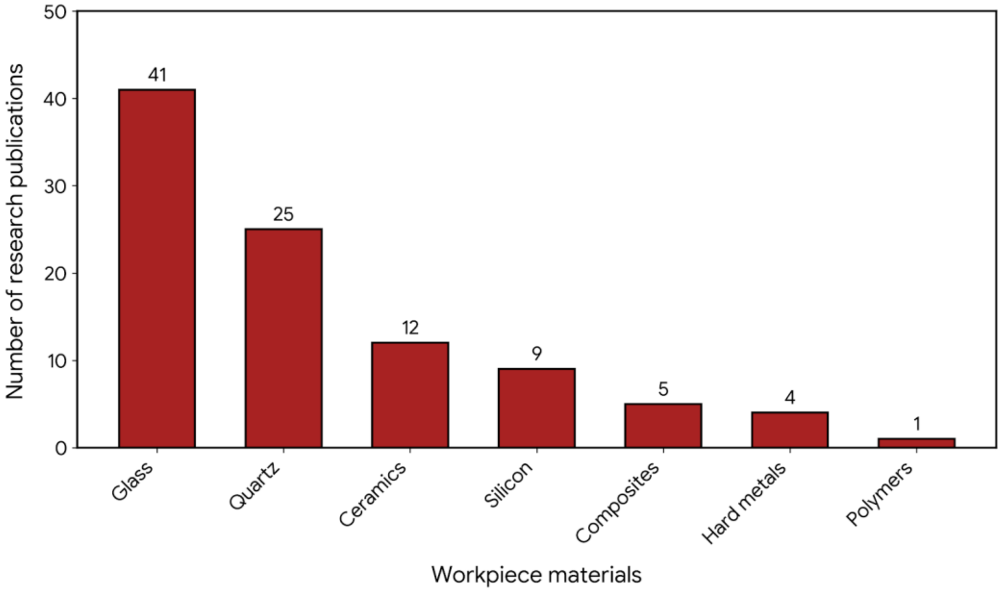

Figure 1. Research trend of advanced engineering materials in the ECDM process

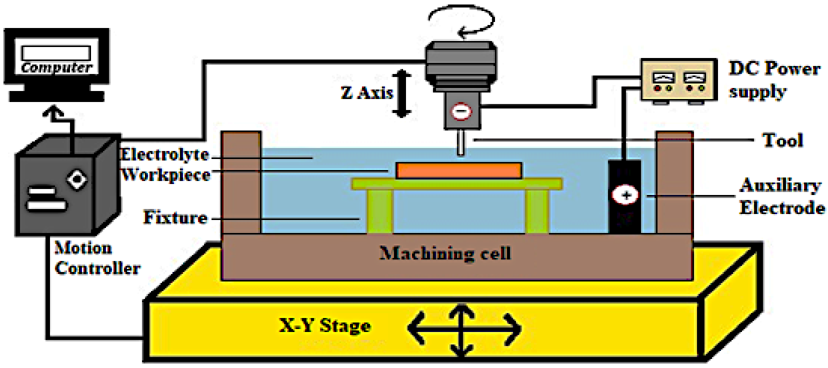

Figure 2. Schematic of ECDM set-up for electrically non-conducting materials

2.2 Electrochemical Discharge Machining

Electrochemical discharge machining represents the well-known non-conventional hybrid micromachining technique in which discharge-based material erosion is integrated with chemical etching. This technique has the potential to fabricate complex, geometrically accurate micro-3D features [52-56]. ECDM is particularly effective for micromachining hard and brittle electrically non-conductive [56-58] and conductive [59] advanced materials, achieving high MRR, a smooth surface finish, and negligible tool wear rate (TWR). Additionally, shape accuracy and MRR can be regulated by electrical process parameters in this process [60, 61]. To complete a circuit, an auxiliary electrode is used for non-conducting materials, whereas for conducting materials, the power source is directly connected to the workpiece [61]. ECDM has been described in the literature under multiple names, further reflecting the inherent complexity of the process [22-27]. Figure 2 shows the schematic of the ECDM setup for non-conducting materials. The setup consists of two electrodes: an auxiliary or counter electrode (anode) and a tool electrode (cathode), and a workpiece submerged in an appropriate electrolyte (typically KOH or NaOH). The auxiliary electrode has a greater surface area (about a factor of 100) than tool electrodes and is usually positioned between 25 and 60 mm distant from the tool. To ensure smooth machining, the tool electrode is dipped into the electrolytic solution at a spacing of about 1-2 mm [62-65]. A continuous or pulse DC power supply creates the potential difference between the anode and cathode. Researchers have also studied reverse-polarity conditions. The key principle that dominates ECDM, that is, the discharge mechanism, is discussed in the next section.

2.2.1 Discharge mechanism

The discharge mechanism depends on principles of both ECM and EDM. The discharge in the EDM process is possible only in the presence of a dielectric medium. In the ECDM process, an electrolytic medium is used as the working fluid rather than a dielectric [48, 66]. The gas (hydrogen) bubbles formed by electrolysis during ECM serve as the dielectric medium required to develop a spark around the tool surface [49]. Figure 3 illustrates the ECDM process working mechanism, which can be explained in the following steps: (i) initiation of electrolysis, (ii) formation and deposition of gas bubbles, (iii) Gas bubbles coalescence and gas film development, (iv) Formation of Discharge.

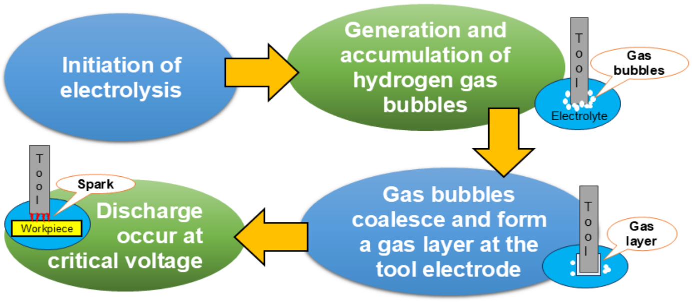

Figure 3. Process mechanism involved in ECDM

Electrolysis occurs at a low voltage (typically 20-30 V) due to the potential difference across the electrodes. This results in the initiation of metal dissolution from the anode surface and dissociation of electrolyte into hydroxide ions [49]. The metal ions formed react with hydroxide ions to produce insoluble metal hydroxide in the electrolyte. Also, in the presence of electrolytes (either alkaline or acidic nature), oxygen and hydrogen gas are formed at the auxiliary and tool electrode surfaces, respectively. The microscopic gas bubbles begin to build up at the tool electrode surface and obstruct the current passage at the tool-electrolyte junction. Such obstruction causes heating and electrolyte vaporisation, creating vapour bubbles [50]. As the applied voltage increases, these vapour bubbles combine with gas bubbles, and their mean radius increases. A layer of hydrogen gas (gas film) forms around the tool when these bubbles combine above the critical voltage threshold (typically above 30 V), depending on the electrolyte's concentration and geometry. This gas (hydrogen) film separates the tool from the electrolyte and limits the contact of the electrolyte with the cathode [42]. If the potential difference is sufficiently high in an electrolyte-tool system, high current densities in the gas film result in an intense electric field (typically 10^7 V/m) at the tool's sharp edges. Further, this leads to the formation of a plasma channel between the tool and the workpiece. Finally, it leads to discharge at the tool edges in the form of electrical discharges [52]. Also, the discharge location continuously changes across the tool face [67-69]. The temperature in the discharge area ranges from 1297-10,000 °Kelvin [34, 53]. During discharge, bombardment of the workpiece by electrons within 25 µm of the tool raises its surface temperature [22]. This finally contributes to material removal by melting and vaporising the conductive or nonconductive workpiece material [54].

Researchers have studied discharge mechanisms using different approaches. Taylor [55] first observed the anode effect. Kurafuji [20] conducted an experimental investigation of the ECDM technique for drilling a 310 µm microhole in glass. Still, they did not provide a physical explanation of discharge during machining. Crichton and McGeough [25] described the various phases of spark formation using streak photography. They also stated that discharge formation results from the generation and growth of gas bubbles. However, there was insufficient detail about the cause of the spark. Further, Basak and Ghosh [34] stated the development of spark as a switching phenomenon for a short time interval with no current, due to the formation of gas bubble bridges around tool electrodes and reported that ohmic heating in electrolyte can be improved following an increase in bubble density, resulting in tool isolation from electrolyte. They presented fairly accurate theoretical models for spark creation. Jain et al. [57] introduced the arc discharge valve theory. Each gas bubble formed because of an electrochemical reaction, and they discovered that breaking these bubbles under a high electrical field produced a comparable arc discharge. However, spark formation in the electrolyte at a deeper level was not illustrated in detail. Kulkarni et al. [54] reported an explanation of the discharge mechanism using a time-varying graph. Researchers claim that discharge occurs when a strong electric field forms as the electrolyte separates from the tool. Again, researchers presented a percolation theory to show how ECDM gets sparked. Gas bubble adhesion and growth were also investigated by researchers [22]. Researchers concluded that the gas layer surrounding the tool electrode causes sparks to form between the workpiece and the tool. This gas layer forms when tiny bubbles merge into larger ones that continue to grow [36].

Additionally, by examining images of current signals and the shapes carved into the machined surface, researchers investigated the structure of sparks. They discovered that the cylindrical discharge shape resulted in a circular machining pattern on the workpiece surface [54, 70]. Simultaneously, these continuous sparks over the workpiece raise the electrolyte temperature, promoting chemical etching and enhancing the surface finish (Ra = 0.08 µm) [35]. Based on experimental results, it was observed that the DC voltage supply significantly contributes to the size and density of gas bubbles. Bubble formation increased, and density improved with increasing voltage. At 30-60 V, the average bubble diameter grows between 25 and 55 µm [61]. The thickness of the gas film formed due to the merging of bubbles ranges from 17 to 29 µm and is directly proportional to the tool radius [62]. When experimenting with a 300 µm tool radius and a machining depth of 303 µm, a minimum gas film thickness of 45 µm was observed [63]. Breakdown of these film layers occurs above the critical voltage, leading to discharge [64, 65]. Additionally, discharge occurs at a current density (higher than its critical value) of approximately 1 A [49]. Researchers also identified several significant factors, in addition to voltage, that influence discharge formation. These factors include the tool geometry, inter-electrode gap (IEG), the machining gap between the workpiece and the tool, electrolyte concentration, nature, and its level above the workpiece [66-69]. To maximise the presence of discharge energy around the work material and achieve high surface quality during machining, the machining gap between the tool and workpiece is to be kept to a minimum, approximately 5-25 µm [70, 71]. Electrolytes of alkaline nature, such as NaOH and KOH, proved more effective and thus favoured more than electrolytes of acidic nature. During machining, a low electrolyte concentration is preferred to achieve a thin layer of gas film [61, 72].

3. Results and Discussion

3.1 Effect of Process Parameters

Researchers have documented their investigations into enhancing the ECDM method and have analysed the direct impact of various process parameters, which constitute the fundamental factors influencing ECDM machining responses. These parameters include the tool electrode, workpiece, electrolyte, auxiliary electrode, electrical parameters, and the tool-workpiece gap, as illustrated in the cause-and-effect diagram in Figure 4. The electrolyte serves as the essential medium in the ECDM process, facilitating chemical etching and gas film formation. Its pH and concentration directly influence the solution's electrical conductivity. Appropriate flushing and temperature regulations are necessary to remove machined debris and to prevent electrolyte boiling. The Electrical category details the energy parameter that connects electrolysis to discharge phenomena. Operators can modulate the intensity of these sparks by adjusting the duty cycle and frequency of the pulse power cycle. The tool electrodes, typically the cathode in an electrical circuit, serve as the focal point for energy concentration. Its specific size, shape, and material conductivity are designed to optimize current density at the tip [12]. Furthermore, the feed rate and tool rotation maintain a consistent inter-electrode gap, thereby ensuring continuous electrolyte replenishment and uniform spark dispersion across the machining zone. The auxiliary electrode functions as the anode, completing the circuit. Its positioning and dimensions provide the necessary stability for high-precision micromachining by maintaining electrical resistance predominantly at the tool tip rather than at the auxiliary site [34].

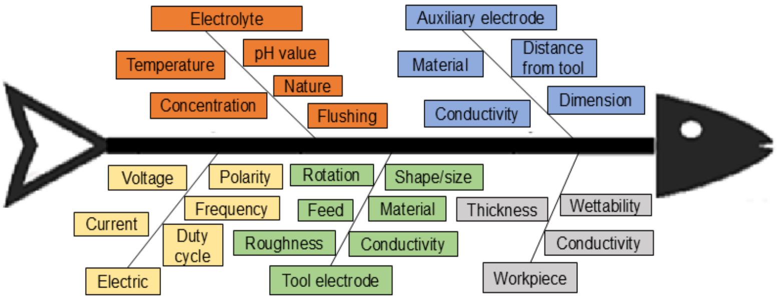

Figure 4. Cause and effect diagram representing ECDM parameters

Based on experimental investigations, researchers have also analysed several input process parameters that substantially influence the performance of ECDM processes. Increasing variable input parameters, such as the applied voltage pulse duration, duty cycle, electrolyte concentration, and conductivity, has been observed to correlate with increased MRR. However, this escalation is typically accompanied by a decline in surface finish and dimensional accuracy [44]. Furthermore, as the pulse frequency decreased, the rate of material removal correspondingly reduced, followed by improvement in surface finish and dimensional accuracy of the fabricated microstructures. The ECDM process can be optimised for efficiency and precision through the meticulous regulation of various electrical and non-electrical input parameters [64]. The parameters and their impact on ECDM performance, including MRR, surface quality, TWR, and overcut of the machined products, are examined and explained in the following section.

3.1.1 Electrical parameters

***Power supply in ECDM*:** The efficiency of the ECDM process is significantly influenced by the power source and various electrical parameters, including voltage, current, pulse frequency, electrode polarity, and duty cycle [73, 37]. Compared to a continuous DC power source, a pulse DC power supply offers enhanced machining efficiency owing to improved spark stability and facilitates the dissipation of concentrated discharge energy. Furthermore, owing to intermittent sparking and cooling in pulsed DC supplies, less heat is generated, resulting in minimal thermal damage to the workpiece after machining [66, 74-76]. In the ECDM experimentations, researchers identified current and voltage essential electrical parameters responsible for discharge formation [34]. Furthermore, it is reported that increasing the current and pulse voltage can enhance the discharge mechanism of the process. Bubble formation escalates as current and voltage increase. These bubbles coalesce to form a thick gas film, thereby increasing discharge intensity and improving the efficiency of the ECDM process [39, 73-77]. Researchers explained the impact of power circuits on ECDM performance. They investigated modified power circuits and determined that the inductance (L), capacitance (C), and resistance (R) individually influenced machining performance. Furthermore, they documented an increase in MRR from 0.12 to 0.15 mg/min during machining with the RC circuit, suggesting its potential to enhance machining precision. Additionally, the author observed that incorporating external inductors into the circuit helped to maintain a stable power supply [75].

Researchers observed greater effectiveness of ECDM machining with a pulse DC power supply than with a continuous DC power supply. A pulsed DC power supply incorporates a rest interval into the machining process. The primary issues arising from its intermittent operation include heat accumulation, gas film instability, and debris entrapment [77, 78]. Further investigation demonstrated that increasing the applied voltage led to the current reaching its maximum within the circuit, thereby increasing the current density [79, 80]. Additionally, an increase in the maximum current across electrodes is observed upon the addition of surfactant to the electrolyte solution. Mixing increases the number of ions in the electrolytic solutions, thereby increasing the current [81]. Another researcher documented enhanced dimensional accuracy of holes, accompanied by a minimal crack count, through experimentation utilising a modified circuit in which current disperses among multiple tool electrodes (power division) [82]. Similarly, upon incorporation of alumina powder (3 wt%) into the electrolyte, multiple discharge peaks were observed, characterised by a distinct current peak, which decreased the mean current from 270 mA to 262 mA [83]. Researchers reported that the peak discharge current distribution was twice as high with the cylindrical tool as with the taper tool [84].

Applied voltage and offset voltage: The applied voltage appears to be a fundamental factor in spark formation and the stability of the machining process. Research has shown that at low voltage, only electrolysis can be initiated. To generate a spark, the applied voltage must exceed the critical voltage [85-87]. This critical voltage depends on several parameters, including the tool electrode diameter, the material and its conductivity, the electrolyte nature and concentration, and the inter-electrode gap [34, 88]. Researchers deduced that achieving high machining efficiency requires high voltage, as it enhances gas bubble formation and stability, thereby reducing machining duration. Nevertheless, this approach compromises the surface quality of the workpiece, leading to microcracks, increased tool electrode wear, and potential workpiece failure during ECDM-based drilling [89, 90]. Additionally, Kim et al. [37] reported that hole surface integrity improved with increasing pulse-voltage frequency. Compared to the two-stage (continuous and uniform) current response waveforms observed in DC voltage-current, the pulse voltage-current waveform comprises three stages: the film development period, the discharge period, and the no-spark period. Generally, compared to pulse voltage, the use of offset pulse voltage offers enhanced spark accuracy and stability in ECDM drilling operation [91]. Researchers documented various phases of voltage waveforms. Stage 1 exhibits a gradual increase in voltage, followed by the inception of discharge at the breakdown threshold, and a sudden decrease leading to an arc at a constant voltage. Stage 2 demonstrates arc discharge during the pulse-on duration, while Stage 3 indicates an abrupt voltage drop to zero. Additionally, during the pulse-on period, no spark is observed as the voltage increment is gradual. Moreover, when the pulse-on duration is excessively brief, discharge phenomena are not detected [40].

Duty factor: The ratio of the pulse-on time (the duration of the power supply) to the total pulse cycle is called the duty factor. SR, MRR, and HAZ, in addition to penetration depth, increase with increasing duration of voltage application, leading to greater heat energy availability throughout the machining zone [37, 92]. Researchers also reported that during ECDM-based drilling, there was no influence observed on the aspect ratio of micro holes with higher values of duty factors (above 0.75) [78]. Pulse-on time significantly influences duty cycle and machining performance [92]. Increasing the pulse-on time of the discharge energy supply during drilling elevates the temperature, thereby enhancing material erosion through melting and evaporation. Researchers also observed that both machining depth and surface roughness (SR) increased simultaneously with increased pulse on time. During the milling process, deviations in pulse-on or pulse-off duration, specifically durations shorter or longer than 0.5 ms, resulted in a corresponding elevation in SR [93]. During pulse-off time (no discharge), film redevelopment, debris removal from the machining area, and cooling of the workpiece are observed [88]. In milling, researchers reported that the pulse-off time during ECDM confines the discharge heat within the machining zone, thereby improving machining resolution. A longer pulse-off than pulse-on duration results in the development of a mechanical crack in the work material due to insufficient heat energy for material removal. With a shorter pulse-off time, there is insufficient flushing of melted debris across the machining zone, resulting in poor surface quality of the machined material [93]. In drilling, a reduction in pulse frequency (the number of pulse cycles per unit time) facilitates increased material removal and SR [37, 92]. In milling, increasing the pulse frequency reduces HAZ and overcut [94].

***Tool* polarity:** Most researchers employed ECDM with direct polarity, wherein the tool electrode was designated as the cathode. Nonetheless, certain studies have also explored reverse polarity, wherein the positive terminal is connected to the tool electrode [48, 95]. A study investigated the influence of reverse tool polarity on machining efficiency through experimental procedures. It was observed that, compared with direct tool polarity, reverse tool polarity enhances chemical etching and material removal. However, it also increases TWR, SR, and dimensional inaccuracy [95]. Another study reported that reverse tool polarity leads to the formation of spherical microholes, whereas direct tool polarity results in conical microholes [48].

3.1.2 Non-electrical parameters

Types of electrolytes: An electrolyte plays a crucial role in achieving the efficiency of ECDM operations [79]. Researchers reported multiple functions of electrolytes during machining, including gas bubble formation, electrochemical etching, and flushing debris from the discharge zone [96, 97]. Table 3 illustrates the types of electrolytes considered for ECDM micromachining. Electrolytes can be acidic, alkaline, or neutral, and each affects micromachining performance. Hence, selecting appropriate electrolytes is vital for achieving stable micromachining and is determined by the desired workpiece material, performance parameters, and machining conditions. Figure 5 shows the research trends in the use of different electrolytes in ECDM processes as reviewed in this report. Researchers studied ECDM and concluded that NaOH- and KOH-based (alkaline) electrolytes are well-suited for micromachining insulating brittle materials.

Table 3. Effect of different electrolytes on machining characteristics in the ECDM process

Electrolyte	Remark								
	Nature	Spark	MRR	TWR	SR	DA	HH	EF	Cost
NaOH [74], KOH [98]	Alkaline	Stable	High	Neg.	Low	High	High	No	Med.
HCl [75], H_2SO_4 [36]	Acidic	Not Stable	Low	Low	High	Low	High	No	High
KCl [34], $NaNO_3$ [99], NaCl [80], KNO_3 [99]	Neutral Salt	Stable	Low	High	Low	Low	Low	Yes	Low
NaOH + KOH [95]	Mixed Electrolyte	Stable	High	Neg.	Low	High	High	No	High
DI water [97]	Other	Stable	Med.	Low	Low	Low	Low	Yes	Low

MRR- Material Removal Rate, TWR- Tool Wear Rate, SR- Surface Roughness, DA- Dimensional accuracy, HH- Health Hazard, EF- Eco-Friendly, Neg.- Negligible, Med.- Medium, DI- De-ionised

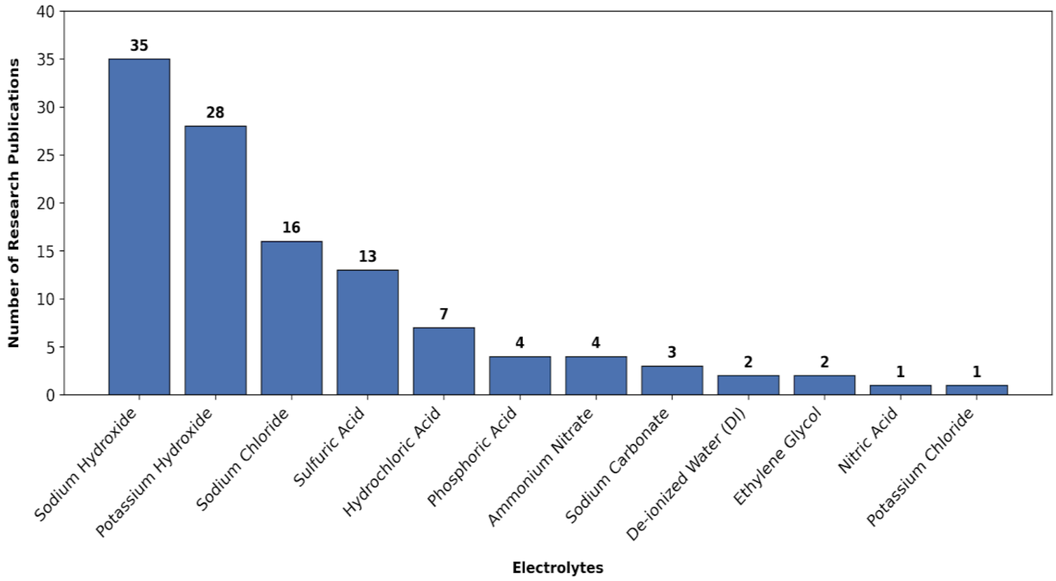

Figure 5. Research trends in the field of electrolytes for the ECDM process

NaOH and KOH significantly contribute to the critical voltage and the development of gas bubbles, and regulate film thickness around the tool hole entrance, with no effect of stray current corrosion observed during drilling-based ECDM operation [74, 37, 100]. Experimentation with KOH-based electrolytes has been widely reported, with improved chemical etching and higher ion mobility than other alkaline electrolytes [41]. Researchers also observed the formation of a dense film even at low voltage when the KOH concentration was high [98]. The influence of mixed electrolytes comprising NaOH and KOH on drilling-based ECDM has also been reported, with improved electrical conductivity observed at specific concentration levels owing to ion saturation. The conductivity of the mixed electrolyte is largely contingent upon the conductivity of the constituent parent electrolytes [43]. Researchers employed plain water [59, 101] and deionised water [97, 102] with low viscosity and resistivity in ECDM-based drilling to find an environmentally acceptable electrolyte. They concluded that, compared with plain water, deionised water is a weak electrolyte with lower electrical conductivity and a greater gap voltage required to cause discharge. Additionally, deionised water enhanced electrochemical dissolution, as seen by electrochemical corrosion pits at hole openings [97].

Electrolyte concentration: It plays a crucial role in determining machining quality and directly influences spark intensity and the critical voltage developed during machining [79]. Increased discharge intensity and reduced machining time are observed as the electrolyte concentration increases. Moreover, as the concentration increases, a critical voltage is observed that decreases slightly [40,79]. Researchers reported that low electrolyte concentration is required to drill dimensionally accurate holes in brittle, thin materials [48]. A decrease in electrolyte concentration reduces SR. With ECDM-based drilling, researchers also reported achieving high-aspect-ratio holes and significant reductions in overcut, taper angle, and TWR at lower electrolyte concentrations [98, 103-105]. However, chemical etching is observed prominently at high temperatures and higher electrolyte concentrations [43, 106]. The study indicated an approximately 50% increase in the microchannel's machining depth following a rise in the NaOH-based electrolyte concentration from 15% to 30% [107].

Electrolyte flow: Enables the necessary circulation of electrolytes to flush out debris accumulated during machining across narrow zones. Generally, during deep-hole drilling, these by-products resist further penetration, affecting machining performance. Thus, electrolyte flow removes these unwanted materials from the discharge zone. Consequently, it enhances machining [45, 108, 109]. Furthermore, comparative studies of electrolyte flow with stagnant electrolyte revealed 40% increase in material erosion during ECDM-based drilling of alumina with stainless steel. Also, 48.38% reduction in overcut was observed at input process parameters of 55 V, 20 wt% NaOH, 64% duty factor, and 500 us pulse-on time [110]. To pursue environmentally sustainable, cost-effective operations, titrated electrolyte flow was examined in a continuous-flow system. The study revealed a substantial effect on wire-ECDM performance, demonstrating a 211.04% enhancement in slit depth and 19.4% decrease in average slit width.

Electrolyte temperature: Studies have reported improvements in ECDM efficiency at elevated electrolyte temperatures. Typically, the electrolyte temperature ranges from 30 to 70 °C during this process. The rate of electrolysis is augmented owing to increased electrical conductivity associated with higher electrolyte temperatures, which consequently leads to the generation of a greater volume of hydrogen gas [43, 74].

Electrolyte level: Another crucial factor in achieving an efficient machining process. A high electrolyte concentration results in a larger contact area between the electrolyte and the tool. Thus, to achieve a stable gas film, the required amount of gas bubbles is too high to surround the tool surface. Consequently, unstable gas films form in the absence of gas bubbles, further reducing machine efficiency [63]. Researchers, while micro-drilling, preferred to dip the tool electrodes into the electrolyte to a depth of 1-2 mm, around which the film is developed [103, 111].

***Influence of surfactants*:** Mixing surfactants into electrolytes is one of many methods used to improve ECDM operations. Surfactants such as SDS (sodium dodecyl sulphate), when added to the electrolyte, enhance current density by releasing large numbers of gas bubbles across the machining zone [112]. The addition of surfactant contributes to a thin gas film by reducing critical voltage and improving tool wettability. Viscosity and conductivity of the surfactant mixed electrolyte vary with surfactant concentration [81, 112]. Sabahi et al. [81] conducted experiments using two types of surfactants (anionic and cationic) at different concentrations, mixed with electrolytes (KOH and NaOH). They observed a significant reduction in the critical voltage with SDS surfactant mixed with NaOH electrolyte, from 25.5 to 19.6 V at 0.236 and 25 wt%, respectively. Further, they reported that surfactants improved the machine's surface quality, reducing HAZ and the risk of damage to the workpiece. They also revealed that, compared to anionic surfactant (SDC), the cationic surfactant mixed electrolyte (CTAB-KOH) enhanced edge hardness and increased machining depth by 114%, while reducing deviation width (1.53 to 1.05) and sidewall damage in the fabricated channel. A similar study with surfactant (SDS) and added electrolyte was reported by another researcher, revealing better surface quality of workpieces and less taper hole [112].

Feed rate: High material removal is observed when the discharge density reaching the workpiece surface is high. Therefore, it becomes essential to control the feed rate to maintain the gap between the workpiece and the tool. During hole drilling based on ECDM at a high feed rate, the thermal energy generated during discharge is concentrated into a narrow region rather than dispersing into the electrolyte, thereby enhancing the rate of material removal [89]. However, a side spark was also observed due to hindrance in film formation when the tool contacts the workpiece at a higher feed rate, resulting in inaccurate microhole dimensions [113]. Another researcher, while performing wire-ECDM, observed inconsistent discharge due to a damaged gas film when the spark gap decreased during the process at a workpiece feed rate greater than 350 μm/min [114]. Zheng et al. [115] conducted micro milling using ECDM. They reported favourable conditions at a tool feed rate up to 3000 μm/min for the fabrication of microgrooves, with noticeable SR and uneven machining observed at high tool feed rates on Pyrex glass.

***Inter-electrode gap*:** The IEG plays a significant role in determining the performance of ECDM processes. When machining non-conductive materials via ECDM, the auxiliary electrode is positioned a few millimetres apart from the tool electrode. This distance between the electrodes is referred to as the IEG. It has been observed that a smaller IEG during machining leads to the formation of an unstable film and uneven discharge [116]. On the other hand, electrode resistance increases with higher IEG in ECDM operation [99]. Also, gas film stability and thickness appear to decrease with increasing IEG, leading to a reduction in current density [72]. Jawalkar et al. [116] observed a microhole with enhanced MRR (by 31 %) due to stable discharge development at a larger IEG of 150 mm.

***Significance of the tool electrode*:** Tool electrodes are crucial in ECDM operations. In machines constructed from non-conductive materials, two electrodes are used: the tool and an auxiliary electrode. Conversely, in the case of conductive materials, only the tool itself functions as an electrode [67]. A counter electrode (anode) is preferred to be 100 times larger than a tool electrode to facilitate higher density at the tool end (cathode) [117]. To enhance micromachining performance, a pointed tool tip may be used to narrow the discharge at the end of the tool electrode. In addition to the tool shape, factors such as its dimensions, material composition, rotational speed, side insulation, and surface morphology were examined to determine their influence on the ECDM operational performance [118].

***Shape and dimension of the tool*:** Table 4 presents various tool shapes employed during the machining process. The majority of researchers favoured cylindrical-shaped tool electrodes with a diameter of less than 1 mm for micro-ECDM procedures [59, 101, 119]. Several studies reported variations in tool shape and dimensions to identify an efficient machining method. Researchers conducted a comparative capability analysis of spherical and cylindrical tools for micro ECDM-based drilling processes. They concluded that spherical-tool electrodes were more efficient than cylindrical ones, facilitating electrolyte action at the tool bottom surface, increasing discharge frequency due to their curved shape, and enabling the production of uniform gas bubbles by reducing current density. They also revealed that the spherical shape of the tool bottom contributes to improved dimensional accuracy of machined holes [42, 120, 121].

Another group of researchers reported a similar comparative investigation of ECDM using cylindrical and flat-sided tools and observed that flat-sided tools result in the formation of a high-quality gas film. Further, the taper and entrance diameter of machined microholes can be minimised by reducing the tool electrode side-wall thickness [122]. Researchers conducted an ECDM-based operation using a stepped tool shape and reported a decrease in SR and the taper angle of the machined hole [123]. A similar study using needle-shaped tools reported higher drill speed at lower voltage than with cylindrical-shaped tool electrodes during drilling [89, 124]. Researchers used fabricated stainless steel tool electrodes in an array (batch) and reported negligible wear due to proper flushing of electrolyte across narrow gaps during the production of micro-holes [125]. Another study found that a tapered sidewall-based tool with a curved front result in enhanced material removal compared to other tool electrode shapes, facilitating the flow of electrolyte across the spark region [126].

Table 4. Influence of tool shape on ECDM efficiency

Tool Shape	Fabrication method	Major features
Spherical [42], Cylindrical [42]	Wire-EDG	Spark frequency and machining depth improved, while hole diameter and machining time decreased.
Flat sidewall-front flat [122]	Wire-EDG	Reduced the taper and the hole's entrance diameter.
Stepped tool [123]	Micro-EDM	Improved the hole's grinding efficiency.
Batch electrode tool [125]	Wire-EDM and SLM	Suitable for the ECDM sinking process.
Surface textured tool [123]	EDM	Enhanced the discharge frequency.

EDG: Electro-discharge grinding, EDM: Electrical discharge machining, SLM: Selective laser melting

Researchers have indicated that variations in tool dimensions may also influence machine performance. Experimental results from ECDM-based drilling show that a 0.52 mm tool diameter yields a higher material removal rate than a 1 mm tool diameter [127]. Additionally, researchers found that increasing the tool surface area from ø 0.1 to ø 0.4 mm could improve the critical current and critical voltage by increasing the area of tool-electrolyte contact, thereby improving the current flow between the electrodes immersed in the electrolytic solution. Nevertheless, to separate more tools from the electrolyte, a high voltage is needed to generate many gas bubbles, and it has been noted that a high critical voltage is necessary for the breakdown of the gas film layers [128]. The rotational speed of the tool has also been studied and found to reduce TWR, thereby increasing the effectiveness of micromachining using the ECDM process [101].

Material and surface morphology of the tool: The electrode material (tool and auxiliary) plays a vital role in achieving precise, stable machining operations. Table 5 shows several tools and auxiliary electrodes used by researchers during ECDM. For conducting experiments, electrode materials used in ECDM need to be electrically conductive, chemically stable, and resistant to bending and corrosion. Figure 6 shows trends in the use of various auxiliary electrode materials in the ECDM process. Many researchers reported using graphite [47, 129] and platinum [64] for auxiliary electrodes. A few researchers also selected stainless steel [101], nickel plate [130], and copper [126] to achieve the desired machining output. Researchers conducted ECDM-based drilling using different materials (tungsten carbide, brass, and steel) of tool electrodes and studied their influence on machining performance. They concluded that, at higher voltages, tungsten carbide followed by steel shows the least tool wear, while brass shows the most. Additionally, because brass has a low melting point, its evaporation begins at a higher voltage than that of other tool electrodes [131].

Table 5. Commonly used electrode materials in ECDM

Tool Electrode	Auxiliary Electrode
Carbon alloy steel [64]	Platinum electrode [64]
Graphite [37]	Graphite [132]
High speed steel [76] [107]	Stainless steel [101]
Copper tool [126]	Copper plate [126]
Stainless steel [47]	Nickel plate [130]
Brass [131]	Platinum foil [133]
Brass wire [130]	
Steel [27]	
Tungsten [28]	
Tungsten carbide [47]	

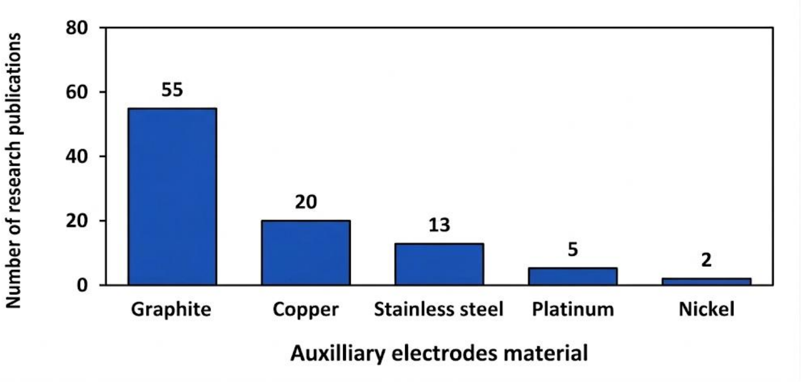

Figure 6. Research trend in the field of auxiliary electrodes for the ECDM process

Figure 7 displays research trends on the usage of various tool materials in ECDM processes. According to another study, tungsten had the highest tool wear among steel, stainless steel, and tungsten. It also proved that the temperature of the tool material could be maintained and controlled by introducing pulse voltage [28]. Another study reported an ECDM-based drilling process using tungsten carbide, stainless steel, and tungsten tool material. Tungsten carbide contributes to lower tool wear and a smaller average machined hole diameter, compared with similar machining conditions [47]. Researchers used a customised tool consisting of a carbon-alloy steel core with a silica-mixed Araldite side-insulation layer. They observed lower overcut and greater machining depth in microholes with insulated tool electrodes than with non-insulated tool electrodes. Moreover, the surface morphology of tools also influences machining efficiency [64].

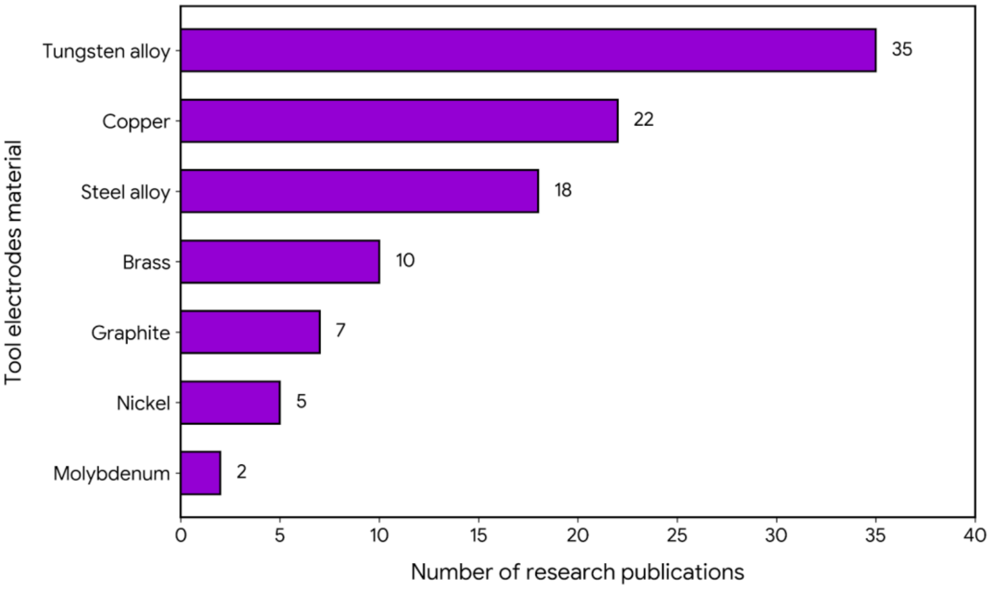

Figure 7. Research trends in the field of tool materials for the ECDM process

Another study reported that the SR of tool electrodes affects the electrolyte's wettability of the tools, thereby influencing the changing thickness of the gas film during the machining process [38]. Xu and Zhang [133] performed an ECDM-based micro-milling process using tools with different surface finishes (smooth and textured). They concluded that, when using the texture tool, micro-sized gaps formed between the tool and the workpiece. This led to the formation of minute gas bubbles and a consistent, thin film, thereby enhancing geometric precision in the final product.

Advancement in tool fabrication: Tool fabrication is required before micromachining, utilising the ECDM process. Researchers have noted that prefabricated microtools exhibit eccentricity and misalignment errors due to re-clamping of the tool electrode, thereby reducing operational precision. Several scholars have documented their respective methodologies, such as wire electro-discharge grinding (WEDG) [42], wire-EDM [125], die-sinking EDM [127], electrochemical processing (ECP) [133], micro-grinding [134], and wire-ECDM [44], for the fabrication of micro tools to achieve the desired tool shape and dimension that further influence machining performance.

3.2 Control Strategies of Response Parameters

3.2.1 Material removal rate

In the ECDM process, the rate of material removal has been extensively studied in most research, primarily through performance evaluation. Reports indicate that MRR is significantly affected by various machining parameters, particularly voltage and electrolyte composition [116, 42]. During microdrilling, researchers observed that a pulsed DC power supply enabled higher material removal (by 160%) than a continuous DC power supply [77]. Researchers also reported a reduction in MRR (from 7.35 to 5.42 mg/min) and an increase in electrolyte level (from 20 to 30 mm) owing to the production of large amounts of discharge on the tool electrode side rather than at the tooltip [135]. Researchers performed ECDM-based micro drilling to fabricate holes in glass (soda lime) material and revealed improvement in MRR (from 3.42 to 9.68 mg/min) with a rise in voltage (from 40 to 60 V), respectively [116]. Further, NaOH-based electrolytes influence greater material removal (by 40 %) compared to $NaNO_3$. Also, a larger inter-electrode gap, an increased duty factor, and a decrease in pulse frequency are found to play crucial roles in achieving a higher degree of material removal, owing to increased discharge energy [37]. Another report revealed that during drilling, rotational speed applied to the tool enhanced material removal (by 42.7 %) when compared to machining without the tool's rotation [66, 101]. Researchers developed a discharge model to estimate MRR via a finite-element simulation that accounts for discharge and evaporation mechanisms. The model was then verified with an experimental study, and an error of 1.95 mg/min was observed [136].

3.2.2 Tool wear rate

Tool wear is caused by tool heating during heat transfer to the workpiece via discharge. During microdrilling, TWR was reduced by 39%, with a corresponding decrease in the concentration of the 1 M NaOH-based electrolyte [137]. On the other hand, TWR increased with increasing applied voltage. Further, the $NaNO_3$-based electrolyte was found to cause higher tool wear than the NaOH electrolyte [116]. Huang et al. [101] conducted micro drilling ECDM operation assisted with tool rotation using different tool diameters (200 to 400 μm) and observed that the development of discharge at the exact location can be prevented by providing rotational motion to the tool electrode and concluded that tool wear could be minimised following a rise in the speed of tool rotation. They also stated that the rate of electrode wear during the ECDM process depends primarily on voltage, followed by tool electrode diameter and rotation speed [59]. Another report found that, with a decrease in tool diameter and an increase in duty cycle, high tool wear was observed owing to improved spark energy for a longer period [37].

3.2.3 Overcut

To achieve the desired geometrical accuracy of the product, overcutting during the machining must be prevented. Jui et al. [131] reported a 22 % reduction in overcut when the NaOH-based electrolyte concentration was reduced to 1 M during microdrilling. Researchers reported that electrolyte concentration and applied voltage play a vital role in minimising overcut. They observed that increasing the voltage increased the overcut due to side sparking around the tool during microdrilling [138]. Further, Saranya and Ravi [64] reported that tool electrodes with side insulation reduced the overcut (by 57 %) of machined channels during micro-milling.

3.2.4 Surface roughness

The quality of the product is significant for micro components, thereby eliminating SR, a primary concern for researchers. Several studies have shown that machining parameters, particularly electrolyte type and concentration, followed by duty factor and pulse frequency, can influence the surface roughness. It was concluded that the SR of microholes decreased from 4.8 to 2.1 μm, accompanied by decreases in pulse frequency (from 100 to 10 kHz) and duty factor (from 75 to 25 %) [37]. During micro milling, improved surface finish (Ra 0.5-0.8 μm) was observed at a low machining speed (5 μm/s) [69]. Jui et al. [131] reported achieving a minimum SR range of 250-350 nm on the fabricated surface of the microhole. Kang et al. [67] established that ECDM-based micro-drilling facilitates lower SR (Ra 5.6 μm) compared to the roughness of EDM-based micro-drilled surface (Ra 10.9 μm). Huang et al. [101] reported that increasing the rotation speed from 0 to 20000+ RPM with rotary tool-assisted drilling can significantly reduce SR from Ra 5.40 to 2.40 μm. Another researcher performed abrasive (small-grit) mixed-electrolyte-based wire-ECDM and reported that the machined surface roughness decreased to 0.84 μm Ra, with refined microcracks observed owing to the abrasive in the electrolyte [139].

3.3 Recast Layer

The recast layer thickness needs to be minimised or avoided at the machined surface to enhance the surface morphologies of final products [96]. During ECDM-based micro-drilling, the recast layer thickness of the machined surface was observed to be reduced by 15 μm compared with the micro-EDM-machined surface (38 μm) [67]. Researchers performed tube-electrode-assisted high-speed drilling using ECDM. They observed a significant reduction in the recast layer in the lateral gap of the micro-hole, due to enhanced electrochemical dissolution that facilitates electrolysis and further removes the recast layer [140].

3.3.1 Heat-affected zone

The material-removal mechanism of the micro-ECDM process is based on discharge-generated thermal energy, leading to the development of a HAZ on the machined surface [92]. This HAZ consists of irregular surface quality, followed by micro-thermal cracks and grooves, which can be eliminated or controlled to achieve high-quality surface integrity in the finished product [141]. Kim et al. [37] performed microdrilling and concluded that the HAZ of the machined surface decreased with increased pulsed-voltage frequency and reduced duty cycle. Another researcher concluded that surfactant-mixed electrolytes have the potential to significantly minimise the HAZ by forming a thin film and reducing stray erosion at the entrance of micro-channels [81]. In experiments with a side-insulated tool, researchers concluded that discharge developing only at the front end due to the tool's side insulation resulted in negligible HAZ across the micro-hole [141].

3.3.2 Taper hole/channel

A taper hole/channel forms due to a longer exposure to electrical discharge and electrochemical action at the entrance of the machined structure, compared to the exit point [101, 137]. Researchers observed a 18% reduction in the taper of the micro-hole at a lower concentration (1 M) of the NaOH-based electrolyte [137]. A similar study using a side-insulated tool reported a reduction in taperness (3.3°) of the machined hole on the quartz surface (600 µm depth) [141]. Reports revealed that the use of tools with textured surfaces during the micro-milling process resulted in the taper angle of grooves being reduced (>3°) in comparison to conventional tool electrodes (~13°) [142]. Further, increasing the tool rotation speed primarily results in discharge at the tooltips, reducing tapping of micro-holes [101]. Furthermore, the use of tubular-shaped tool electrodes (dia. 500 µm) and high flushing pressure (up to 12 MPa) during micro-hole fabrication could significantly minimise the taper angle of the machined structure [96].

3.3.3 Hole depth and aspect ratio

Miniature components for medical and industrial applications require the fabrication of holes with smaller entrance and exit diameters, followed by deeper machining. Tool electrodes play a vital role in achieving a higher-depth, small-diameter microstructure [143]. Jui et al. [131] reported drilling of a high aspect ratio (of 11) micro-hole using NaOH (1 M) added electrolyte. Han et al. [138] performed a micro-milling operation using a textured tool. They succeeded in fabricating grooves with an aspect ratio of 1:4. Another researcher observed that a spherical-tip tool is more suitable for developing a smaller-diameter, high-machining-depth micro-hole than a cylindrical tool [42]. A similar report suggested that an electrode tool with side insulation could fabricate a micro-hole with an entrance diameter of 5 µm and a depth of 500 µm [141].

3.4 ECDM Variants

Several operations based on ECDM principles, such as drilling, milling, dressing, turning, cutting, and die-sinking, have been introduced by researchers (see Figure 8). These variations have been highly successful in creating a range of micro- and nano-profiles. All the variants share similar working principles, except for their tool configurations and tool movements. Figure 9 illustrates the research trends in the use of different variants of ECDM processes, based on the number of publications that are reviewed in this report. ECD-Drilling is the most widely explored approach, accounting for 37.0% of publications, followed by ECD-Milling at 27.8%. Turning, Wire-ECDM, and Die-sinking are among the other categories with smaller proportions; ECD-Dressing is the least studied at 1.9%.

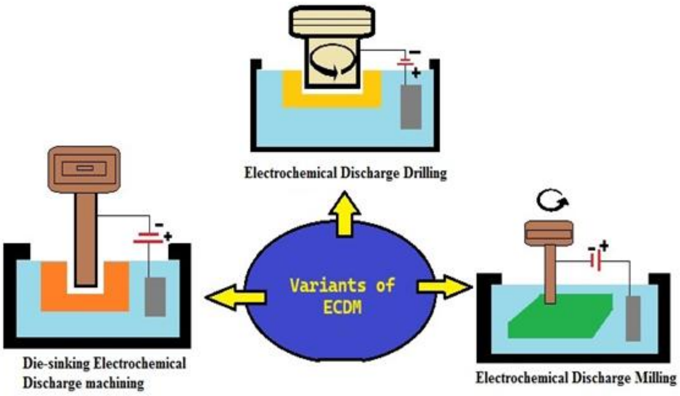

Figure 8. Variants of the ECDM process

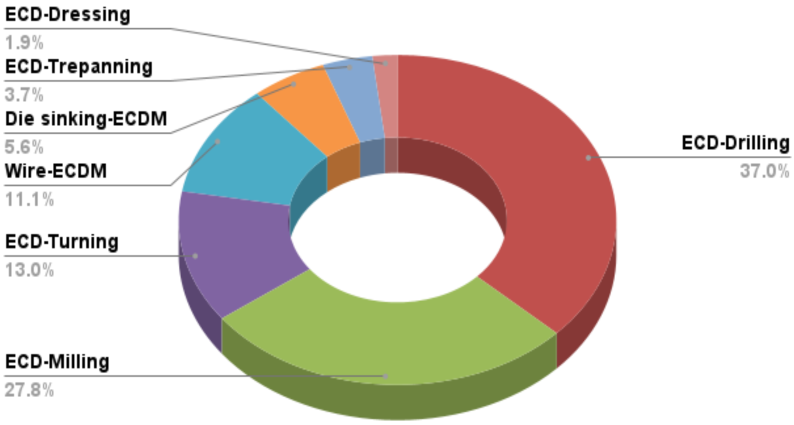

Figure 9. Research trends of publications on the variants of the ECDM process

Table 6 illustrates the machining output across various ECDM process variants. It demonstrates significant flexibility through diverse adaptations, each tailored for specific high-precision machining outputs. Key variants include drilling and milling for creating micro-holes and microchannels, respectively. Selected configurations of these variants and their performance metrics are discussed in the following section.

Table 6. ECDM process variants

ECDM process variants	Machining outputs
Electrochemical Discharge Drilling [48]	Through and blind holes (Cylindrical, conical, and spherical)
Electrochemical Discharge Milling [69]	Micro channels and grooves (through and blind) and (straight and curved), micro-pillars, walls, and pyramid
Electrochemical Discharge Turning [30]	Micro grooves on cylindrical surfaces
Electrochemical Discharge Dressing [31]	Dressing of metallic grinding wheels
Wire-ECDM [44]	Slicing, straight through grooves
Die sinking-ECDM [144]	Micro dies
Electrochemical Discharge Trepanning [33]	Deeper holes

3.4.1 Electrochemical discharge drilling

The ECDD process facilitates the drilling of precise, high-aspect-ratio microholes (both through and blind) in substrates composed of advanced engineering materials of various thicknesses. Electrically nonconductive materials (silicon nitride ceramics [28], silicon wafers [109], steels [59], borosilicate glass [86], Pyrex wafer [129], other glass wafers [48, 145], and e-glass-bar-epoxy composite [146]) as well as conductive materials (cobalt, low-alloy steels, chrome, titanium and nimonic alloys) can be drilled using the ECDD process, resulting in a quality machined surface identical to an electrochemically machined surface. During ECDD, the interaction between tool motion and discharge complicates operation, as discharge energy depends on several process parameters, such as power supply, tool electrode, and electrolyte. The tool electrode is given progressive and controlled motion along the z-axis to perform ECDM-based drilling. In ECDD, vital parameters that affect the spark energy over the machining area are drilling depth and machining voltage. Therefore, the precision of a machined hole (mean diameter) is considered as a function of machining voltage and drilling depth [147]. The mean diameter of a micro hole produced by combining drilling depth and machining voltage is categorised into three zones: A (28-37 V, 100 μm), B (30 V, 200 and 300 μm), and C (< 30 V, < 100 μm). Here, hole depth depends on drilling speed and is independent of machining voltage [86]. For better repeatability of ECDD operation, gas film thickness plays a crucial role and needs to be reduced. During ECDD, repeatability is achieved by mixing liquid soap (surfactant) into the electrolyte to maintain a thin gas film and minimise differences in intermittent discharge energy [112].

Tool electrodes play a crucial role during the ECDD with a high aspect ratio. A high machining rate is achieved with the cathode (tool electrode) having high thermal conductivity during the discharge regime, whereas a low machining rate is observed during the hydrodynamic regime [148, 149]. The roughness of the tool electrode indicates its wettability, and it is generally considered that coarser tool electrode surfaces are required to achieve high MRR [122]. A tool electrode with a spherical bottom face has higher accuracy and machining rate than a cylindrical tip, as the curved surface reduces contact between the tool and workpiece, resulting in better electrolyte flow into the machining zone and the tool end [150]. By switching the tool electrode polarity to straight (cathode) and reverse (anode), respectively, conical and spherical cross-sectional holes can be created in ECDD. In the case of straight polarity, chemical etching decreases with increasing hole depth, unlike in reverse polarity (Hickling-Ingram mechanism), resulting in distinct cross sections. Additionally, during operation, good surface quality is observed due to chemical action on arc-discharged surfaces [48]. Researchers have reported the versatility of the ECDD process, used to design a high-aspect-ratio, micro-crack-free, and nearly polished surface microdevice prototype of fused silica, and to fabricate conical holes with minimum machining time (30 s) [151].

3.4.2 Electrochemical discharge milling

The electrochemical discharge milling process has the potential to produce complex 3D micro-features, such as microchannels, in glass, quartz, and composite materials. An ECDM-based milling operation requires a rotary tool (cylindrical wheel tip) arrangement as a cutting tool, with travel along the provided path. Researchers studied the fabrication [29, 152, 93] and surface texturing [69] of microchannels and microgrooves [153]. Milling based on ECDM processes has demonstrated the ability to fabricate microfeatures, including pillars, walls, pyramids, and grooves. The rate of tool rotation and tool travel are considered very significant variables affecting this machining process [40]. Tool rotation rate promotes electrolyte flow into the machining zones, resulting in grooves with sharper edges and narrower widths. Researchers observed that the tool rotation rate does not affect the groove depth. Also, wider, shallower microgrooves are achieved at higher tool rotation rates. A layer-by-layer material-erosion technique during milling was demonstrated for fabricating deep, narrow microgrooves. This technique helped achieve a smooth surface finish by facilitating electrolyte flow into narrow, deep machining gaps. Zheng et al. [115] developed optimal parameters of 40 V DC, pulse on/off = 2 μs/2 μs, and tool travel and rotation rates of 1000 μm/min and 1500 rpm, respectively, for the development of precise microfeatures on glass [115].

3.4.3 Die-sinking electrochemical discharge machining

Die sinking electrochemical discharge machine is utilised for the development of small and shallow dies on electrically conductive [27] and non-conductive materials [144]. To achieve a high sinking rate, hollow tools (bronze, inner and outer diameters of 3.7 and 9.4 mm, respectively) were used during experimentation, with an optimum input setting of 20-30 V DC, 120 g/L $NaClO_3$ electrolyte, and 3-18 mm/min tool feed rate. Consequently, the surface quality and dimensional tolerance of the developed shape are observed to be identical to those of conventional EDM and higher than those of the ECM process [27].

3.4.4 Electrochemical discharge dressing

Electrochemical discharge dressing is a variant based on the ECDM process developed for the dressing of damaged micro-grinding tools. In electrochemical discharge dressing, the electrolyte has a significant role as a dielectric, a dresser, a cooling and flushing agent to remove debris from the operating zone. Research revealed a free-bulged grain on a grinding wheel via ECDM-based drilling. Also, SR was reduced by 50% due to a reduction in the normal force exerted by the micro-grinding tool [154].

3.5 ECDM Hybrid Variants

Variants of ECDM have demonstrated their potential for operations such as drilling, milling, and dressing, as discussed earlier. Further, to enhance ECDM performance, such as efficiency and repeatability, researchers have developed hybrid methods for ECDM-based operations. Figure 10 shows different hybrid variants of ECDM processes. Hybrid variants, such as magnetic-field-assisted, vibration-assisted, and powder-mixed ECDM, have been employed to improve machining performance.

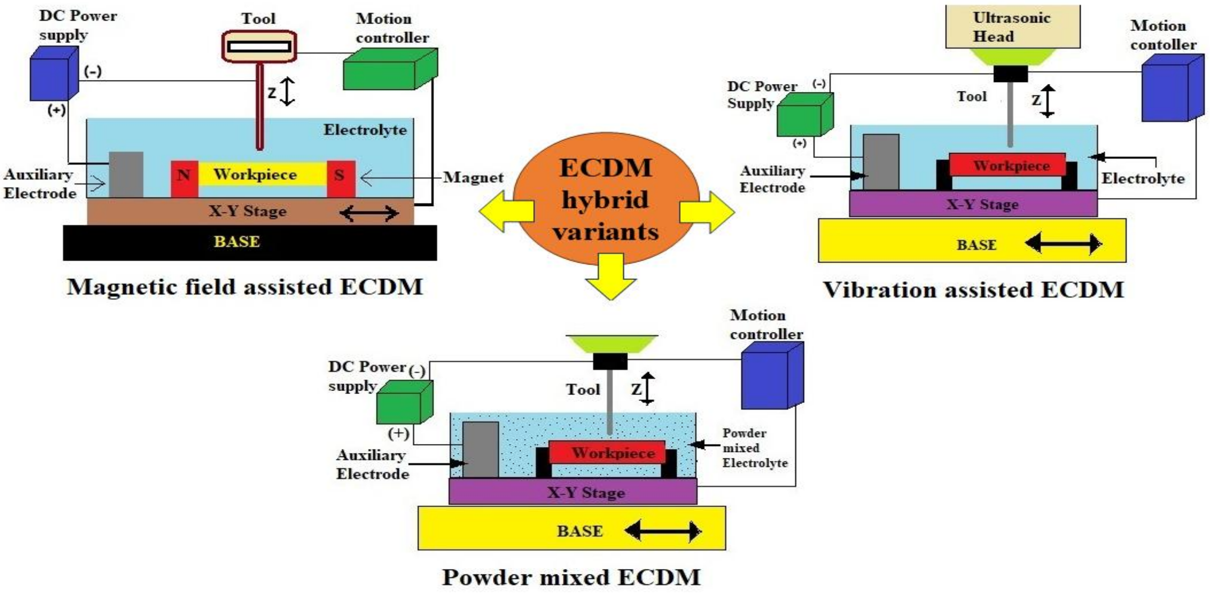

Figure 10. Different hybrid variants of ECDM processes

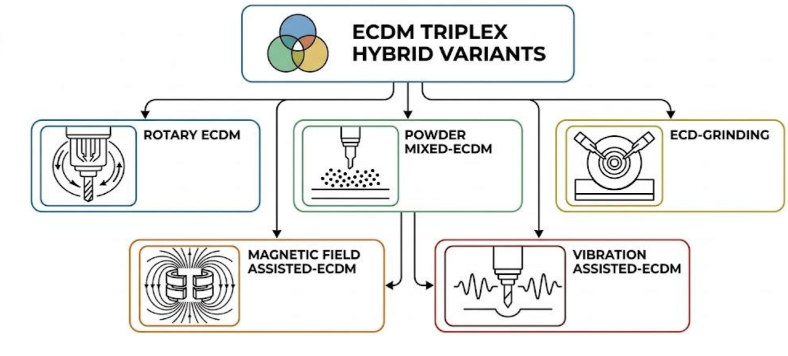

Figure 11. ECDM-based triplex hybridisation methods

These variations combine standard electrolyte setups with auxiliary components such as magnets or ultrasonic heads to improve accuracy and output quality. Specialised outputs, such as micro dies and the dressing of metallic grinding wheels, are made possible by these combinations. External energy sources used for such purposes can be classified into primary and secondary sources, as illustrated in Figure 11. In ECDM-based triplex hybrid methods, the primary energy source for material erosion is electrochemical discharge, with a secondary energy source used for simultaneous, controlled interaction with ECDM processes. These triplex hybrid methods have shown their potential to enhance machining efficiency and improve precision, performance, and productivity [155-158]. The following section discusses a few ECDM-based triplex methods and their development over time.

3.5.1 Powder mixed ECDM

Powder-mixed ECDM involves adding abrasive particles to the electrolytic solution during machining to achieve repeatable operation and a high surface finish. Research revealed an improved surface finish (by 45.05 %) due to reduced direct impact of discharge energy, enabled by the presence of aluminium oxide (Al_2O_3) abrasive particles within the gas film. The behaviour of conductive powder particles between the workpiece and the tool electrode determines the reduction in discharge energy. Conductive powder particle behaviour has resulted in stable discharge and uniform charge transfer between the workpiece and tool electrode during machining of a Niobium-based alloy in an alumina particle (5 µm dia.) suspension in an electrolytic solution (sodium hydroxide). Consequently, the SR from 1.11 µm to 0.61 µm with the PM-ECDM process [83].

3.5.2 Magnetic field-assisted ECDM

Due to insufficient electrolyte flow and unpredictable discharge behaviour at increased machining depths, the ECDM process exhibits reduced machining efficiency and compromised precision geometry. Magnetic-assisted ECDM is a novel method that significantly enhances ECDM processes, improving machining efficiency and accuracy. This approach is simple and needs no modification in the machining setup. Cheng et al. [41] proposed a magnetic-assisted ECDM approach to improve micro-hole drilling performance and concluded that it achieved efficient machining and improved micro-hole accuracy compared to conventional ECDM-based drilling. A magnetic field-assisted ECDM apparatus involves integrating a magnetic unit with a tool or workpiece. Different magnet positions achieve different magnetic field configurations (upward and downward). During magnetic-assisted ECDM operations, magnetic fields generate a Lorentz force that induces magnetohydrodynamic (MHD) convection, increasing electrolyte circulation within narrow gaps and expanding the gas bubble coverage area and the void fraction. Further, MHD convection maintains stable gas-film quality by reducing the deposition of gas bubbles at the entrance to the microstructure during machining, thereby improving the material-removal rate and reducing machining time [155]. With enhanced electrolyte circulation, researchers reported improved machining efficiency by 57.4% and geometrical accuracy by 23.8% [41].

Table 7. ECDM hybrid variants process

Electrochemical discharge machining process				
Hybrid variants	External energy involved	Variation in applying	Remark	
			Improved	Reduced
Powder mixed-ECDM [81, 83, 38, 139]	Abrasive cutting (mechanical)	Electrically non-conductive and conducting micro/nano-sized powder.	Surface finish, spark stability, and MRR.	Microcracks, recast layer, and slit size.
Magnetic field-assisted ECDM [41, 65, 44, 49, 107, 155]	Lorentz force (mechanical)	A ring, rectangular or disc-shaped magnet, is applied in the direction of the downward and upward magnetic field.	Electrolyte circulation in the machining zone, penetration depth, gas-film stability, and machining accuracy and efficiency.	HAZ, overcut, and machining time.
Vibration-assisted ECDM [47, 138, 158]	Ultrasonic vibration (mechanical)	Ultrasonic vibration is applied to tools, electrolyte, or the workpiece.	Electrolyte circulation in the machining zone, gas film quality, surface finish, and machining depth.	Machining time, burrs, and hole diameter.

3.5.3 Vibration-assisted ECDM

Researchers used vibrational energy (ultrasonic vibration) during ECDM-based deep-hole fabrication to facilitate electrolyte supply across the narrow region between the tool tip and the workpiece top surface. In this process, vibration can be applied to a workpiece [158], a tool electrode [159], or an electrolyte [138]. Research concluded that material removal was enhanced (by a factor of two) with the introduction of low-frequency tool vibration (0-30 Hz) during ECDM-based drilling of deep micro holes (300 µm in 10 sec) [158]. Another researcher used ultrasonic vibration (1.7 MHz) of electrolytic solutions to modify the geometry of the gas film and observed uniform discharge around the tip and the tool electrode, resulting in less taper with increased machining depth (from 320 µm to 550 µm) [138]. Furthermore, denser, broader discharge pulses were observed with increasing vibration amplitude (from 2 to 3.5 µm), thereby improving surface integrity while concurrently decreasing the MRR. According to percolation theory, faradic current generates a wide current pulse at a low bubble density near the bottom face of the tool [158]. Table 7 shows the machining output obtained through various hybrid variants of the ECDM processes. It emphasizes the external energy sources used and their influence on machining performance. Each of the three variants has been shown to improve spark stability or electrolyte circulation, thereby enhancing machining accuracy. The use of vibrations or powders considerably improves surface finish and removes unwanted features such as burrs and microcracks. The primary goal of magnetic and vibration assistance is to reduce machining time, thus speeding up and refining the process.

Figure 12 shows the research trends in hybrid variants of ECDM processes, based on the number of publications that are reviewed in this report. It demonstrates that the most researched approach is ultrasonic vibrations-assisted ECDM. Followed by MF-ECDM and PM-ECDM, respectively. A smaller percentage of the current research area is devoted to other hybrid techniques, such as Rotating Tool-ECDM, Wire-ECDM, and Laser-assisted-ECDM. According to the literature, the most popular methods for increasing the effectiveness and accuracy of the ECDM process at this point are mechanical vibration and magnetic field interventions.

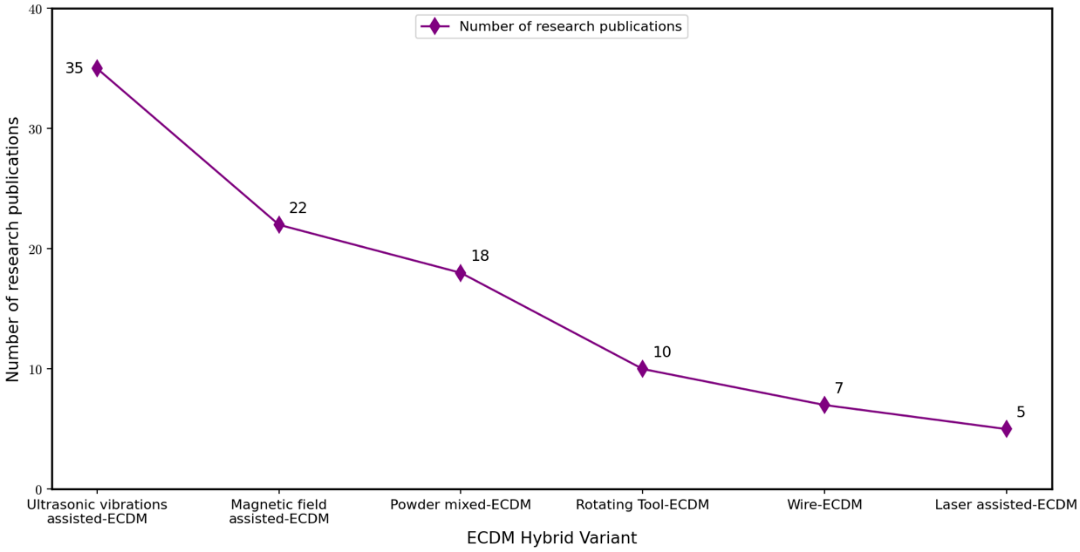

Figure 12. Research trends in the publications on hybrid variants of the ECDM process

3.6 Future Research Potential

The last few years have seen significant progress in ECDM, particularly in optimising process parameters, developing advanced tool materials, and enhancing surface integrity [49, 160, 161]. Despite the advancements, challenges remain in ECDM, particularly in achieving consistent process stability and sustainability, minimising tool wear, and ensuring high surface integrity [48, 162, 163]. Present studies on ECDM focus on improving material erosion and machined surface quality. However, several other machining parameters, such as HAZ, dimensional overcut, tool erosion, recast layer, tapering effect, and microcracks, require further investigation [164]. Also, aspects such as process modelling, advanced real-time monitoring systems, and AI-driven control systems to dynamically adjust process parameters have not yet been explored [165]. To scale ECDM for large-scale manufacturing, green technologies and waste-reduction strategies to make the process more environmentally friendly have not been thoroughly explored [166]. The machinability of semiconductive, conductive, and other non-conductive materials, i.e., ultra-high-temperature ceramics, metal matrix composites, sandwich materials, and additive manufacturing materials, needs to be examined [167].

Additionally, the feasibility of the tools produced from metal matrix composites [168, 169] or via powder metallurgy [170] should be investigated. Electrolytes also play a vital role in determining machining performance, as reported by researchers. Using an efficient, non-hazardous to health, environmentally friendly (water-based), and economical electrolyte [50, 171] is the prime topic of investigation. Furthermore, only a limited number of studies have investigated the potential of various ECDM variants, including ECD-grinding, lathe-type ECDM, and die-sink ECDM. In addition, several triplex hybrid methods—such as magnetic field-assisted ECDM, powder-mixed ECDM, and vibration-assisted ECDM—present new opportunities to enhance the precision of ECDM geometry and improve process efficiency in the machining of advanced engineering materials. The industrial adoption of the ECDM process will serve as a benchmark for the progress of research conducted over the past few years. Advancements in process efficiency, precision, repeatability, and sustainability are driving the industrial adoption of ECDM. Optimised process parameters facilitate the fabrication of complex microprofiles with high aspect ratio and superior surface finish, characterise minimal heat-affected zone, taper, and micro cracks to ensure dimensional accuracy during machining, modifications to the tool's surface, shape, and motion, coupled with maintaining a constant machining gap, can enhance the gas's ability and quality [172]. The utilisation of abrasive, environmentally acceptable mixed electrolytes may improve machining efficiency and mitigate hazardous effects. Furthermore, analysing hybrid ECDM variants to improve accuracy and stability during machining can yield better machining outcomes and address existing limitations.

4. Conclusions

This review article is based on current research practices across several areas of the ECDM process, its variants, and hybrid methods to enhance machining performance. It highlights recent advancements, challenges, and innovations in this hybrid machining process, focusing on developments in process parameters, discharge mechanisms, power supplies, tool and workpiece materials, surface integrity, material removal, and process modelling. In addition, the effects of process parameters, such as voltage, current, pulse duration, and electrolyte, which play a crucial role in machining efficiency, are discussed in detail. Over the past few years, research in ECDM has focused on optimising process parameters, improving tool-workpiece interaction, enhancing surface quality, implementing process monitoring and control, generating profiles, and developing advanced models to predict machining outcomes.

The variants of ECDM, such as drilling-based ECDM, have the potential to form high-aspect-ratio (11:1) deep microholes with spherical and conical profiles and to fabricate microfeatures with dimensions less than 100 µm. Similarly, milling-based ECDM has also attracted attention for its ability to fabricate surface textures on channel surfaces and serpentine-shaped microchannels (depth and width of 30 and 70 µm, respectively, SR of Ra 0.099 µm). Moreover, hybrid ECDM machining is an evolving approach that enhances machining capabilities and efficiency. These hybridised variants, such as magnetic field-assisted ECDM, ultrasonic-assisted ECDM, and powder-mixed ECDM, improve debris removal, the sparking mechanism, and electrolyte circulation in the machining zone. All these variants have demonstrated the potential of such hybrid approaches for industrial applications of the ECDM process in achieving complex, contradictory objectives, such as minimal SR, high MRR, and minimal HAZ and recast layers.

The ECDM process and its variants are highly effective in precision machining, including the fabrication of microchannels and microholes on advanced non-conductive materials such as ceramics, glass, and composites, as well as other challenging-to-machine materials. The performance of ECDM is primarily influenced by gas film formation, which is regulated by parameters such as the tool-workpiece gap, tool-electrode movement, and the electrolyte (recommended KOH or NaOH. Enhancements in gas film quality, machining depth, and MRR are achieved through pulsed voltage, tool material and rotation, an abrasive-mixed electrolyte, and maintaining a consistent workpiece-to-tool gap. These factors improve electrolyte circulation and facilitate the removal of undesired gas bubbles within the machining zone. Spherical tools are preferred as they reduce taper and overcut compared to pointed and cylindrical tools. Surface-textured tools promote efficient machining and improved wettability, resulting in a higher-quality surface finish. Furthermore, hybrid ECDM variants such as MF-ECDM, PM-ECDM, and Rotational-ECDM enhance machining performance by improving material erosion, accuracy, repeatability, and process stability.

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Declaration of Competing Interest

The author declares no conflicts of interest.

CRediT Authorship Contribution Statement

Ashish Ranjan (Methodology; Data curation; Writing - original draft; Resources)
Nav Rattan (Conceptualization; Analysis; Visualisation; Supervision)

Availability of Data and Materials

The data supporting this study’s findings are available on request from the corresponding author.

Ethics Declarations

This study did not involve human participants or animals. Ethical approval was therefore not required.

Generative Artificial Intelligence Declarations

The authors stated that generative AI was not used to generate content, ideas, or theories. We have just utilised AI to enhance readability and refine the language. This was used with extreme human control and oversight. The authors take full responsibility for reviewing and approving the content.

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