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REVIEW PAPER

Reviewing Sustainability Interpretation of Electrical Discharge Machining Process using Triple Bottom Line Approach

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Abstract

Nontraditional machining processes are frequently used in product manufacturing when either the material is difficult to machine, or a very precise geometry is required. Electrical discharge machining (EDM) is considered as a popular nontraditional machining process. EDM process is used to machine a diverse range of engineering materials such as hard materials, ceramics and modern composite materials. It is primarily used in the finishing of components related to aerospace, automotive, surgical, electronic and biomedical industrial sectors. However, high energy consumption, hazardous dielectric waste generation, toxic emissions and fire hazards are the major concerns with respect to sustainability. The present study reviews the state-of-the-art research performed to explore the sustainability aspects of EDM process under the framework of three pillars or triple bottom line sustainability approach. The study reveals economic, environmental and social concerns for the EDM process. Major economic concerns were found to be energy consumption, electrode preparation and treatment of dielectric fluid. Major environmental concerns were based on the hazardous emissions and disposal of dielectric fluid. However, major social concerns were linked with the inhalation of fumes, skin diseases and fire or explosion related threat. The study also recommends different solutions for all economic, environmental and social concerns.

Keywords Electrical discharge machining · EDM · sustainable manufacturing · Triple bottom line · Three pillars of sustainability

1 Introduction

In this continuously evolving technological era where every sector of industry is progressing rapidly, there was an enormous stress on manufacturing sector to develop novel machining techniques to machine harder materials, provide better surface finish, generate complex geometrical designs and achieve higher geometrical accuracy. To cater the aforementioned needs of the manufacturing sector, nonconventional machining processes were developed [1]. Electrical discharge machining (EDM) is one of the most widely practiced nonconventional machining processes used in the manufacturing sector for the machining of electrically conductive materials. EDM is a thermoelectric process in which high frequency sparks generate heat which melts the work piece in the presence of a dielectric fluid. The beginning of EDM is traced back in 1770, when an English Chemist Joseph Priestly exposed the erosive influence of electric arc and spark [2]. The breakthrough development in EDM was conducted by two Russian scientists B.R. Lazarenko and N.I. Lazarenko in 1943. Their work consists of controlling the destructive effect of electric spark to machine materials [3]. In 1950, the RC (resistance–capacitance) relaxation circuit was utilized to better control the EDM process. In 1980, the development of computer numeric control (CNC) coupled with EDM to provide more accurate process control [4].

The EDM process generates temperature in the range of 8000–12,000 K to vaporize the material [1]. Some latest studies based on collisional-radiative models revealed that plasma temperature can reach up to 25,000 K [5]. The EDM process is termed as non-contact material removal process mainly resulting in higher level of dimensional accuracy. EDM is a popular machining process for the manufacturing of dies, molds,

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punches, gears, fixtures, cutting tools and surface texturing patterns on steels rolls. It is utilized for such applications because regardless of the hardness of the work material, both conductive and non-conductive materials can be machined. However, to machine non-conductive materials through EDM approach, specialized conditions and environment are required. Different variants of EDM process can handle a diverse range of engineering materials such as hard materials, ceramics and modern composite materials [1]. Literature [1, 6] points out that non-conductive advanced ceramics can be processed through EDM using an assisting electrode (AE) based methodology. The AE method consists of having an additional conductive layer on the workpiece material. It is primarily used in the finishing of components related to aerospace, automotive, surgical, electronic and biomedical industrial sectors. The initial spark happens between the electrode and this conductive layer. Once the conductive layer finishes, carbon particles cracks because of the separation of kerosene molecule at high energy that generates pyrolytic carbon on the top surface making the machining process feasible [1, 6].

As a result of the rising awareness of sustainable development, the manufacturing sector is under immense pressure to align the manufacturing-based activities towards improved environmental performance [7, 8]. Previously, manufacturing sector was more focused towards achieving functional performance of a product under optimized cost-effective route. By implementing sustainable manufacturing practices, production companies can enhance economic gain, and at the same time improve environmental and social performances. These practices mainly deal with the procedures of reducing harmful environmental effects, and energy consumption [9]. The approach of evaluating sustainability by means of economic, environmental and social aspects is termed as the "Triple Bottom Line (TBL)" approach [10].

Most of the available literature focused on the economic, technical and environmental performances of the EDM process. There is a need to explore the sustainability of EDM process using the TBL approach, so that the social aspects can also be included in the overall scene. This current paper reviews the EDM process for its sustainability assessment using the TBL approach. The study provides useful conclusions regarding the environmental impacts involved in the process. The study also reveals personnel health and occupational safety related issues for the EDM process. Finally, the study suggests futuristic directions and recommendations for the research work to be conducted to make EDM processes more sustainable in nature.

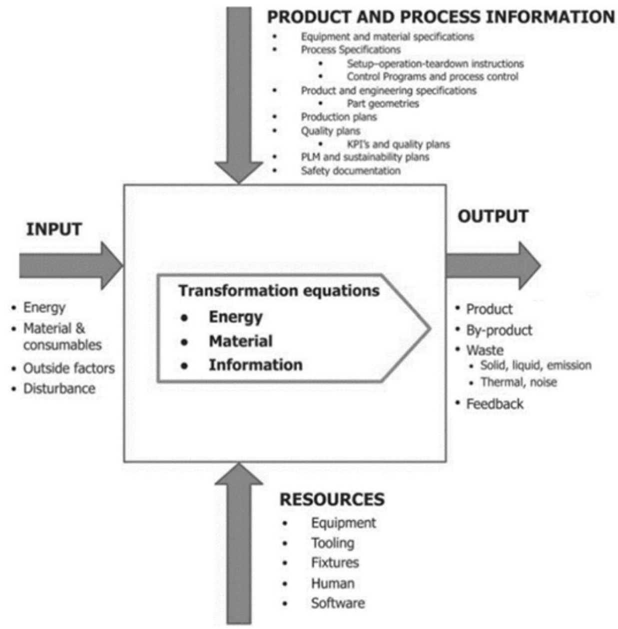

Fig. 1 Schematic illustration of unit manufacturing process as per ASTM E3012-16 Standard [15]

2 Sustainability Characterization Methodology

Manufacturing process utilizes some form of energy and transforms raw material or intermediate product into final or desired product. Manufacturing processes are grouped into various categories such as solidification, material removal, deformation, particulate processing, heat treatments, coating/deposition, welding and adhesive bonding etc. [8, 11]. When it comes to the sustainability assessment of these manufacturing processes, their associated environmental impacts can vary a lot due to their different natures and interaction with the environment. Keeping in view that a product is fabricated using a number of manufacturing processes the overall product sustainability assessment is a challenging and resource consuming task. To enhance the ease of assessing sustainability for different manufacturing processes, standardized procedures are required. It has been observed that literature related to the sustainability characterization frameworks for EDM process is not documented.

Several researchers have focused their efforts to characterize different unit manufacturing processes (UMPs) to facilitate the sustainability assessment of those processes. As per the available literature [12–14] characterization process is linked with the documentation of inputs and outputs associated to the process, process information and resource transformation. Similar effort has been made by the standard namely "Standard guide for characterizing environmental aspects of manufacturing" [15]. As per the ASTM E3012-16 standard, the characterization of any UMP is shown in Fig. 1. The standard facilitates manufacturing information flow by incorporating four elements namely inputs, outputs product and process information and resources.

To establish sustainability assessment, a unified framework is required to incorporate environmental, economic and social dimensions. Sustainability assessment of conventional machining has been reviewed using TBL approach [16]. To characterize sustainability, the current study utilized the traditional triple bottom line (TBL) approach using economic, environmental and social components as shown in Fig. 2 [14].

Figure 3 provides the schematic illustration of the proposed TBL based methodology. The methodology is composed of the four main steps.

- *Step 1* This step is based on the understanding of the functional principle of the EDM process.
- *Step 2* After the understanding of the process physics, step 2 requires the building of input and output inventories of the process.
- *Step 3* Triple bottom line (TBL) sustainability approach is synchronized for the EDM process using the traditional economic, environmental and social components.
- *Step 4* Future recommendations are made to make EDM process more sustainable in nature.

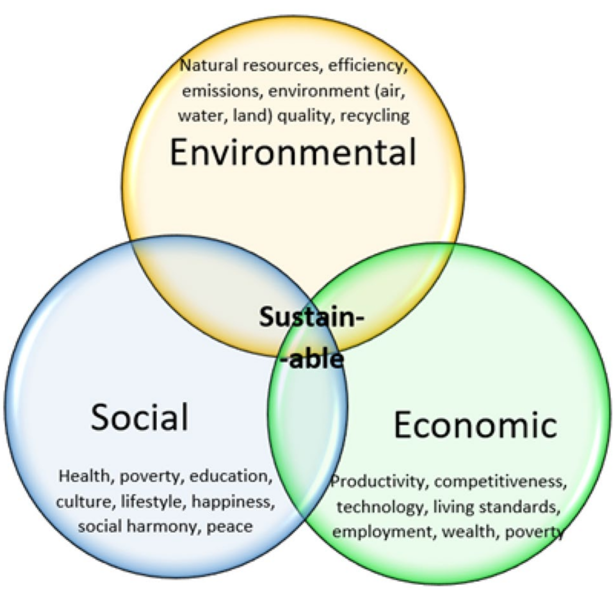

Fig. 2 Schematic illustration of TBL approach redrawn from [65]

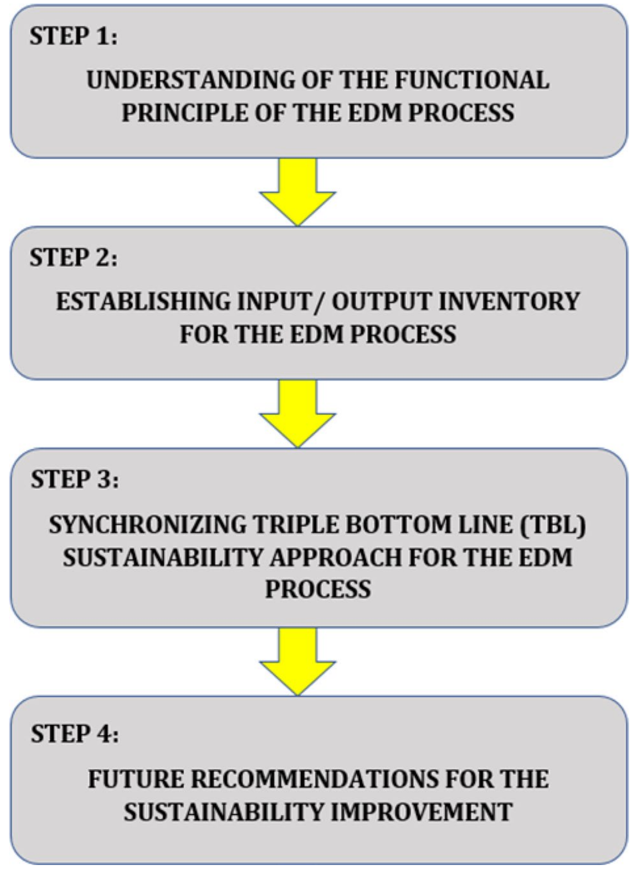

Fig. 3 Sustainability assessment methodology for the EDM process

3 Electrical Discharge Machining Process

3.1 Functional Principle

EDM machines consist mainly of five elements, an electrode, a work piece immersed in dielectric, electrode delivery system, dielectric pumping system and pulse width modulated power supply system. The power supply system provides high frequency modulated pulsed voltage to the electrode which is held at a pre-set gap from the workpiece and is controlled by a servo control mechanism. The dielectric levels are maintained by the dielectric pumping system which includes dielectric fluid in the reservoir, a pump and a filter to keep the dielectric away from contaminations. The concept of EDM can be summarized by Fig. 4, here electrode and the workpiece both are submerged in dielectric fluid and the distance between them in less than few tens of microns [17, 18]. The electrode can be moved to the required direction and to increase or decrease the gap.

The process of spark generation starts when an appropriate voltage difference is generated between the electrode and work piece due to the applied voltage, an electrostatic force develops between them which causes the

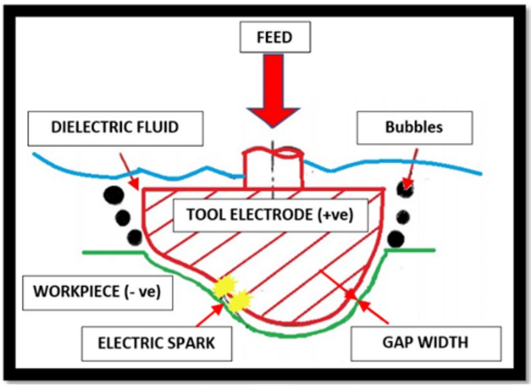

Fig. 4 Schematic illustration of EDM process (adopted from [17, 18])

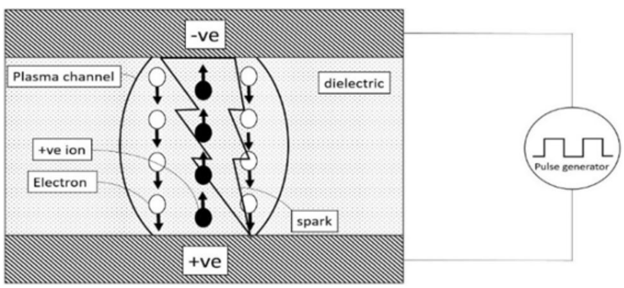

Fig. 5 Schematic view of spark generation in EDM process (adopted from [66])

electrons available at the cathode to move towards the anode at that location where least distance is between them, but this gap is already filled with dielectric fluid as shown in Fig. 5 [17].

The dielectric molecules cause restriction in the flow of electrons, initiating collisions with one another and ultimately resulting in the ionization of dielectric fluid. This process keeps repeating itself and eventually a very high concentration of ions and electron form a plasma, which is a very thin ray of ionized molecules of dielectric fluid. The high-speed electrons strike the surface of anode and cause heat generation due to the conversion of their kinetic energy. The heat generated at this point can be at 8000–12,000 K [19], enough to vaporize or melt the material and as soon as the pulse voltage is turned off the melted material gets removed from the workpiece by the collapsing pressure of plasma. Some latest studies based on collisional-radiative models revealed that plasma temperature can reach up to 25,000 K [5]. Chung and Chu [20] studied the role of pulses during micro-EDM according to inductance, capacitance and voltage. High inductance decreases machining time and tool wear, but side gap increased. Lin et al. [21] investigated the hybrid setup of EDM with ultrasonic vibration and assisted magnetic force. The study provided higher MRR and lower surface roughness.

3.2 EDM Variants

Basic EDM process has been modified into several variations to facilitate different industrial usages. EDM has two main types known as ram/sinker and wire-cut EDMs. In ram/sinker type EDM, tool is connected to the ram that can be adjusted to maintain gap for electric spark. In the other EDM type, wire-cut (WEDM) utilizes a thin single strand electrically charged wire to make intricate cuts. There are several variations of these basic EDM processes, formed due to their popular industrial significances. These variations are micro EDM, micro wire-cut, electric discharge milling, electric discharge grinding (EDG), electric discharge texturing (EDT), electric discharge drilling (EDD), ultrasonic aided EDM, mole EDM and double rotating electrodes EDM.

In EDM sinker, the workpiece is submerged under dielectric fluid and is widely used in the drawing and die making industries [22]. On the other hand, drilling EDM uses a rotating cylindrical electrode which passes through the work piece forming the hole or any required cross-section. Cutting EDM uses conductive wire as an electrode and is used to create complex shapes and to cut hard materials. Similar to cutting EDM, Electric discharge grinding (EDG) uses a rotating wheel as an electrode instead of wire as an electrode in the mechanism of metal removal. Micro-EDM is a process where workpiece is usually below 1mm size, it delivers high precision and very fine micro detailing [23]. Powder mixed electric discharge machining (PMEDM) involves addition of conductive powder in to the dielectric fluid to decrease the insulative properties of the dielectric. Due to the presence of these powder particles, the insulating strength is decreased, and the spark gap distance is increased between tool and workpiece. This methodology promotes the uniform spread of electric discharge in all directions resulting in improved material removal rates [24].

3.3 Industrial Significance

This section describes the different industrial applications related to different variations of EDM process. The main advantage of EDM process is linked with the non-contact-based nature of the process. As a result, there are no cutting forces being generated in the process, and the process can produce small, precise and fragile engineering components as mentioned earlier. The process also enables to produce parts with burr free edges, favoring it for the production of complex automotive and aerospace components. When it comes to the practical implementation of the EDM process, certain limitations have also been reported in literature [19]. When EDM processes are compared with the traditional machining processes, the material removal rate (MRR) for EDM processes is noticeably lesser. On the other hand, the preparation of consumables and electrodes takes reasonably valuable time.

Previously, the scope of EDM was limited to mold, die and tool manufacturing industries but now with the development of all these variants of EDM, it is utilized by biomedical, electronics, automotive and aerospace industries for prototype and product development. Due to enhanced precision and accuracy powder mixed EDM can be used to manufacture orthopedic, spinal, ear, nose and throat implants and surgical instruments such as blades and dental equipment. PMEDM also improved the surface finish at reduced associated cost [25]. In another study, the potential of EDM processing was explored for the components related to the nuclear industry [26]. The mentioned study considered separator-type object made of 99.99% elecrolytic chrome consist of 85 cells. EDM processing is favored because the product requires very high accuracy and roughness should not exceed 0.4 Ra. The study revealed suitable machining parameters including size of process discharge gap [26].

3.4 EDM Processing of Modern Engineering Materials

It is also important to reveal EDM capabilities with respect to processing different classes of engineering materials. This section exposes the possibilities of EDM processing on different classes of engineering materials.

There are several studies where processing of difficult-to-cut materials has been investigated using EDM processing methods. It has been observed that the cutting speed increases with peak current and pulse interval in wire EDM process [27]. In another study influence of peak current, pulse on time, pulse off time and servo reference voltage was investigated on material removal rate (MRR) and surface roughness [28]. The study incorporated ANOVA to analyze the influence of input parameters on MRR and roughness. Peak current and pulse on time were found to be dominant parameters towards MRR and roughness. Another study compared the machining performance of dry EDM milling with oil EDM milling when machining cemented carbide using copper tungsten pipe. The results showed that dry EDM is more production friendly as it provided higher machining speed and lower electrode wear ratio. When spark type EDM was used to machine NiTi shape memory alloy by means of Cu and W–Cu electrodes with different levels of electric current and pulse duration, W–Cu electrode was found more stable [29]. In another study graphite and copper-infiltrated-graphite electrodes were used to machine René 108 DS nickel superalloy using spark EDM. Lowest wear ratio was observed for graphite electrode at low discharge current and high voltage-based settings [30].

To have superior wear resistance and durability modern ceramics have been used to several manufacturing applications such as fabrication of molds used in injection molding and extrusion processes. Recent developments in ceramic industry such as electrically conductive oxide ceramics has permitted the used of EDM processing on these parts. To enhance damage tolerance of alumina based ceramics zirconia is dispersed called as zirconia toughened alumina (ZTA) [31]. It has been observed that higher discharge energy for shorter duration of time can cause cracks in ceramics. However, proper machining parameters can control or avoid these cracks. Volume flow rate for flushing debris controls feed rate and drill oversize [32]. When machining TiC/Ni cermet using copper electrode under EDM sinker, it is found that peak current increases both surface roughness and material removal rate [33]. Nonconductive ceramics are also very popular engineering materials due to their high strength, ability to with stand high thermal loads and resistance to corrosion. They are also very difficult to machine using conventional machining due to their extreme brittleness. In this case EDM processing can be viable option using assisted electrode. Spalling was found to be the dominant material removal mechanism when processing nonconductive ZrO_2 ceramic using copper foil as assisting electrode [34]. Another study investigated the machining performance of newly developed conductive ceramic (YN/SiC) produced using Yttrium Nitrate (YN) under micro-EDM. The performance was compared with stainless steel SUS304. For the energy below 10 μJ, machining time was small for YN/SiC [35].

Several studies have also been conducted to reveal the potential of EDM processing for modern composite materials. A study investigated the discharge behavior of Si3N4 ceramic/carbon nano-structure composites. Two different workpiece materials (Si3N4) ceramics/carbon nanotube (CNT) and graphene nano platelet (GNP) composites were examined. Assisting electrode method provided better hole edge shape for GNP composites under low conductivity [36]. Another study examined two different types of ceramic particulate reinforced Al matrix composites such as Al/SiCp and Al/Al_2O_3p under wire-EDM setup. The study developed a semi-empirical model for the surface roughness using machining parameters. The study also provided useful understanding towards the effects like powder- mixed EDM and poor spark transitivity [37]. For the curved profile machining using wire EDM pulse-on time, servo voltage, and wire tension were found to be the most vital parameters towards the radius of curved profile shaped in tungsten carbide-cobalt composite (WC–Co). The study utilized regression-based model and ANOVA to figure out most important parameters [38]. When machining Si3N4–TiN composites under spark EDM using copper electrode, improved MRR was observed for higher current and pulse on time levels [39] (Table 1).

Table 1 Processing of different engineering materials using EDM

Material type	EDM setup	Remarks
A) Difficult-to-cut alloys		
Ti6Al4V [2]	Process: Wire EDM Electrodes: High-speed brass wire and zinc-coated brass wire (with 0.25 mm diameter)	The study revealed that the cutting speed increases with peak current and pulse interval. ANOVA exposed that voltage, injection pressure, wire feed rate and wire tension have less influence on the cutting speed.
Ti6Al4V [3]	Process: Wire EDM Input parameters: Peak current, pulse on time, pulse off time and servo reference voltage Electrode: Brass wire with diameter 0.25 mm	ANOVA was performed. Peak current and pulse on time were found to be dominant parameters towards MRR and roughness
Cemented Carbide (G5) [4]	Process: Dry EDM milling vs oil EDM milling Electrode: Copper tungsten pipe	The results showed that dry EDM is more production friendly as it provided higher machining speed and lower electrode wear ratio
NiTi Shape Memory Alloy [7]	Process: EDM (Spark type) Electrode: Cu and W–Cu electrodes were used with electric current of 4, 6 and 8 A. Pulse duration was 6.4, 25 and 50 µs	Results were found more stable with W–Cu electrode than the Cu electrode MRR was not found sensitive to the electrode materials used in this study
René 108 DS nickel superalloy [9]	Process: EDM (spark type) Electrode: Two electrodes namely graphite and copper-infiltrated-graphite were used	The study used factorial design using parameters of current, voltage, duty cycle and electrode polarity Lowest wear ratio was observed with graphite at low discharge current and high discharge voltage
B) High performance ceramics		
ZTA-TiC [10]	Process: EDM drilling Electrode: Copper tube electrodes (Type-D) with a diameter of 2 mm. IME 63 (oelheld GmbH, Germany) was used as oil based dielectric fluid	Higher amount of discharge energy can cause cracking in ceramics, to avoid crack proper parameter selection is required. Debris flushing is required and has influence on drill oversize and feed rate
TiC/Ni Cermet [11]	Process: EDM Sinker Electrode: Copper electrode, dia 2 mm Kerosene was the insulation medium	The study investigated influence of peak current and pulse duration on surface roughness and material removal rate. The study found that both MRR and surface roughness increase with increasing peak current.
Nonconductive ZrO_2 ceramic [12]	Process: EDM Die-sinking Electrode: Copper electrode (3 mm × 3 mm), adhesive copper foil was used as assisting electrode	Increase in power increase MRR. Spalling was found to be dominant mechanism for material removal.
Conductive SiC ceramic such as Yttrium Nitrate (YN), YN/SiC and Stainless Steel SUS304 [13]	Process: Micro-EDM Electrode: WC–Co 10%, dia 300 µm Experimental settings: Voltages (80, 100, 120 V), Feed rate: 1.0 µm/s and spindle speed: 2200 rpm	The study compared number of shorts, machining time, entrance clearance, material removal rate (MRR), and debris size for mirco-EDM processing of YN/SiC and SUS304. For the energy below 10 µJ, machining time was small for YN/SiC MRR is inversely proportional to machining time

Table 1 (continued)

Material type	EDM setup	Remarks
C) High performance composites		
(Si_3N_4) ceramics/carbon nanotube (CNT) and graphene nano platelet (GNP) composites [14]	Process: EDM sinker Electrode: Cu electrode with 8 mm dia.	The study investigated the discharge behavior of Si_3N_4 ceramic/carbon nano-structure composites Assisting electrode method provided better hole edge shape for GNP composites under low conductivity
Ceramic particulate reinforced Al matrix composites such as Al/SiC$_p$ and Al/Al$_2$O$_{3p}$ [15]	Process: Wire EDM Settings: Dielectric used was deionized water, 15 µS/cm	Developed a semi-empirical model for the surface roughness using machining parameters The study provided useful understanding towards the effects like powder-mixed EDM and poor spark transitivity.
Tungsten carbide-cobalt composite (WC–Co) [38]	Process: Wire EDM Electrode and Setup: Brass wire of 0.25 mm dia was used De-ionized water was used as a dielectric medium	The study incorporated regression modeling and ANOVA to identify the important parameters towards performance The study found that pulse-on time, servo voltage, and wire tension are the most vital parameters towards the radius of curved profile shaped in WC–Co
Si_3N_4-TiN composites [16]	Process: Spark EDM electrode and Settings: Copper electrode current (3,4,5,6 and 7 A) Spark gap voltage (30, 32.5,35,37.5 and 40 V)	The study performed multi-objective optimization on Si3N4-TiN composites using gray relational analysis Better MRR was observed when current and pulse on time was increased

4 Building Input and Output Inventory

To conduct sustainability assessment of the EDM based processes, it is essential to create and understand the input and output inventories associated with the EDM process. Both input and output inventories have been reported in Fig. 6. The main input requirement for EDM process is linked with the high demand of electrical energy. This energy demand can be divided into two requirements, where the major portion of this electrical energy is needed to operate the equipment and to perform the machining operation by using electric spark to vaporize workpiece material. Besides that, electricity is also required to operate the pumping and filtration systems. Other major inputs are related to the tool and workpiece materials supplies.

In addition to that, good amount of resources is required to prepare the tool for EDM operation. In the manufacturing processes, the output is a finished product but most of the times the final product is accompanied by some by-products with considerable impacts on sustainability. When it comes to the outputs of the EDM process, the finished machined part has been attributed as a major output. Besides that, dielectric waste containing metallic chips, tool wear, toxic fumes and emissions have also been produced.

5 Synchronizing TBL Approach for The EDM Process

Sustainability concept is linked with development, as per Brundtland Commission, sustainable development is to "meets the needs of the present without compromising the ability of future generations to meet their own needs" [40, 41]. The basic idea behind sustainability is to conserve our natural resources and reduce the negative impacts caused by the human actions. Sustainability is a broad concept that covers the interrelation of economy, society and environment. This relationship is named as triple bottom line or three pillar of sustainability approach [42–44]. Figure 7 represents the concept of triple bottom line approach synchronized for the EDM process.

The economic concerns of EDM process are represented by achieving high productivity, reducing overall cost and reducing the lead time involved in tool preparation. The environmental concerns are linked with reducing electricity and material consumptions, minimizing wastages and replacing hazardous materials with green materials. The social aspects are addressed by reducing the toxic fumes and emissions, minimizing fire and electricity-based hazards and implementing appropriate work safety rules and regulations.

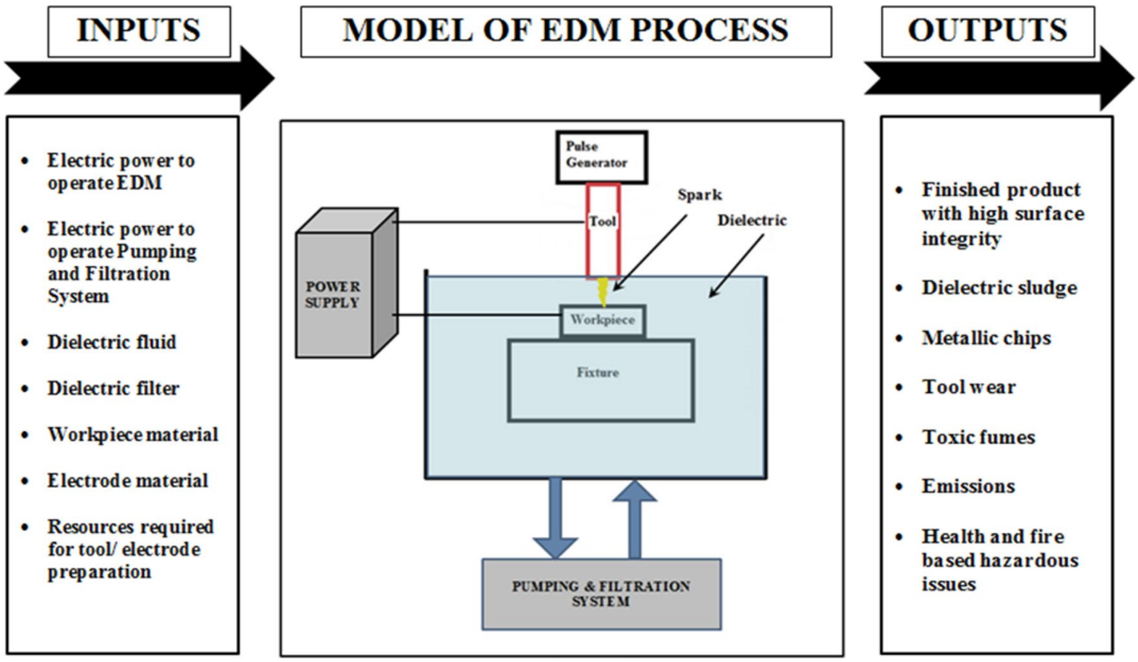

Fig. 6 Input and output based representative model of EDM process

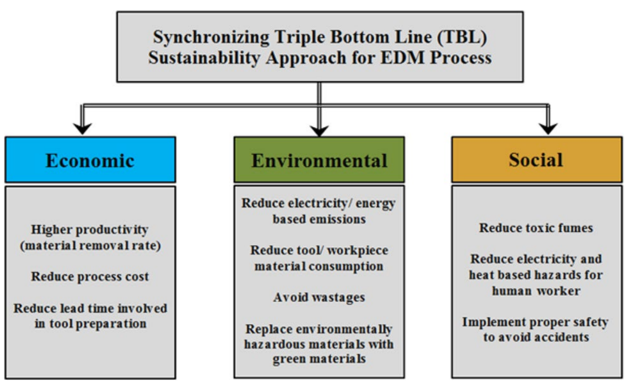

Fig. 7 Synchronizing TBL approach for the EDM process

5.1 Economic Concerns

EDM is an energy extensive process because energy is required not only for the EDM process but also for the pumping and circulation of dielectric fluid throughout the process, apart from that a substantial portion of energy is utilized for the cooling of electrode and the workpiece. Experimentation was conducted in a study [22] to measure the electrical power consumed during the roughing and finishing operations. The study utilized copper electrode, hard metal and a hydrocarbon-based dielectric and it was found that around 65% of the power was used by the pumping system of dielectric fluid. The study revealed that the generator responsible for causing the sparks consumed around 10% power during the roughing and finishing operations, however discharge frequency and discharge current can change the power consumption. Fans, lightning and drive systems make up around 10% of power and other accessories like compressor requires 15% of the total power consumption. Apart from the power consumption, EDM process also requires some consumable materials such as compressed air, dielectric fluid, dielectric fluid filter, air filter etc. A study was conducted [22] to evaluate the consumption of these item, the study was conducted for 2000 h of machining operations because the consumables are directly related to working hours.

As EDM process involves very high temperature and heat generation so the metal erosion occurs are at workpiece as well as on electrode. After certain hours of operation this electrode start to lose it accuracy and it needs replacement. The wearing out of electrode depends upon the composition of the electrode and associated electrical parameters, normally this characteristic is indicated by Electrode wear ratio (EWR) or Tool wear ratio (TWR). The electrical parameters are important towards the selection of electrode material. The electrode wear ratio of some of the commonly used electrodes is Graphite (130%), Copper (43%), and tungsten copper (36%). Electrode wear ratio depends upon a few factors like composition, density, melting point, electrical resistivity and hardness [45]. Another study proved that besides these factors, the process parameters like peak current, discharge gap, voltage pulse and dielectric fluid play a vital role in reducing the electrode wear [46].

Energy Monitoring and Optimization; one of the major economic concerns with EDM process is its energy extensiveness but methods have been proposed to either monitor the energy usage or to plan and optimize the process to reduce the power consumption. Such a monitoring and analysis method has been proposed [47] in which a real time monitoring system is developed for micro EDM milling process, the system included sensors which were implemented by open source hardware and software. The results of the conducted experiments showed that the material removal process required only 3% of the total energy of the process but the rest of the energy was utilized by the auxiliary systems like dielectric pump, electrode cooling and drive systems. Another technique is developed to cater the economic concern by process planning system [48], it utilizes computer aided process planning system. The concept behind the planning system is to plan the process parameters, optimize them and compare the available resources before starting the machining process, in this experiment they compare parameters two different dielectrics and obtained the results without wasting any of the resources. The authors of studies [22] and [47] reported that the auxiliary systems like electrode cooling and dielectric pump are one of the reasons of high energy consumption. Cryogenic cooled EDM process was observed in a study [49], the experimentation was conducted by cooling a copper electrode by liquid nitrogen and process parameters were analyzed. The results showed good quality surface finish, faster material removal rates and less electrode wear which all can save considerable amount of cost and energy.

5.2 Environmental Concerns

The EDM processes possess two major threats to the environment; those are the hazardous emissions and the disposal of contaminated dielectric fluid. There are different types of dielectrics used in EDM processes, where the most common are mineral oil based or organic dielectric fluids and hydrocarbon based dielectric fluids. The emissions depend upon various factors like type of dielectric fluid, electrode material and workpiece material. It was found in [50] that regardless of the electrode or workpiece, the emitted chemical fumes included benzene, vapor of mineral oil, polycyclic aromatic hydrocarbons (PAH), mineral aerosols and various by-products generated by the dissociation of oils. Besides these fumes, due to high temperature dissociation of hydrocarbon from dielectric fluid the decomposed carbon particles get collected on the electrode and slow the process.

Another study [51] calculated the total emission by considering an R8340 electrode, X36CrMo17 workpiece, and hydrocarbon BP200T dielectric fluid at a level of 35 mm and with varying discharge current (32A, 64A, 128A, 192A) as in Fig. 8. Different combinations of electrodes and

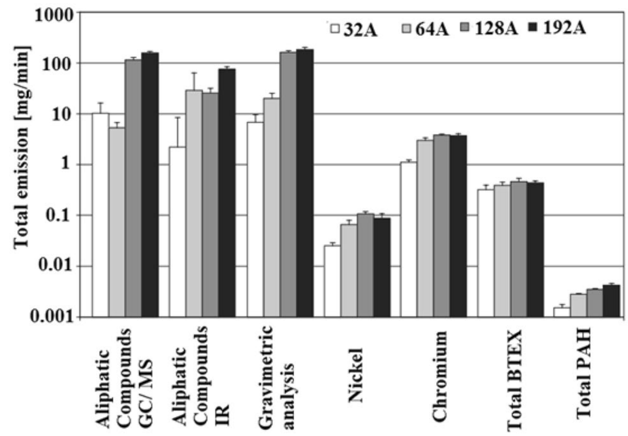

Fig. 8 Total emissions observed for the different discharge currents (adopted from [65])

workpieces were also used to obtain the results; it shows that besides other fumes now aliphatic compounds and metal fumes or aerosol concentration was a major change. Especially in this case the concentration of chromium was around 4–6 mg/min and aliphatic compounds reached 100mg/min level which are highly dangerous for the living organisms if inhaled. Besides the aerosols, the metal particles machined down from the workpiece or the electrode mix together to form an erosion slurry or sludge. This slurry then passes through the dielectric filter where some of the metal particles are collected but other smaller or less concentrated particles pass directly through it and are collected by the dielectric. The type of material found in the slurry depends upon the selected electrode type and workpiece.

It was found that after certain cycles of operation, the dielectric loses its properties and needs to be replaced, a case study [52] was done to estimate the amount of required dielectric fluid based on a hydrocarbon based dielectric and it was found that if a large EDM machine is used for 7200 h annually then 3556 l of dielectric fluid will be required. This huge amount of dielectric requirement is an environmental and economic concern as well. The slurry contains hazardous materials like lead, cadmium etc which are a threat to our environment, so this slurry needs to be disposed properly and cannot be dumped into a landfill. The reason for the end of life treatments of dielectric and the filter media being expensive is that it has to go through chemical-physical-biological processes to minimize its harmful content, after which it can be disposed in special waste landfill or can be burned in incinerators.

Use of Green Alternatives as Dielectric Fluids; the other concern is the dielectric fluid, firstly it is constantly circulating and collecting the eroded metal and getting contaminated, secondly, end of life treatment is very expensive. *Jatropha curcas* oil based bio-dielectric is suggested as a viable replacement for the conventional hydrocarbon based dielectric [53]. In this investigation process parameters were compared with that of a conventional dielectric and it was concluded that Jatropha showed similar response times, but it increased the material removal rate and surface finish. So, *J. curcas* oil proved to be a better and sustainable alternative to hydrocarbon-based dielectric. A relatively similar experiment was conducted to find a greener and cost-effective dielectric fluid which involved waste vegetable oil [54]. In this experiment, the process parameters were investigated and compared with a hydrocarbon based dielectric fluid, the output parameters like material removal rate, electrode wear, surface finish were not compromised instead showed almost similar results to those of hydrocarbon-based dielectric but there were no harmful emissions, no fire hazards, no disposal issues and most importantly cheaper than any other alternative.

As explained earlier, experiments and studies have been conducted to find the greener alternative of hydrocarbon based dielectric fluids. The authors of studies [53] and [54] proved that Jatropha BD and waste vegetable oil are greener alternatives with no toxic emissions and as both of them are vegetable base oil so they can be treated and disposed without causing any harm to the environment. Another green alternative to conventional dielectric is Deionized water, there are few studies conducted to compare the process parameters and machining performance [55]. The study concluded that with less peak current and pulse duration better surface finish can be obtained but the environmental aspect of deionized water is controversial, although there are less toxic emissions but on the contrary the deionizing resins are added into the water which after certain cycles of operation collect the eroded metals and contaminants which will eventually need to be removed and it requires to be treated before disposal, also the machining performance aspect has been debated [56].

Dry and Near Dry EDM Processes; Other techniques used to make EDM process more sustainable are Dry EDM and Near Dry EDM, both techniques do not require the workpiece and electrode to be sunk in dielectric fluid resulting in no toxic fumes and sludge. The dry EDM process employs compressed air or inert gasses instead of dielectric fluid, the high-pressure gasses pass through a special cavity made inside the electrode. This gas serves the purpose of dielectric, also it helps in reducing the excessive heat from the workpiece and facilitates in removal of metal eroded debris. The rotary motion of the electrode provide stability to the dry EDM process [57]. Both methods are environmentally friendly and sustainable, but the machining performance gets compromised in these methods. An investigation was carried out to compare the machining characteristics of near dry EDM with dry and wet EDM and it was concluded that at high energy discharge levels the material removal rate and electrode wear ratio was eight times faster in wet EDM than in dry and near dry EDM. At low discharge energy levels the material removal rates and electrode wear ratio were 1.6 and 1.8 times better than wet EDM [58].

5.3 Social Concerns

The social aspect of EDM process involves the machine operator or programmer and his surroundings. The operator is at the highest risk due to either contact with dielectric, inhalation of fumes or explosion. The most common issues to the operator are from the exposure to dielectric fluid, especially in the case of hydrocarbon based dielectric fluid because they are aromatic, paraffinic, naphthenic and skin irritants. A study [59] was conducted in aerospace industry which concluded that hydrocarbon-based dielectric was the leading cause of contact dermatitis among the operators. The other highest risk is inhalation of fumes or aerosols, now first risk involved is the inhalation of the dielectric vapors, as high temperatures are involved which cause the dielectric to vaporize, as metal particles are present in the dielectric so if inhaled this can cause adverse effects like allergic reaction, asthma and lung diseases [60].

The fumes and aerosols generated by EDM process consist of aliphatic compounds, metals, volatile organic compounds (VOC) like benzene, toluene, ethylbenzene, and xylene (BTEX) and polycyclic aromatic hydrocarbons (PAHs). A study [61] compared the concentration of fumes generated with the changes in the process parameters like peak current and pulse duration and it found that with dielectric level 80 mm, 7 A peak current and 520 µs, the aerosol concentration was 5.19 mg/m^3 which is slightly above the threshold limit value for permissible respirable aerosols which is 5 mg/m^3. A morphology study [62] was conducted which found that the particulates released from the EDM process can be in nano-range and these nano-particles, if inhaled can easily enter the respiration system and can cause severe inflammation to respiratory track which can lead to breathing disorders and cardio vascular diseases.

The concentration of aerosols like aliphatic compounds and metals can vary with the change in dielectric levels, the more the dielectric level is the less the concentration of aerosols whereas no effect was recorded on the concentrations of VOCs, PAHs and BTEX. Different hydrocarbon-based dielectrics are used but the most famous is kerosene because of its low cost, provides good surface finish and fast removal rate on the contrary it poses a huge threat to humans who come physically in contact with it. According to a study done on the effects of kerosene on human body, if kerosene vapors are inhaled constantly they can lead to asthma, acute lower respiratory diseases, dyspnea, neurotoxicity and lung cancer [63]. Apart from fumes and vapors, kerosene if comes in contact with skin it effects the dermal barrier function, increases carcinogen absorption and effects the ability of skin to retain water. Also, the vapors of kerosene can cause mild eye irritation to the operator. Besides these hazards the potential threat to the operator is fire and explosion.

A hazard and operability (HAZOP) [61] study was conducted to evaluate the hazards associated with EDM process and the study indicated the vulnerability of EDM process towards fire and explosion. As EDM process involved spark and plasma generation which is definitely happening at very high temperatures and the dielectric used are commonly hydrocarbon based like kerosene which is having flash point around 37–65 °C and auto-ignition temperature around 220 °C [64], so due to insufficient cooling the dielectric fluid reaches its flash point, it vaporizes, combines with atmospheric oxygen and this becomes an air fuel mixture which upon contact with spark can cause an explosion. Now this explosion will be enhanced and will lead to an uncontrollable fire if there are no proper ventilation and exhaust systems present. Lastly the electromagnetic produced during the plasma generation have a potential safety concern for the operator, although the magnitude of radiations is very minor but constant exposure can eventually lead to DNA fragmentation, but this issue is controversial and not enough literature is available to assure its legitimacy [56] (Table 2).

6 Conclusions and Future Recommendations

The paper presents TBL based methodology to review the sustainability aspects of the EDM processes. All the input and output parameters were considered and their impact towards the three pillars of sustainability was explained in detail from the reviewed literature. The paper also reports some best sustainable practices currently being used in the industry such as alternatives to hydrocarbon based dielectric fluid, energy optimization planning methods and dry/

Table 2 Summary of TBL exposed factors influencing sustainability of the EDM process

Economic concerns
Difficulties with dielectric fluid
With the passage of time dielectric fluid gets contaminated with eroded material and end of life treatment is expensive
Recommendations Conventional hydrocarbon-based dielectric should be replaced with green dielectric fluids such as *Jatropha curcas* oil, waste vegetable oil and de-ionized water etc.
Energy consumption
High value of energy consumption due to the nature of EDM process. A major portion of the energy consumption in EDM process is utilized in the cooling of electrode and pumping of dielectric fluid
Recommendations Energy optimization methodologies such as computer-controlled process planning can be adopted
As major energy consumption is involved in the cooling of electrode and pumping, cryogenic cooled EDM process provided encouraging energy and cost saving results
Electrode material consumption
Most commonly used electrode materials have high electrode wear ratio that results in frequent tool preparation
Recommendations Using electrode material with low electrode wear ratio can improve the overall economics of the EDM process. However, electrode selection is strongly linked with the workpiece quality, so it is driven as per workpiece quality criterion
Environmental concerns
Hazardous emissions
The emitted chemical fumes included benzene, vapor of mineral oil, polycyclic aromatic hydrocarbons (PAH), mineral aerosols and other hazardous by-products
Recommendations Use of green dielectric fluids such as *Jatropha curcas* oil, waste vegetable oil and de-ionized water etc.
Use of dry or near dry EDM processes results in no toxic fumes and sludge
Disposal of contaminated dielectric
The dielectric slurry contains hazardous materials like lead, cadmium etc., and act as threat to our environment. This slurry needs to be disposed properly and cannot be dumped into a landfill. However, dielectric treatment is very expensive
Recommendations Use of green dielectric fluids such as *Jatropha curcas* oil, waste vegetable oil and de-ionized water etc.
Use of dry or near dry EDM processes results in no toxic fumes and sludge
Social concerns
Vulnerability towards fire and explosion
Insufficient cooling the dielectric fluid in the presence of oxygen can become air fuel mixture and spark can cause explosion. Improper exhaust and ventilation system can couple and make fire and explosion worse
Recommendations Efficient and well design cooling and ventilation system can eradicate this issue
Operators health and safety concerns
Inhalation of kerosene vapors for longer duration can lead to asthma, acute lower respiratory diseases, dyspnea, neurotoxicity and lung cancer
Skin contact with kerosene can lead to the dermal barrier function, increases carcinogen absorption and effects the ability of skin to retain water.
Nano-particles released during EDM can easily enter the respiratory system and can cause breathing disorders and cardio vascular diseases.
Recommendations Use of green dielectric fluids, proper safety equipment and efficient ventilation system can solve these concerns

near dries EDM. The paper highlights some of the research gaps to be considered for the future research studies. These gaps are energy conservation systems, end of life treatment of dielectrics, detailed life cycle analysis and hazard evaluation for the operating environment of EDM process.

- It has been observed that EDM processes are favorable to process modern engineering materials such as modern ceramics and composites where traditional machining is difficult to perform due to brittle nature of material.
- It has been observed that higher amount of discharge energy can cause cracking in ceramics, to avoid cracks proper parameter selection is required.
- When machining non-conductive ceramics, spalling was found to be a dominant mechanism for material removal.
- For machining nano-composites such as carbon nanotube (CNT) and graphene nano platelet (GNP) composites, assisting electrode method found to be very effective and provided better hole edge quality for GNP.
- Literature revealed that auxiliary systems consumes a major portion of energy. This motivates the need to address this high energy consumption by utilizing energy efficient pumping systems or using green energy technologies.
- Cryogenic cooled EDM process provided encouraging energy and cost saving results.
- The end of life (EOL) treatment of dielectric fluids is very expensive option. Utilization of dry or near dry EDM can resolve this issue.
- Vulnerability towards fire and explosion has been observed as a major social concern especially in case of kerosene oil as a dielectric fluid. Properly designed cooling system and ventilation can cater this issue.
- There is a huge contribution by the type of electrode material and workpiece material in the aerosol production, hazardous emissions and sludge generation. With that comes the need to develop an analytical computer aided model which will include the data about the type of electrode and workpiece materials, dielectric types and toxicity of emissions. The simulation model can incorporate electrode types, workpiece material and dielectric types, and simulated results can generate the total associated toxic emissions.
- Detailed life cycle analysis (LCA) based studies should be conducted for the different variants of EDM process as this will provide a better understanding of the cost effectiveness and sustainability.

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Compliance with ethical standards

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