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OPEN Assessment of electrode materials in EDM of SS316L: energy consumption, electrode wear, dielectric consumption, GHG emissions, and economic viability for sustainable development

Muhammad Asad Ali^{1,2}✉, Muhammad Huzaifa Raza³, Sana Ehsan², Muhammad Sana⁴, Muhammad Umar Farooq⁵, Muhammad Jawad⁶ & Adeolu A. Adediran^{7,8}✉

With the growing emphasis on cleaner production in the manufacturing sector, minimizing energy consumption (EC), greenhouse gas (GHG) emissions, and operational costs—without compromising process performance—has become essential for sustainable development. This study investigates the environmental and economic impacts of electric discharge machining (EDM) of annealed SS316L stainless steel, focusing on EC, electrode wear (EW), dielectric usage, and associated GHG emissions and carbon costs. To enhance machining sustainability, key EDM parameters—pulse ratio (P_R), peak current (I_p), and graphene nanoplatelet powder concentration (P_C)—were optimized. Moreover, three electrode materials (aluminum, brass, and copper) were comparatively evaluated for their influence on performance and environmental impact. The findings indicate that EC is predominantly influenced by I_p , whereas pulse ratio has the greatest effect on EW and dielectric consumption (DC) and their corresponding GHG emissions and carbon costs. Among the materials tested, copper electrode demonstrated the most favorable performance, offering lower EC, minimal wear, and reduced emissions due to superior electrical and thermal conductivities. In contrast, aluminum electrode resulted in significantly higher energy use and environmental impact, while brass electrode showed intermediate performance. Specifically, GHG emissions and carbon costs were found to be 20.98%–30.90% higher with brass and 58.70%–80.64% higher with aluminum compared to copper electrode. Finally, the outcomes were mapped against relevant United Nations Sustainable Development Goals (SDGs), emphasizing the broader significance of sustainable manufacturing practices in EDM in terms of clean energy, and responsible consumption and production.

Keywords Energy consumption, GHG emissions, Carbon cost, EDM, Sustainable manufacturing, Sustainable development goals

Abbreviations

MRR Material removal rate

¹College of Mechanical and Electrical Engineering, Nanjing University of Aeronautics and Astronautics, Nanjing 210016, China. ²Department of Industrial and Manufacturing Engineering, Faculty of Mechanical Engineering, University of Engineering and Technology, Lahore 54890, Pakistan. ³Department of Data and Systems Engineering, The University of Hong Kong, Pok Fu Lam, Hong Kong. ⁴Department of Mechanical and Industrial Engineering, Montana State University, Bozeman 59717, Montana, USA. ⁵Department of Mechanical Engineering, University of Michigan, Ann Arbor, MI 48109, USA. ⁶Department of Industrial Engineering, University of Engineering and Technology, Taxila 47050, Pakistan. ⁷Materials Design & Structural Integrity Research Group, Materials and Metallurgical Engineering Department, Federal University Oye-Ekiti, Oye-Ekiti, Ekiti State, Nigeria. ⁸Department of Mechanical Engineering Science, University of Johannesburg, Johannesburg, South Africa. ✉email: ma_ali@nuaa.edu.cn; dladesoji@yahoo.com

GHG	Green house gases
I_p	Peak current
P_R	Pulse ratio
EC	Energy consumption
P_{ON}	Pulse on time
Ra	Surface roughness
EDM	Electric discharge machining
C_p	Powder concentration
EW	Electrode wear
DC	Dielectric consumption
P_{OFF}	Pulse off time

During the twenty-first century, global climate warming has proven to be one of humanity's most critical challenges. Greenhouse gas emissions are the major source of climate change. With 14,400 Mt CO₂ eq., China remains the largest contributor to global GHG emissions in 2022¹, and these emissions are expected to exceed 20,000 Mt CO₂ by 2030². Among China's three major industrial sectors (services, manufacturing, and agriculture), the manufacturing industry contributes significantly to GHG emissions due to EC³. The sole iron and steel manufacturing industry is responsible for 15% of China's total GHG emissions⁴. In response to increasing global demands for carbon neutrality, Chinese government regulations have compelled enterprises to set ambitious CO₂ emissions targets in their manufacturing processes⁵. Most of these emissions are released as a result of the consumption of fossil fuel energy. Nonetheless, energy efficiency in developing countries remains considerably lower than in developed nations, particularly within the manufacturing sector. This disparity is further exacerbated by low rates of energy and material utilization, leading to substantial CO₂ emissions⁶. Efficient utilization of energy and materials can significantly lower CO₂ emissions produced during manufacturing processes while also boosting overall enterprise efficiency⁷. The advent of new concepts like technological innovation, sustainability, and intelligent manufacturing are driving substantial transformations within manufacturing practices. To strengthen their competitive advantage, companies are employing a range of strategies to identify and adopt the most effective technologies⁸.

With the demand for sustainable manufacturing, non-conventional manufacturing processes are often considered more environmentally friendly due to their material efficiency, lower waste generation, and reduced reliance on toxic substances⁹. In contrast to conventional machining, this machining process directly utilizes energy to remove material from the workpiece, eliminating the discrepancies between the electrode and the workpiece^{10,11}. It is capable of processing conductive materials of any hardness and has been effectively implemented in sectors such as aerospace, die manufacturing, and high-precision industries, including medical equipment and instruments¹². EDM is one of the non-conventional machining methods that mainly relies on the removal of workpiece material through spark discharges^{13,14}. The spark discharges raise the temperature in the machining zone up to 12,000 °C, which melts and evaporates material from the workpiece surface. The tool face and workpiece are submerged in dielectric fluid, where sparking occurs. The dielectric fluid serves not only as an insulating medium but also as a coolant while flushing debris from the machining zone¹⁵. Dielectric fluid characteristics ensure stable and consistent spark discharges^{16,17}. The intensity of the sparking is regulated by parameters such as I_p , P_{ON} , P_{OFF} , open voltage, spark gap, dielectric fluid characteristics and electrode properties^{18,19}. The optimization of these parameters can significantly improve energy efficiency, which aids in controlling not only GHG emissions but also machining costs²⁰.

Researchers have adopted a variety of methodologies to reduce the GHG emissions generated during the EDM process. Xu et al.²¹ considered I_p , P_{OFF} and pulse width for optimization to reduce the machining time, Ra, EC and GHG emissions. Increasing pulse width initially led to significant reductions in machining time, EC, and carbon emissions, followed by a slight rise, while Ra steadily increased. Similarly, higher I_p consistently lowers machining time, energy use, and GHG emissions, with Ra also on the rise. In their study, it was concluded that the GHG emissions resulting from electrical EC constitute approximately 50% of the total GHG emissions. Zhang et al.²² investigated the impact of I_p , P_{ON} , P_{OFF} and magnetic field intensity on toxic aerosol emissions (containing fine particles of carbon, silicon, aluminum, and their oxides), MRR, surface integrity, and EW. I_p was examined as the major factor affecting all response measures. The optimization of all variables can reduce the aerosol emissions and EWR by 15% and 10%, respectively, and increase the MRR by 6.6%. Zheng et al.²³ developed predictive models for the estimation of EC and CO₂ emissions. In their study, total CO₂ emissions include emissions from material (workpiece blanks, dielectric fluid and filters), energy (electric power consumed in machining, CNC system, wire moving cooling system, feed system, and pulse system), and undesired emissions (treatment of waste liquids, ineffective filters, exhaust gases, and scrap materials). It was observed that the proposed models have a prediction accuracy of 96.55% for single part processing.

Ming et al.²⁴ analyzed the impact of I_p , P_{ON} and duty cycle on MRR, Ra, energy efficiency, and exhaust/aerosol emissions (PM1.0, PM2.5 and PM10). Their results showed that energy efficiency has a direct relation to Ra. In parametric analysis, I_p has made a significant contribution to maximizing energy efficiency and reducing exhaust emissions. Camposco-Negrete²⁵ optimized the machining variables, including P_{ON} , servo voltage, and open voltage, to reduce the carbon emissions produced by the consumption of electric power. Their findings revealed that carbon emissions could be reduced by up to 14.09% depending on the thickness of the workpiece. Dwivedi and Choudhury²⁶ investigated and quantified the fine particulate matter emissions produced from the tool and workpiece materials and hydrocarbons from the dielectric fluid combustion. Fine particulates (sized 1 ~ 20 µm) of different elements with distinct proportions, such as carbon (32.85%), iron (2.48%), copper (1.80%), chromium (0.21%), and nickel (0.17%), were found in the emissions. Hannan et al.²⁷ studied the influence of I_p , P_{ON} , duty cycle, and pulse gap, along with the electrode material, on the carbon emissions from the electric

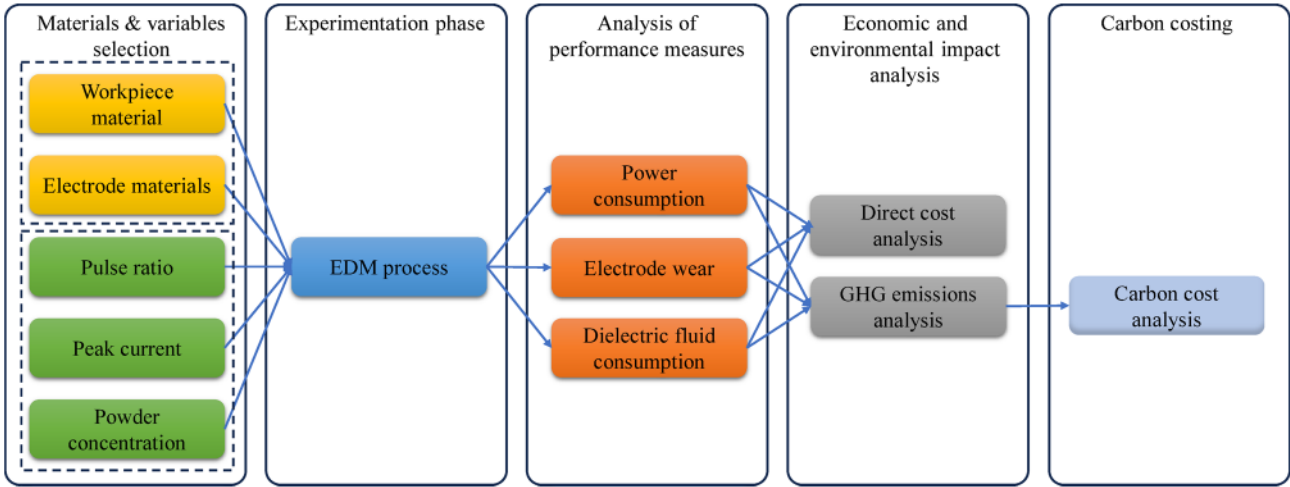


Fig. 1. Process flow for experimentation and analysis.

Elements	C	Ni	S	Cr	P	Si	Mo	Mn	Fe
wt.%	0.03	10.9	0.03	17.2	0.045	0.75	2.1	1.6	Balance

Table 1. Elemental composition of workpiece material SS316L.

Materials		Physical properties					
		Melting point (°C)	Density (kg/m ³)	Electrical conductivity (S/m)	Thermal conductivity (Wm ⁻¹ K ⁻¹)	Heat of fusion (kJ/kg)	Thermal diffusivity (m ² /s)
Workpiece material	SS316L	1390–1440	8000	1.35 × 10 ⁶	16.3 (at 100 °C)	275	2.68 × 10 ⁻⁷
Tool materials	Brass	940	8730	15.9 × 10 ⁶	150	168	3.75 × 10 ⁻⁵
	Copper	1083	8960	58.5 × 10 ⁶	401	206	11.7 × 10 ⁻⁵
	Aluminum	660	2750	36.9 × 10 ⁶	237	398	9.7 × 10 ⁻⁵

Table 2. Physical, electrical and thermal characteristics of workpiece and electrode materials.

power, dielectric fluid, and EW. In their findings, it was examined that copper electrodes offer lesser emissions from EC, while brass electrodes perform better in terms of reduced carbon emissions from EW and dielectric fluid consumption.

Based on the extensive literature review, it has been observed that most of the studies on EDM have considered the emissions from energy and aerosols produced due to the breakdown of dielectric fluid²⁸. However, extensive research is needed on GHG emissions from electric power, EW, and dielectric fluid consumption, as a significant number of emissions are produced at the extraction of metals for electrodes and refining fossil fuels (kerosene oil) for dielectric fluid. Moreover, none of the studies have reported on the impact of characteristics of dielectric fluid on GHG emissions production. Therefore, this study investigates the impact of graphene nanoparticles in the dielectric fluid along with other machining variables (P_r and I_p) on the GHG emissions from EC, EW, and dielectric fluid evaporation. Besides this, the impact of different electrode materials such as aluminum, brass, and copper has also been examined to limit GHG emissions in the EDM process. Moreover, this study provides an in-depth discussion of the United Nations SDGs in relation to the response measures examined, covering aspects that have not been previously addressed.

Material and methods

This section covers the selection of materials used for the workpiece and electrodes, EDM variables and their respective ranges, and the machining process and response measurement. The process flow for the current study is provided in Fig. 1. The low-carbon austenitic steel SS316L has been selected as a workpiece material owing to its vast applications in the biomedical, defense, and aeronautical sectors²⁹. The elemental composition of selected workpiece material is provided in Table 1. The physical, electrical and thermal properties of the selected workpiece material have been provided in Table 2. A slab of SS316L alloy having dimensions of 170 × 90 × 8 mm³ has been obtained for the machining trials. Annealing treatment has been performed at 550 °C for 2 h, followed by furnace cooling to relieve the internal stresses and improve the material removal process. Moreover,

Parameters	Ranges/values
P_R (-)	0.5–1.5
I_p (A)	10–20
Graphene P_C (g/L)	0.5–1.5
Depth of cut (mm)	4
Flushing pressure (Kg/cm ²)	7
Flushing time (μ s)	4
Spark voltage (V)	8

Table 3. EDM variables and constant parameters for experimentation.

Characteristics	Details
Color	Greyish black
Particle thickness	2–10 nm
Particle diameter	2–10 μ m
Bulk density	~ 0.1 g/mL
True density	2.3 g/cm ³
Electrical conductivity	80 MS/m
Thermal conductivity	4000 W/m-K
Carbon content	> 99%
Specific surface area	20–40 m ² /g

Table 4. Characteristics of graphene nanoparticles.

Exp. No	EDM variables		
	P_R	I_p (A)	P_C (g/L)
1	0.5	10	0.5
2	0.5	15	1.0
3	0.5	20	1.5
4	1.0	10	1.0
5	1.0	15	1.5
6	1.0	20	0.5
7	1.5	10	1.5
8	1.5	15	0.5
9	1.5	20	1.0

Table 5. Variables settings for experimentation based on Taguchi L9 array.

the annealing process improves the electrical properties of steel, which allows for more efficient energy transfer during the EDM process. This can lead to higher MRR and efficient energy utilization. Three different electrode materials, including aluminum, brass, and copper, have been chosen to investigate sustainable alternatives for machining. Uniform-sized electrodes of 10 mm diameter and 600 mm length were extracted using a universal lathe machine. The physical, thermal and electrical characteristics of electrode materials are specified in Table 2.

To enhance the machining performance and sustainability of the process, EDM variables need to be optimized. Therefore, P_R , I_p and P_C in the dielectric fluid have been selected for optimization in this study. EDM variables and their selected ranges are presented in Table 3. Graphene nanoparticles mixed with kerosene oil are used as dielectric fluid. The properties of the graphene nanoparticles are provided in Table 4. The addition of graphene nanoparticles in the dielectric fluid significantly enhances the thermal and electrical conductivities of dielectric fluid, resulting in even dissipation of heat energy. An adequate quantity of graphene nanoparticles in the dielectric fluid enhances the spark discharge strength and maintains the optimal spark gap between the electrode and the workpiece, which helps remove workpiece material uniformly.

The experiment has been designed using the Taguchi L9 array based on selected EDM variables. The same design is repeated for each electrode material for the comparative analysis; hence, a total of 27 experimental trials has been performed. Settings of the EDM variables based on the Taguchi L9 array have been provided in Table 5. Machining performance has been assessed through EC, EW, and DC. Moreover, this study has also investigated the GHG emissions and direct costs incurred due to EC, EW, and dielectric fluid consumption. EC and its associated cost and GHG emissions have been calculated using Eqs. (1)–(4). EW and DC and their associated costs and GHG emissions are calculated using Eqs. (5)–(10).

$$EC = V \times I_p \times t_{efficient} \quad (1)$$

$$t_{efficient} = t_{total} \times \text{duty cycle} \quad (2)$$

$$ECC = EC \times UEC \quad (3)$$

$$ECE = EC \times CEF \quad (4)$$

$$EW = W_i - W_f \quad (5)$$

$$EWC = EW \times UMC \quad (6)$$

$$EWE = EW \times ME \quad (7)$$

$$DC = v_i - v_f \quad (8)$$

$$DCC = DC \times UDC \quad (9)$$

$$DCE = DC \times DE \quad (10)$$

V is the open voltage, and $t_{efficient}$ is the effective time when the sparking is produced during the experiment. t_{total} is the total machining time of an experimental trial. ECC is the EC cost, UEC is the unit energy cost, ECE is the GHG emissions from EC, and CEF is the GHG emissions per unit (kilowatt hour) of energy consumed. W_i and W_f are the initial and final weights of the electrode before and after the experimental trial. EWC is the EW cost, UMC is the unit material cost, EWE is the GHG emissions from EW, and ME is the GHG emissions per unit (kg) of material. v_i and v_f are the initial and final volumes of the dielectric fluid before and after the experimental trial. DCC is the DC cost, UDC is the unit dielectric fluid cost, DCE is the GHG emissions from DC, and DE is the GHG emissions per unit (liter) of dielectric fluid.

Results and discussion

In this study, the environmental footprints of the EDM process have been analyzed based on EC, EW and DC due to their significant contribution to GHG emissions, as illustrated in Fig. 2. However, the analysis of GHG emissions, material cost, and carbon cost are presented in China's scenario due to its significant contribution to global GHG emissions.

Analysis of energy consumption, GHG emissions, and associated costs

In EDM, EC is mainly driven by the EDM variables; therefore, it is necessary to optimize the EDM variables to limit and utilize energy efficiently. Mean effects analysis shows that the low P_R exhibits a lower time span per pulse for the energy supply; thus, EC is lower at 0.5 but increases successively when the P_R is raised to 1.5, as shown in Fig. 3. Similar behavior has been observed for all electrodes. I_p has been observed to be more sensitive to EC as its increase from 10 to 20 A EC rose from 0.515 to 0.653 kWh for the aluminum electrode. Brass and copper electrodes also exhibit nearly the same trends. A higher I_p aims to produce intense sparking to remove workpiece material; thus, more energy is consumed. A distinct behavior has been observed in the case of P_C as the increase in P_C from 0.5 to 1.5 g/L decreases EC for all electrode materials. A rise in the quantity of graphene nanoparticles significantly increases the conductivity of the dielectric fluid. This leads to an efficient supply of

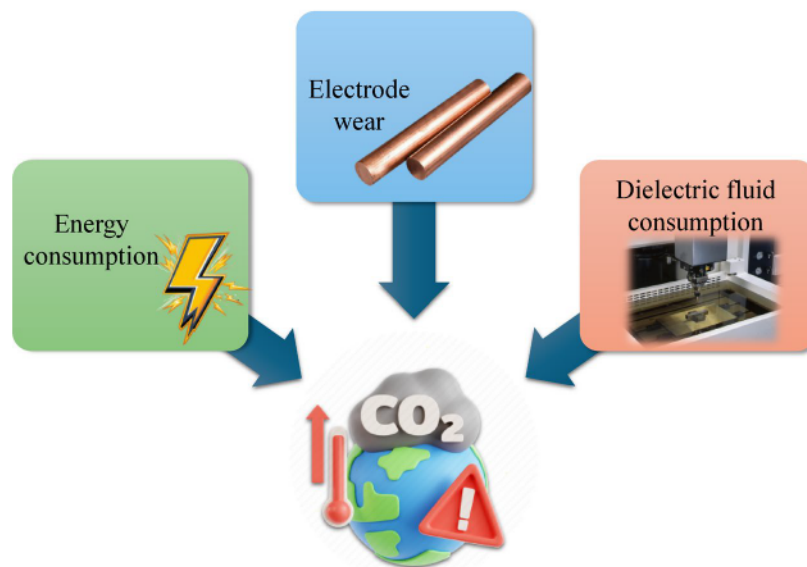


Fig. 2. Source of GHG emissions in EDM process.

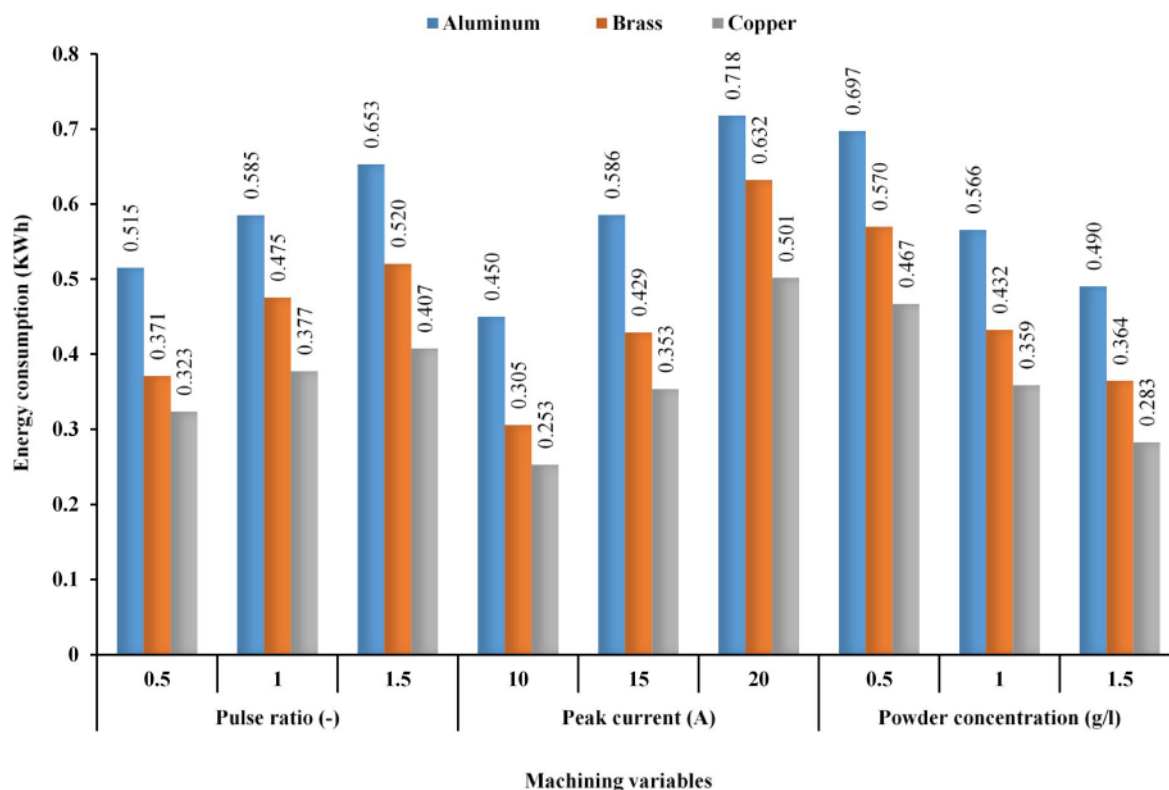


Fig. 3. Mean effects analysis of EDM variables for EC.

energy to the machining zone for the workpiece material removal, ultimately reducing the need for a higher amount of discharge energy; hence, EC decreases with higher P_c .

Analysis of electrode materials revealed that aluminum electrode consumed a relatively higher amount of energy, followed by brass, while copper yielded the lowest EC (Fig. 3). EC mainly relies on the electrical and thermal conductivities of the electrodes. In comparison with other electrode materials, brass has the lowest electrical and thermal conductivity. Low electrical conductivity means more energy is dissipated as heat due to resistance, and less spark energy is supplied to the machining zone for material removal. Moreover, brass also has low thermal conductivity and tends to retain heat, resulting in localized overheating (and an increase in electrical resistance); therefore, a higher amount of energy is consumed in the case of brass electrode. Copper, owing to its highest electrical conductivities, offers efficient and smooth current flow for the spark discharges and removes workpiece material effectively²⁹. Moreover, its higher thermal conductivity facilitates quick dissipation of heat and consumes less energy in resistive heating. Efficient heat dissipation allows optimal discharge conditions where most of the energy is utilized in material removal. On the other hand, aluminum has an intermediate electrical and thermal conductivity compared to copper and brass; still, its EC is the highest (0.718 kWh). This is mainly due to the low thermal stability and the low melting point of aluminum (as compared to brass), which makes it unable to withstand the thermal stresses of EDM without deforming or melting. A significant amount of energy is consumed in melting and wearing down the aluminum electrode material instead of eroding the workpiece material. The sparking intensity of all electrode materials and the amount of workpiece material removal at time 't' are illustrated in Fig. 4.

GHG emissions due to EC mainly rely on the source of electricity. In the case of China, the power sector mainly relies on thermal, solar, hydro, nuclear and wind power. Percentage contribution of different power sources and their respective carbon emissions are provided in Table 6. Based on the contributions and GHG emissions, the carbon emission factor has been computed as 0.6144 kgCO₂ eq./kWh for China's electricity. The mean effects of EDM variables on GHG emissions due to the utilization of electrical energy have nearly the same trends as discussed for EC. It has been observed that GHG emissions due to EC rose from 198.5 to 250.2 g CO₂ with an increase in P_r from 0.5 to 1.5, as shown in Fig. 5. This increase in GHG emissions is more significant in the case of the aluminum electrode than the brass electrode. An increase in I_p from 10 to 20 A also raises the GHG emissions (from EC) from 155.4 to 308.1 g CO₂ for the copper electrode. Subsequent GHG emissions have been observed in the case of brass electrode, while aluminum electrode yields significantly higher GHG emissions ranging from 276.3 to 441 g CO₂. GHG emissions from EC decrease from 186.7 to 173.6 g CO₂ with the increase in P_c from 0.5 to 1.5 g/L in the dielectric fluid while using copper electrode. Relatively higher GHG emissions have been observed for the brass electrode, followed by the aluminum electrode when P_c is increased.

While computing the machining cost due to EC, two types of costs are considered: one is the direct cost incurred due to the consumption of electricity, and the second one is the environmental taxes incurred due to the GHG emissions produced by the EC. Although the carbon cost is not significant as compared to the direct cost,

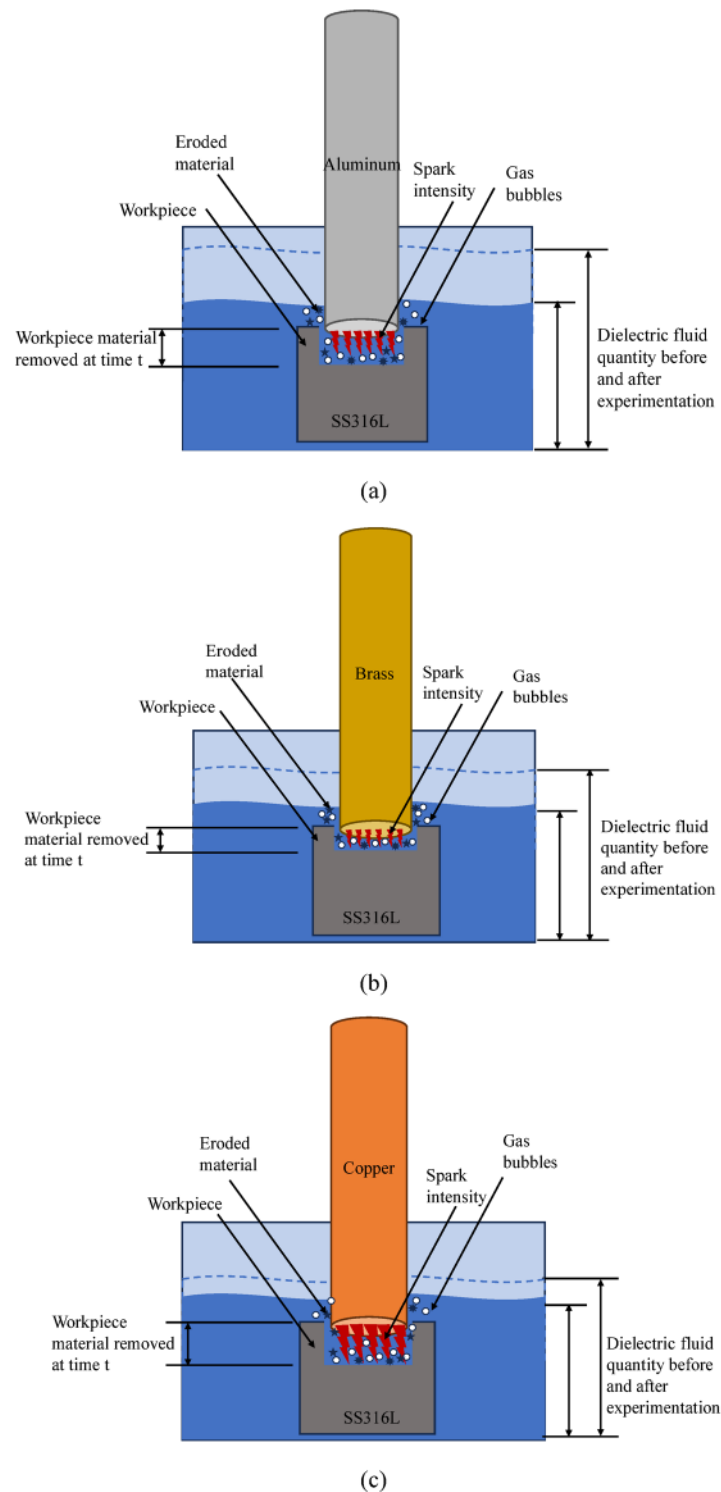


Fig. 4. The schematic illustration depicts the sparking intensity; amount of workpiece material removed at time t and volume of dielectric fluid consumed during the EDM process for (a) aluminum, (b) brass and (c) copper electrodes.

Source	Thermal power	Solar power	Hydropower	Nuclear power	Wind power
Carbon emission factor of China's electricity	0.9976	0.0142	0.0188	0.0122	0.01
2025 forecast percentage (%)	61	5.92	19	3.5	10.58

Table 6. Carbon emissions from different power sources in China³⁰.

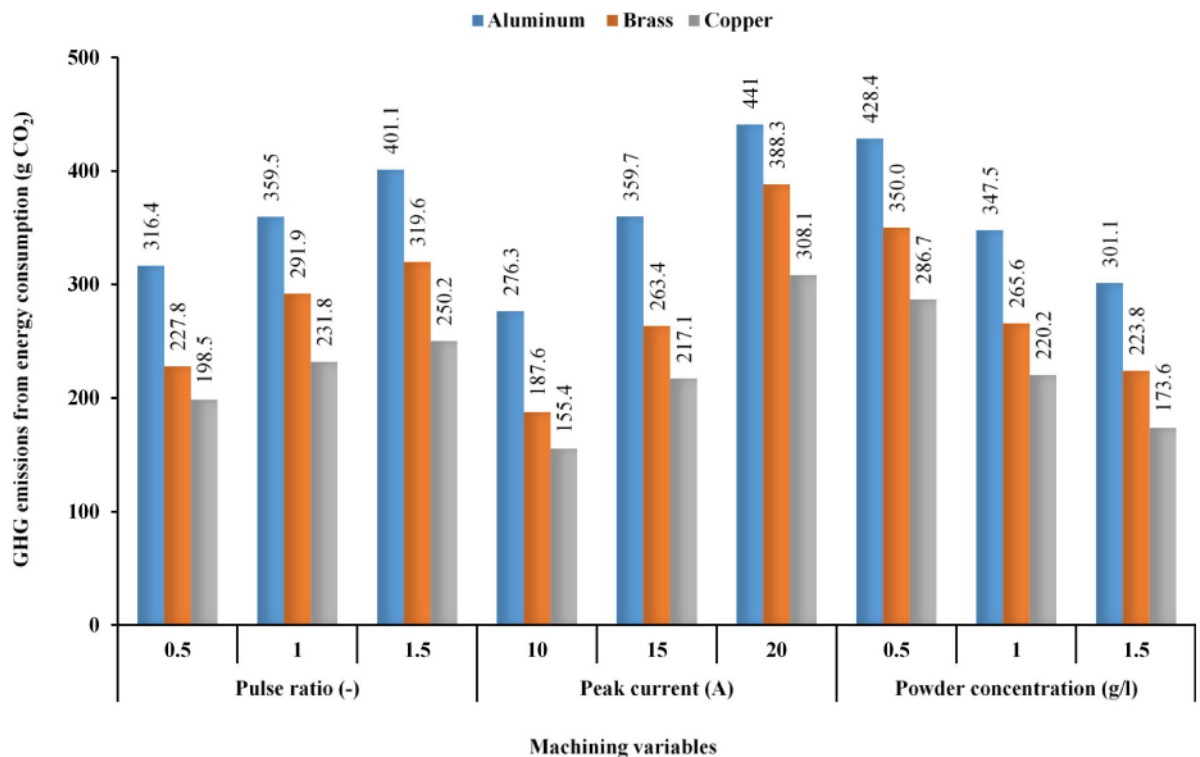


Fig. 5. Mean effects analysis of EDM variables for GHG emissions from EC.

it still needs to be considered to provide accurate costing methodologies to the manufacturing industry, where a significant amount of energy is consumed. Unit electricity cost of 0.64 RMB/kWh (commercial unit price) and unit carbon cost of 103.49 RMB/tonne CO₂ have been considered in this study. It has been observed that the energy cost rose from 0.207 to 0.261 RMB with an increase in PR from 0.5 to 1.5 while carbon cost increased from 0.0205 to 0.0259 RMB for copper electrode (Fig. 6). Brass electrodes offer subsequent higher energy and carbon costs, followed by aluminum electrode. With the increase in I_p , the energy cost rises significantly from 0.162 to 0.321 RMB, while carbon cost also has a relative hike from 0.0161 to 0.0319 RMB in the case of copper electrode. Aluminum and brass electrodes also have a similar pattern for the associated cost increment with respect to the I_p . An increase in P_c from 0.5 to 1.5 g/L reduces the energy cost from 0.299 RMB to 0.181 RMB and its associated carbon cost from 0.0297 to 0.0180 RMB for copper electrode. A similar trend has been observed for aluminum and brass electrodes.

Analysis of electrode wear, GHG emissions, and associated costs

During the material removal process, spark discharges not only eradicate the workpiece material but also remove some of the electrode material from its facing surface, which is regarded as EW. The worn surface of the electrode significantly influences the workpiece surface characteristics and dimensional accuracy; therefore, it is inevitable to consider EW as one of the key performance measures in the EDM process. Like other performance measures, EW is also influenced by the selected EDM variables. It has been analyzed that the increase in P_R from 0.5 to 1.5 expedited the EW (Fig. 7). A lower P_R (lower P_{ON} and higher P_{OFF}) provides less time for the spark discharges to deliver the energy, resulting in less removal of the workpiece and electrode material. Moreover, a longer P_{OFF} in a lower P_R provides more time for the electrode to cool, which prevents electrode facial surface from melting and evaporation and maintains its structural integrity. At a higher P_R , P_{ON} is higher and supplies more discharge energy to the machining zone, resulting in the melting of material from electrode surface. A shorter P_{OFF} at a low P_R remains insufficient for cooling, exacerbating thermal erosion. In addition, insufficient flushing of debris during a short P_{OFF} leads to localized wear spots on the electrode surface, as accumulated particles cause micro-cutting/erosion effects³¹. A rise in I_p from 10 to 20 A increases thermal and mechanical wear. At higher I_p , more discharge energy is supplied to the machining zone, which melts and evaporates the electrode material, resulting in increased wear and vice versa. Increased melting of electrode and workpiece material at higher I_p produce more debris, which may also cause abrasive and adhesive EW.

A distinct behavior for EW has been observed by the varying nano-powder. It has been analyzed that the increment of graphene nanoparticles in the dielectric fluid from 0.5 to 1.5 g/L reduces the EW to a significant extent. The increment of the graphene particles enhances the electrical conductivity of the dielectric fluid and allows the stable and efficient distribution of spark discharges. Moreover, the higher thermal conductivity of the graphene nanoparticles helps in the dissipation of heat energy effectively and prevents the temperature rise on the electrode surface, hence minimizing its thermal erosion. The comparative analysis of electrode materials depicts that copper electrodes offer the least wear during the EDM process (2.07 g), as shown in Fig. 7. This is

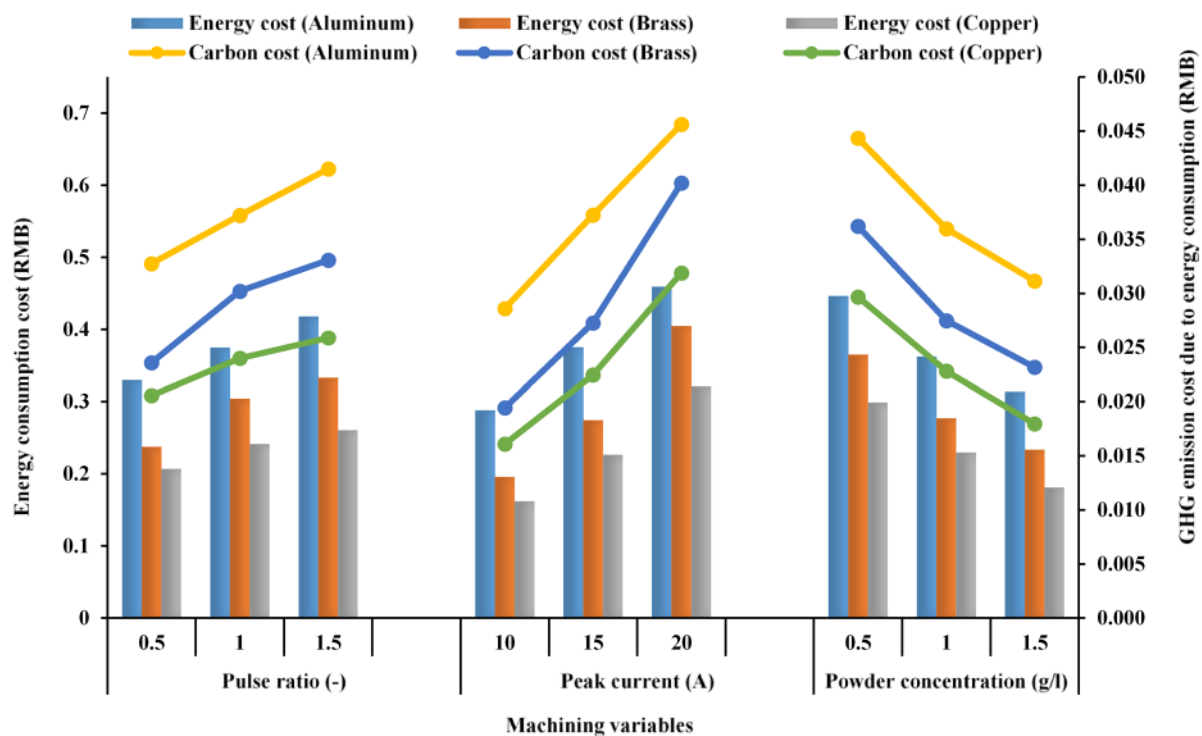


Fig. 6. Mean effects analysis of EDM variables for EC cost and its associated carbon cost.

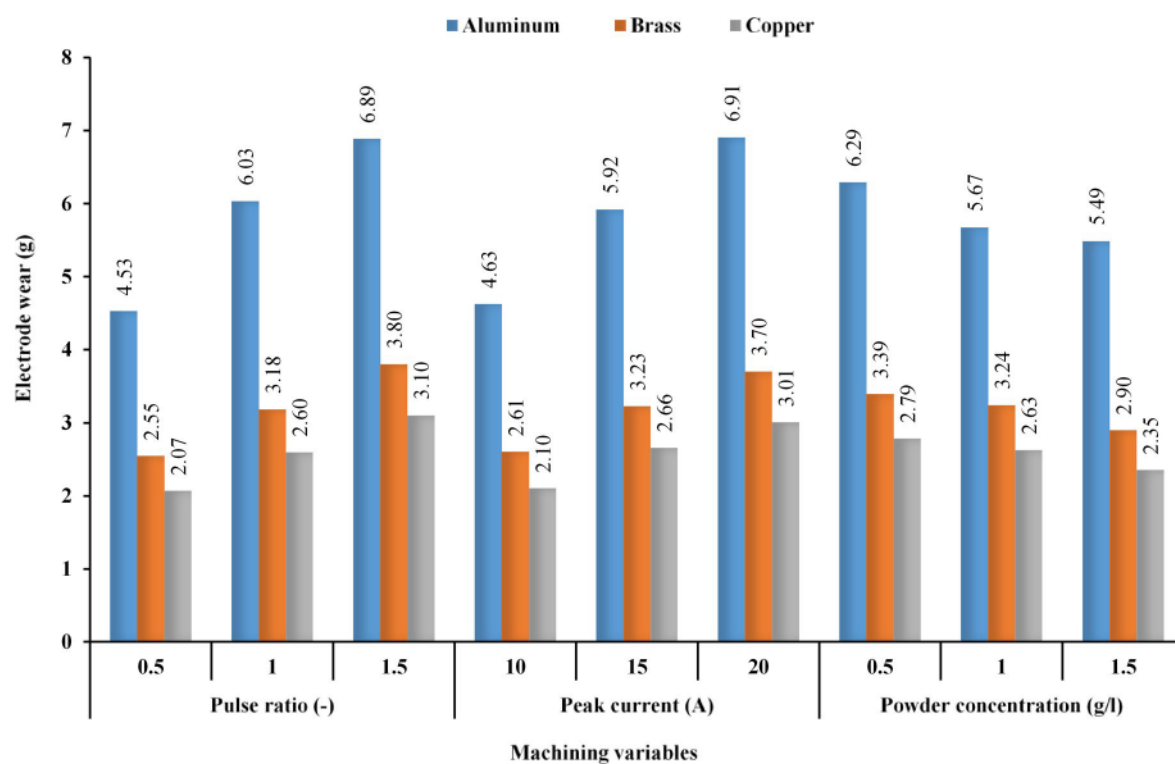


Fig. 7. Mean effects analysis of EDM variables for EW.

mainly due to its higher melting point (1083 °C), which makes copper more resistant to melting and erosion. On the other hand, brass has a lower melting temperature (940 °C) than copper; therefore, more erosion results when intense spark discharge is produced in the machining zone. Aluminum has the lowest melting temperature (660 °C), which indicates that it is highly susceptible to elevated temperatures during machining. For this reason,

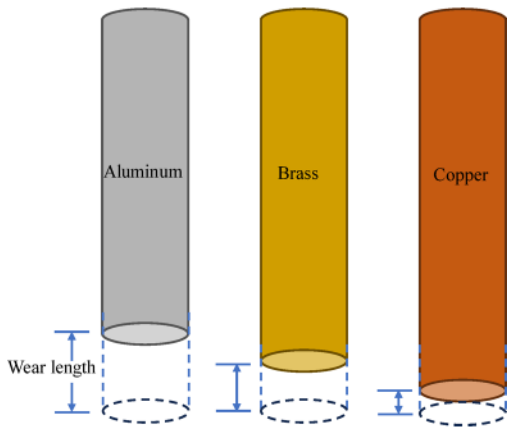


Fig. 8. Comparative analysis of EW through schematic illustration.

Material	GHG emissions
Aluminum electrode	11.4 kg CO ₂ eq./kg
Brass electrode	2.34 kg CO ₂ eq./kg
Copper electrode	3.02 kg CO ₂ eq./kg
Dielectric (Kerosene oil)	2.45 kg CO ₂ eq./L

Table 7. GHG emissions per unit of electrode material and dielectric fluid^{32,33}.

higher EW has been perceived in the case of aluminum electrode, followed by brass and copper. Comparative wear of aluminum, brass and copper electrodes after the machining trials has been illustrated schematically in Fig. 8.

The extraction and manufacturing process of metals and alloys produce significant amounts of emissions to the environment, which can't be ignored when utilizing these materials. In the EDM process, the electrode material is melted and vaporized, which is hard to recycle. Therefore, it is necessary to estimate the GHG emissions produced due to electrode erosion/consumption. Emissions produced due to the unit production of electrode materials are provided in Table 7. Mean effects analysis has been performed for the GHG emissions released due to EW. It has been observed that the increase in P_R from 0.5 to 1.5 aggravated the GHG emissions from 6.21 to 9.30 g CO₂ using copper electrode (Fig. 9). However, brass electrode offered relatively less GHG emissions than copper electrode, which is mainly due to the inclusion of a significant proportion (30%–40%) of zinc metal in the brass alloy, whose extraction and processing yields reduced emissions. In the case of aluminum electrode, GHG emissions are significantly higher than those of copper and brass electrodes, ranging from 51.63 to 78.49 g CO₂. Higher GHG emissions due to aluminum electrode are attributed to two prime reasons: first is the highest wear of aluminum electrode (due to its low melting point), and second is its excessive GHG emissions of 11.4 kg CO₂ eq. (per kg) which are nearly 4~5 times higher than copper and brass. Further, the increase in I_p from 10 to 20 A also exaggerated the GHG emission from 6.31 to 9.02 g CO₂ for copper electrode, which is attributed to an increase in its wear rate. Comparable trends are observed for brass and aluminum electrodes; however, its quantification is significantly higher for the aluminum electrode. Increase in the graphene nanoparticles in the dielectric fluid from 0.5 to 1.5 g/L aid in reducing the GHG emissions from 8.36 g CO₂ to 7.06 g CO₂ for the copper electrode. Increased proportion of nanoparticles enhanced the conductivity of the dielectric medium, which reduces the EW and its associated GHG emissions. Similarly, substantially higher GHG emissions are due to aluminum electrode erosion, ranging from 71.70 to 62.53 g CO₂.

EW not only contributes to GHG emissions but also encounters the tooling cost. This tooling cost mainly includes the direct cost of the EW/consumption, and the other one is its carbon cost. Unit material cost of electrodes and dielectric fluid are provided in Table 8. As EW accelerates with the increase in P_R (0.5–1.5), electrode consumption/wear cost of copper and its associated carbon cost also increases from 0.119 to 0.179 RMB and from 0.00064 to 0.00096 RMB, respectively (Fig. 10). The EW cost and carbon cost of brass are significantly lower than copper due to its reduced unit cost (36.08 RMB/kg). It has been analyzed that the unit cost of aluminum is the lowest (27.35 RMB/kg), and its EW cost is even higher than copper electrode (ranging from 0.124 to 0.188 RMB), which is primarily due to elevated EW with the increase in P_R . A rise in I_p from 10 to 20 A also increases the EW and its direct material and carbon costs of copper from 0.121 to 0.174 RMB and from 0.00065 to 0.00093 RMB, respectively. Aluminum also again has the highest EW cost, while brass has the least cost when varying the I_p . Increased nanoparticles' proportion in the dielectric fluid aids in reducing EW and its material cost and associated carbon cost. The EW cost of copper is reduced from 0.161 to 0.136 RMB, and its carbon cost also decreased from 0.00087 to 0.00073 RMB when graphene nanoparticles increased from 0.5 to 1.5 g/L. Similar behavior has been observed in the case of brass and aluminum electrodes.

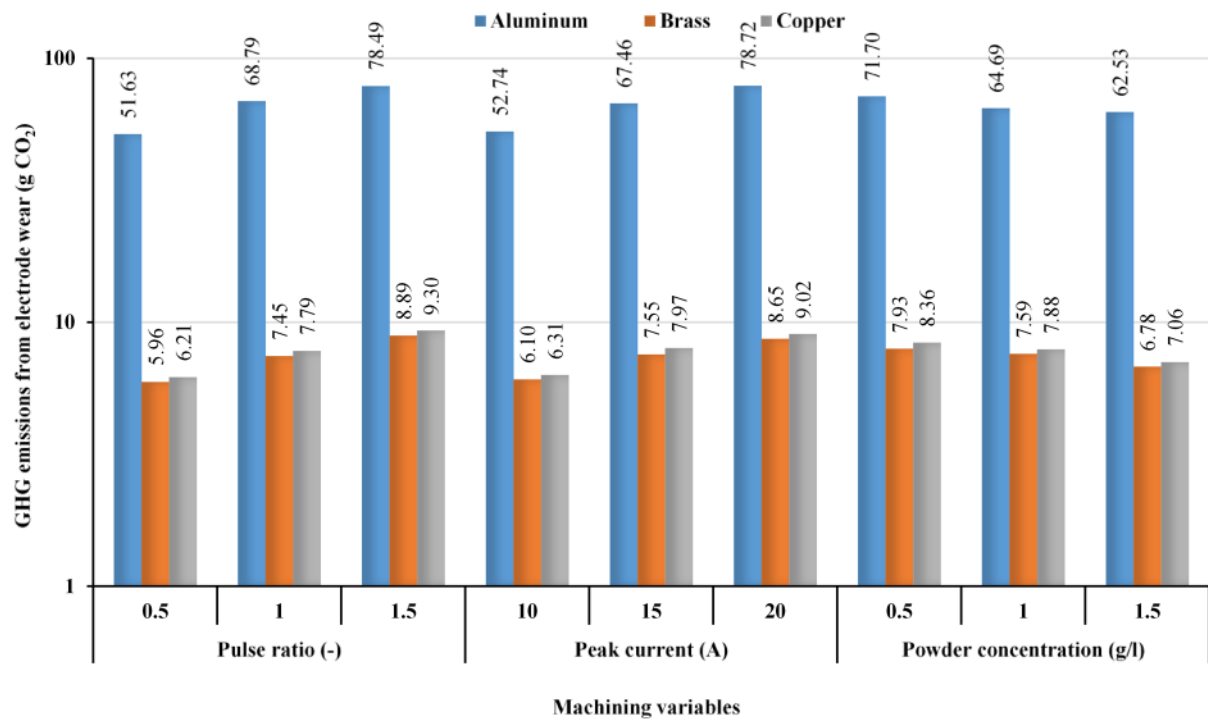


Fig. 9. Mean effects analysis of EDM variables for GHG emissions due to EW.

Materials	Cost
Aluminum	27.35 RMB/kg
Brass	36.08 RMB/kg
Copper	57.72 RMB/kg
Kerosene oil	3.69 RMB/L

Table 8. Unit cost of the electrode and dielectric fluid materials.

Analysis of dielectric fluid consumption, GHG emissions, and associated costs

In the EDM process, dielectric fluid is also consumed due to evaporation and decomposition, which not only produces GHG emissions but also incur costs. In this study, kerosene oil is used as a dielectric fluid with a boiling point of 300 °C, while temperature in the machining zone can rise to 12,000 °C. The temperature in the surrounding region also rises to 1000 °C, which can easily evaporate the dielectric fluid. Therefore, it is required to optimize the EDM variables to minimize dielectric fluid consumption to limit the machining cost. Mean effects analysis revealed that the increase in P_R from 0.5 to 1.5 significantly raised the consumption of dielectric fluid (Fig. 11). At a lower P_R (0.5), P_{ON} is almost half of the P_{OFF} which means that the heat generated due to spark discharges will remain only for a short duration, and there will be more duration (P_{OFF}) to cool down the dielectric fluid in the machining zone. At a P_R of 1.5, the P_{ON} is almost 50% higher than the P_{OFF} and spark discharges are produced for a longer time span. Therefore, the heat will remain in the machining zone for more time and accelerate the evaporation of dielectric fluid. Moreover, low P_{OFF} will provide an insufficient duration for cooling down the dielectric fluid and building up the heat in the machining zone, and this phenomenon also contributes to the higher evaporation of dielectric fluid. In the case of a rise in I_p from 10 to 20 A, the intensity of spark discharge increases significantly, generating tremendous heat in the machining zone. This elevated temperature leads to the increased evaporation rate of dielectric fluid. Mean effect analysis revealed that the increase in the proportion of graphene nanoparticles from 0.5 to 1.5 g/L positively influenced the dielectric fluid consumption. Graphene nanoparticles, owing to their higher thermal conductivity (4000 W/mK), increase the overall thermal conductivity of the dielectric fluid and allow more efficient heat dissipation. This effective heat dissipation helps lower the maximum temperature in the machining zone, potentially reducing the evaporation rate of the dielectric fluid. Moreover, the increase in the quantity of nanoparticles increases the viscosity of the dielectric fluid and limits the ability of the dielectric fluid to evaporate.

In the comparison of electrode materials, it has been shown that copper has the least dielectric fluid consumption, as shown in Fig. 11. Even though copper has the highest electrical conductivity of 58.5×10^6 s/m, it may evaporate more dielectric fluid from the machining zone. However, it has higher thermal conductivity along with higher conductivity of the dielectric fluid (due to highly conductive graphene nanoparticles), dissipating

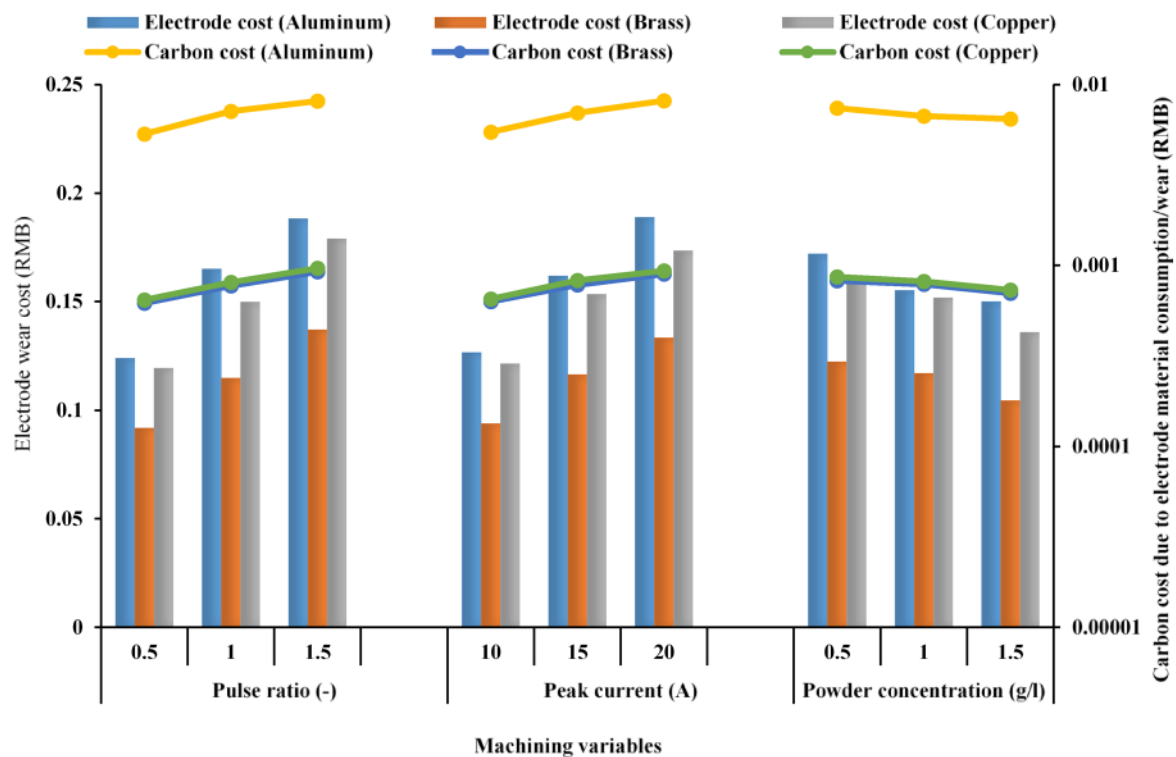


Fig. 10. Mean effects analysis of EDM variables for EW cost and its associated carbon cost.

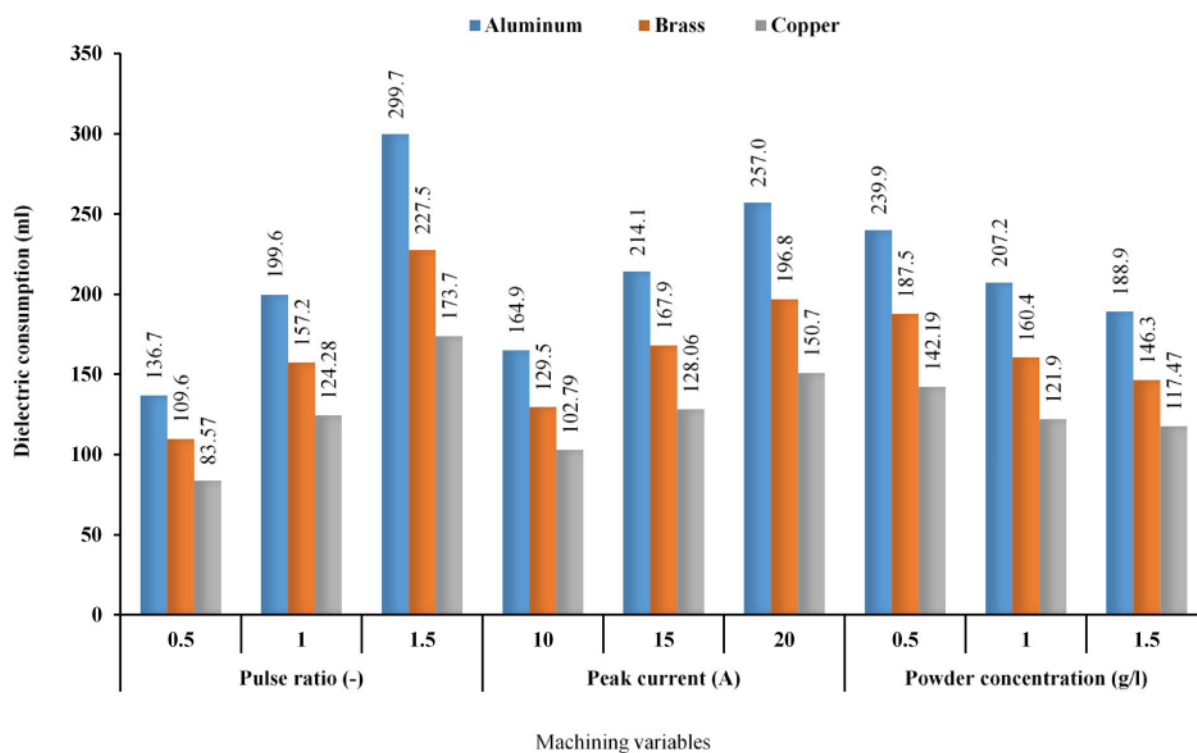


Fig. 11. Mean effects analysis of EDM variables for dielectric fluid consumption.

the heat energy in the machining zone more effectively, and it may not lead to as much localized heating in the dielectric fluid. Therefore, low dielectric fluid consumption has been observed in the case of copper electrode. Brass has the lowest thermal conductivity of $150 \text{ W m}^{-1} \text{ K}^{-1}$ among all electrodes, which means brass electrode may experience more localized heating, potentially leading to greater evaporation of the dielectric fluid in the immediate vicinity of the electrode, resulting in relatively higher dielectric fluid consumption. The analysis shows that aluminum has the highest dielectric fluid consumption among all electrodes, even though it has more reasonable electrical and thermal conductivities than the brass electrode. Dielectric fluid consumption is also associated with a higher wear rate of aluminum electrode. Rapid wear of aluminum electrode increases the spark gap between electrode and workpiece, resulting in more dielectric fluid in the machining zone and higher dielectric fluid consumption due to localized heating. The consumption of dielectric fluid before and after machining trials for aluminum, brass and copper electrodes are schematically illustrated in Fig. 4.

The consumption of dielectric fluid is also deemed a potential source of GHG emissions. The entire life cycle of kerosene oil, including extraction, refining and transportation, requires energy and produces GHG emissions. Higher consumption of dielectric fluid due to higher evaporation rates can exacerbate serious environmental issues. Therefore, the impact of selected EDM variables on the emissions from the dielectric fluid has been investigated. Mean effects analysis shows that GHG emissions from the DC significantly rose from 204.8 to 425.6 g CO₂ using a copper electrode with the increase in P_R from 0.5 to 1.5 (due to spark discharges for longer duration), as shown in Fig. 12. Comparative analysis of electrode material shows that aluminum electrode offers notably lower GHG emissions, ranging from 334.9 to 734.3 g CO₂ upon increasing P_R , while brass electrode has moderate GHG emissions. An increase in I_p from 10 to 20 A elevates the GHG emissions from 251.8 to 369.2 g CO₂ for copper electrode. A similar trend with lower value has been observed for aluminum followed by brass electrode. A rise in the graphene P_C in the dielectric fluid decreases the GHG emissions from 348.4 to 287.8 g CO₂ (for copper electrode) due to uniform heat distribution in the surroundings, reducing the chances of dielectric fluid evaporation. Aluminum and brass electrodes also have nearly the same pattern for the reduction in GHG emissions; however, brass offers the lowest GHG emissions.

Intense sparking in the cutting zone evaporates dielectric fluid to a significant extent, incurring the cost. The P_R increases the direct DC cost and its carbon cost from 0.308 to 0.641 RMB and from 0.021 to 0.044 RMB, respectively, for the copper electrode (Fig. 13). At the same time, aluminum electrode incurs a higher cost, followed by brass electrode, which has a slightly lower cost (than aluminum), with similar trends. In the case of a rise in I_p (using copper electrode), dielectric fluid consumption cost and its carbon cost increased from 0.379 to 0.556 RMB and 0.026 to 0.038 RMB, respectively. The application of aluminum electrode has the highest DC and carbon cost, whilst brass electrode encounters relatively lower costs. Increasing the graphene nanoparticles in the dielectric fluid reduces the DC cost due to the limited evaporation of kerosene oil. It has been observed that the increment in nanoparticle proportion resulted in decreasing direct dielectric fluid cost and its carbon cost from 0.525 to 0.434 RMB and from 0.036 to 0.030 RMB, respectively, for copper electrode. Similar trends

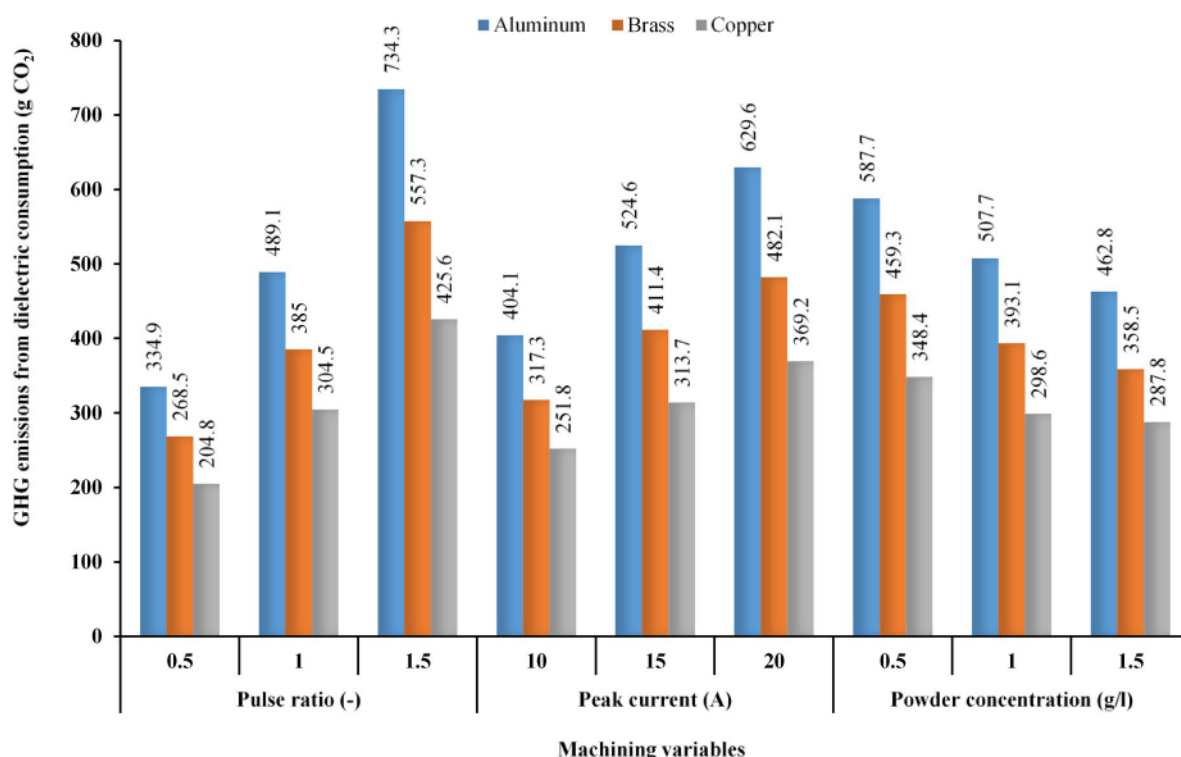


Fig. 12. Mean effects analysis of EDM variables on GHG emissions due to dielectric fluid consumption.

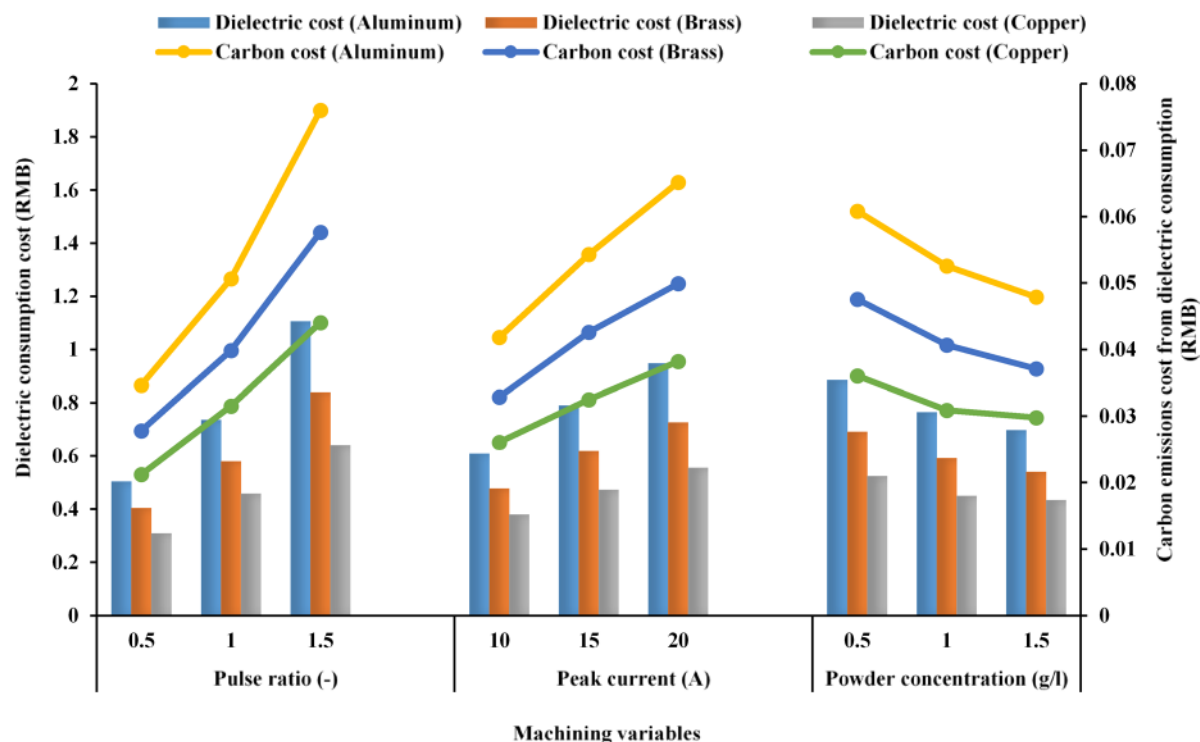


Fig. 13. Mean effects analysis of EDM variables for dielectric fluid consumption cost and its associated carbon cost.

have been observed for other electrodes; however, dielectric fluid cost and its carbon cost are relatively higher for aluminum electrode; however, brass electrode offers moderate costs.

Significant effect analysis

Among different EDM variables, I_p has been observed as most significant due to its major contribution of 52.73%, 59.33% and 57.76% to the EC for aluminum, brass and copper electrodes, respectively. However, the P_c has the second largest contribution to EC, while the P_r has the least contribution. Based on the experimental results, empirical relationships are developed between EDM variables and response measures. Using correlations and pattern identified, regression models are developed to predict scenarios other than the experimental ones. It has been observed that the regression models developed have p-values less than 0.05, which shows the significance of the models. Moreover, the adequacy of models has also been assessed based on the coefficient of determination R^2 , R^2 (adjusted) and R^2 (predicted), which depicts the accuracy of the prediction capabilities of the developed models. From Table 9, it can be analyzed that the adequacy measures include numeric values close to unity, which depicts the effectiveness and reliability of the developed models. The regression models for EC for aluminum, brass and copper electrodes have been provided as Eqs. (11)–(13), respectively.

Analysis of EW shows that the EDM variables such as P_r , I_p and P_c have p-values of less than 0.05, which is significant; however, their percentage contribution to the EW varies. From Table 9, it can be seen that P_r has the highest contribution of 43%, 48.28% and 47.46% for aluminum, brass and copper electrode, which shows that a slight variation in P_r can significantly affect the EW. However, I_p makes the second most significant contribution to EW for all electrode materials, followed by P_c . The P-value of regression models for EW revealed that the developed models are significant. It supports the significance of the independent variables in explaining the variability in the dependent variable. Moreover, the adequacy measures (R^2 , R^2 (adjusted) and R^2 (predicted)) are close to 1, which depicts a well-fitting regression model with meaningful relationships between variables. The developed models for EW for all electrode materials have been provided in Eqs. (14)–(16).

ANOVA has also been performed for dielectric fluid consumption for aluminum, brass and copper electrodes (Table 9). It has been observed that the p-values for all EDM variables are less than 0.05, which depicts their significance as illustrated in Table 9. However, percentage contribution has been assessed to differentiate among the variables, which shows that the P_r has the most significant contribution of 69.45%, 68.12% and 72.84% for aluminum, brass and copper electrodes. On the other hand, I_p has the subsequent most contribution to dielectric fluid consumption while P_c has the least contribution of 6.79%, 8.31% and 5.48% to the dielectric fluid consumption for aluminum, brass and copper electrodes, respectively. The p-values for the regression models are also less than 0.05, which depicts the significance of the independent variables in explaining the variability in the dependent variable. The analysis of the adequacy measures revealed that the values of the coefficient of determination are close to unity, which shows that the models are efficient enough to predict the dielectric fluid

ANOVA for EC						
Parameter	Aluminum electrode		Brass electrode		Copper electrode	
	P-value	%age contribution	P-value	%age contribution	P-value	%age contribution
Regression model	<0.0001		0.001		0.001	
P _R	0.002	13.93	0.016	12.42	0.034	6.62
I _P	<0.0001	52.73	0.001	59.33	<0.0001	57.76
P _C	<0.0001	31.56	0.004	23.46	0.001	31.69
Adequacy measures						
R ²	0.9822		0.9521		0.9607	
R ² (adjusted)	0.9716		0.9234		0.9371	
R ² (predicted)	0.9303		0.8211		0.8406	
ANOVA for EW						
Parameter	Aluminum electrode		Brass electrode		Copper electrode	
	P-value	%age contribution	P-value	%age contribution	P-value	%age contribution
Regression model	0.009		0.003		0.003	
P _R	0.008	43.00	0.002	48.28	0.003	47.46
I _P	0.009	40.24	0.004	36.86	0.005	36.34
P _C	0.205	5.00	0.074	7.47	0.071	8.30
Adequacy measures						
R ²	0.8824		0.9261		0.9210	
R ² (adjusted)	0.8119		0.8818		0.8735	
R ² (predicted)	0.5189		0.7146		0.6844	
ANOVA for DC						
Parameter	Aluminum electrode		Brass electrode		Copper electrode	
	P-value	%age contribution	P-value	%age contribution	P-value	%age contribution
Regression model	<0.0001		<0.0001		<0.0001	
P _R	<0.0001	69.45	<0.0001	68.12	<0.0001	72.84
I _P	<0.0001	22.14	<0.0001	22.20	<0.0001	20.58
P _C	0.006	6.79	0.003	8.31	0.004	5.48
Adequacy measures						
R ²	0.9839		0.9862		0.9890	
R ² (adjusted)	0.9742		0.9780		0.9824	
R ² (predicted)	0.9464		0.9601		0.9609	

Table 9. ANOVA and adequacy measures for regression models for EC, EW, and DC.

consumption values with great accuracy. The developed regression models for the prediction of dielectric fluid consumption are provided in Eqs. (17)–(19) for all electrode materials.

$$\text{EC (Aluminum)} = 0.2520 + 0.1377 \times P_R + 0.02680 \times I_P - 0.2073 \times P_C \quad (11)$$

$$\text{EC (Brass)} = 0.0214 + 0.1494 \times P_R + 0.03267 \times I_P - 0.2054 \times P_C \quad (12)$$

$$\text{EC (Copper)} = 0.0964 + 0.0841 \times P_R + 0.02485 \times I_P - 0.1841 \times P_C \quad (13)$$

$$\text{EW (Aluminum)} = 0.84 + 2.356 \times P_R + 0.2279 \times I_P - 0.804 \times P_C \quad (14)$$

$$\text{EW (Brass)} = 0.778 + 1.251 \times P_R + 0.1093 \times I_P - 0.492 \times P_C \quad (15)$$

$$\text{EW (Copper)} = 0.636 + 1.031 \times P_R + 0.0902 \times I_P - 0.431 \times P_C \quad (16)$$

$$\text{DC (Aluminum)} = -38.1 + 163.0 \times P_R + 9.20 \times I_P - 51.0 \times P_C \quad (17)$$

$$\text{DC (Brass)} = -12.9 + 117.86 \times P_R + 6.728 \times I_P - 41.16 \times P_C \quad (18)$$

$$\text{DC (Copper)} = -10.1 + 90.13 \times P_R + 4.791 \times I_P - 24.71 \times P_C \quad (19)$$

Overall GHG emissions and carbon cost assessment

Comprehensive analysis shows that energy, electrode material and dielectric fluid are the three major contributors to the GHG emissions produced during the EDM process. However, electrode materials have distinct behavior for GHG emission sources. From Table 10, it can be observed that aluminum has higher GHG emissions from EC, EW and dielectric fluid consumption. In contrast, brass has moderate GHG emissions from EC and dielectric fluid and offers the lowest GHG emissions in terms of EW. Copper electrode yields the lowest GHG emissions due to EC and dielectric fluid consumption, and its EW yields moderate GHG emissions. The overall

Electrode material	GHG emission sources		
	EC	EW	Dielectric fluid
Aluminum	High	High	High
Brass	Medium	Low	Medium
Copper	Low	Medium	Low

Table 10. Comparative analysis for GHG emissions contributors and electrode materials.

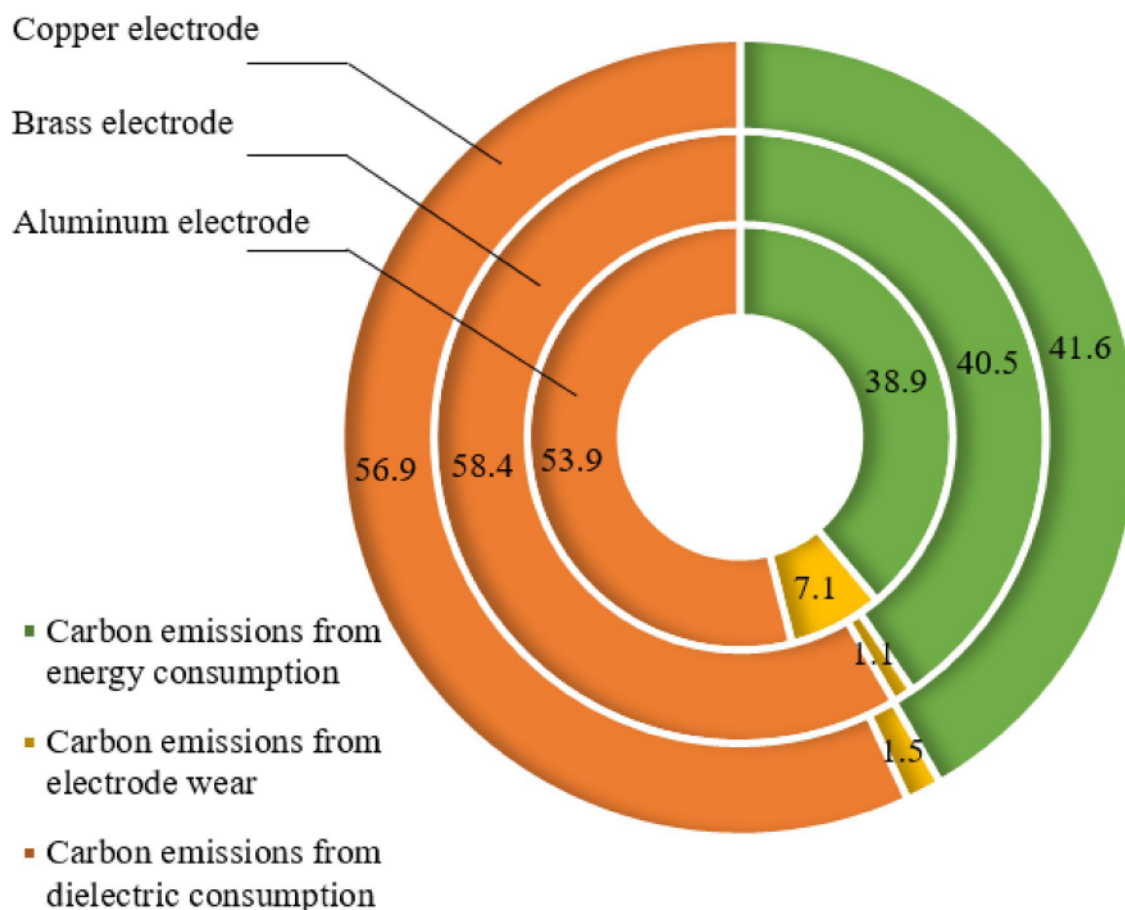
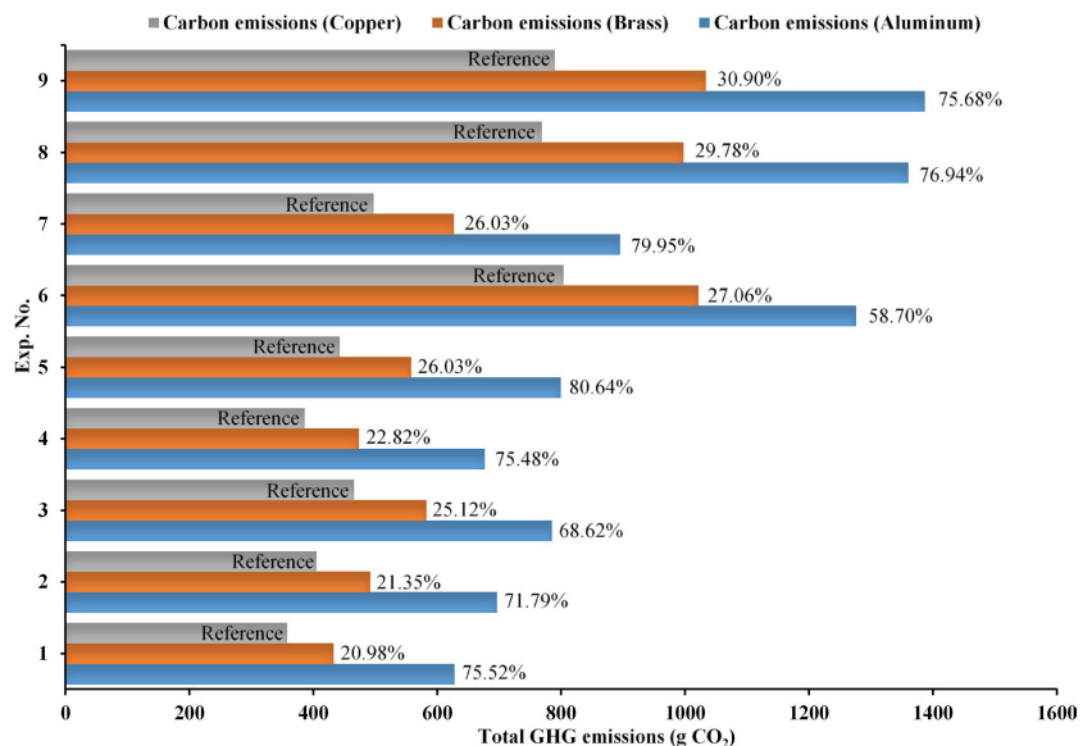


Fig. 14. Percentage contribution analysis for the GHG emission factors (EC, EW and dielectric fluid consumption).

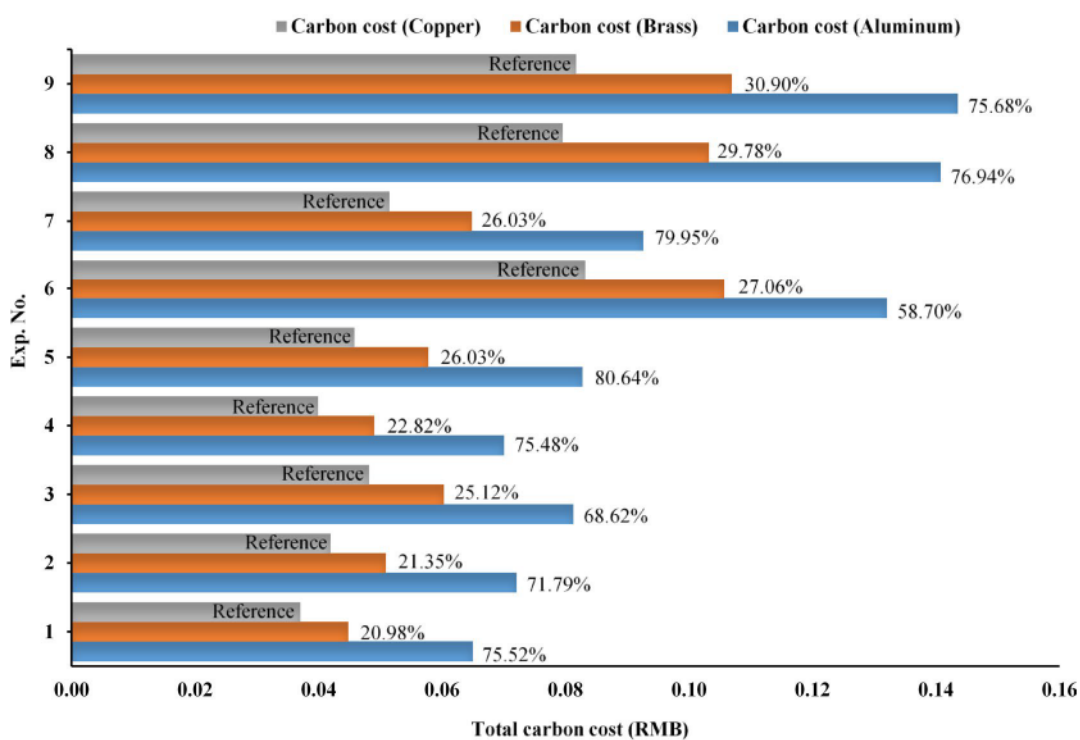
selection of the best electrode materials for a sustainable and environmentally friendly EDM process depends on the quantification of GHG emissions from all sources.

The quantification of GHG emissions is distinct for each source; for example, GHG emissions for dielectric fluid consumption are significantly higher than those of other sources (EC and EW). The percentage of GHG emissions from different sources for all electrode materials have been provided in Fig. 14. In the case of copper electrode, dielectric fluid consumption contributes almost 56.9%, while EC has a subsequent contribution of 41.6% to the overall GHG emissions. EW, on the other hand, has the lowest contribution of 1.5% to the overall GHG emissions as a very small amount of electrode material is consumed/eroded during the EDM process, specifically in the case of copper electrode (due to its higher melting point). The brass electrode has nearly similar behavior in terms of the contribution of different carbon sources. In the case of aluminum electrode, the percentage contribution of GHG emissions from EW is significantly higher (7.1%) than others. These emissions are mainly attributed to the higher EW rate of aluminum and significantly higher GHG emissions per kilogram of aluminum (due to its extraction and processing) than copper and brass materials.

Owing to the distinct behavior of electrodes, it is necessary to assess their cumulative effects for the selection of environmentally friendly alternatives for electrodes in the EDM process. The analysis shows that aluminum electrode has the highest GHG emissions and carbon cost than copper and brass, as shown in Fig. 15. A



(a)



(b)

Fig. 15. Percentage comparative analysis for electrode materials for (a) total GHG emissions and (b) total carbon cost.

comprehensive analysis has been conducted with reference to the copper electrode due to its better performance in terms of GHG emissions and carbon cost. It can be analyzed that the brass electrode yields higher GHG emissions and carbon cost ranging from 20.98 to 30.90% than the copper electrode. However, the usage of aluminum electrode yield significantly higher GHG emissions and carbon costs are 58.70 ~ 80.64% than copper. Comparative analysis shows that pure copper can be used as electrode material in order to limit GHG emissions and carbon cost from EC, EW and dielectric fluid consumption.

Sustainable development goals

This study evaluates key environmental and economic parameters of EDM applied to SS316L, focusing on EC, EW, dielectric fluid usage, greenhouse gas emissions, and their associated costs. These parameters have direct implications on several SDGs, indicating the broader relevance of this work beyond manufacturing efficiency.

SDG 7: Affordable and Clean Energy

EC in EDM significantly impacts SDG 7 (Affordable and Clean Energy). High energy use not only increases operational costs but also strains energy resources and contributes indirectly to carbon emissions³⁴. By analyzing and optimizing energy input, this research supports more efficient industrial energy use, promoting cleaner production methods that align with the global goal of energy sustainability.

SDG 9: industry, innovation, and infrastructure

The wear of electrodes directly relates to SDG 9 (Industry, Innovation, and Infrastructure)³⁵ and SDG 12 (Responsible Consumption and Production)^{36,37}. Electrode consumption reflects material usage efficiency; excessive wear leads to increased demand for raw materials and waste generation. Improving electrode longevity and minimizing wear helps reduce resource depletion and supports sustainable industrial practices by promoting material conservation and reducing manufacturing waste.

SDG 12: responsible consumption and production

Dielectric fluid usage further ties into SDG 12³⁸. Dielectrics in EDM often contain chemicals that can pose environmental risks if not managed responsibly. Optimizing DC reduces chemical waste and potential environmental contamination, aligning the manufacturing process with responsible resource management and waste minimization goals.

SDG 13: climate action

Importantly, the measurement of GHG emissions connects this research to SDG 13 (Climate Action)³⁹. EDM processes consume electricity which, depending on the energy source, contributes to carbon emissions. Quantifying and seeking to reduce these emissions through process optimization contributes to mitigating climate change impacts, reinforcing the necessity of integrating climate considerations in manufacturing innovations.

Finally, assessing the cost implications of these environmental parameters reinforces the economic dimension of sustainability embedded in SDGs 7, 9, and 12. Efficient energy use, reduced material consumption, and minimized environmental impact translate into lower operating costs and improved economic viability, encouraging wider adoption of sustainable manufacturing technologies. In summary, this investigation demonstrates that improving EDM process parameters not only enhances machining efficiency but also contributes meaningfully to the global agenda for sustainable industrial development as shown in Fig. 16. Such integration of environmental and economic considerations is essential to transition manufacturing sectors toward sustainability and fulfill the commitments outlined in the SDGs.

Conclusion

This study investigates the influence of selected EDM variables and electrode materials on machining performance measures such as EC, EW, dielectric fluid consumption, and associated GHG emissions, as well as direct and carbon costs. To enhance the machining performance, P_R , I_p and P_C are analyzed and optimized, along with the analysis of the impact of electrode materials (aluminum, brass and copper). The findings of the current research are presented as follows:

- Analysis of the main effects revealed that the lower levels of P_R (0.5) and I_p (10 A) while the higher level of graphene P_C (1.5 g/L) are adequate in reducing the EC, EW and DC and associated cost, GHG emissions and carbon cost.
- Copper electrode offered the least EC (0.253 kWh), GHG emissions (155.4 g CO₂) and direct energy cost (0.162 RMB) and carbon cost (0.016 RMB), due to higher electrical and thermal conductivity than brass and aluminum electrodes.
- EW analysis revealed that aluminum electrode resulted in the highest wear (6.89 g) and direct electrode cost (0.189 RMB) due to its lower melting temperature than copper and brass. However, its GHG emissions (78.72 g CO₂) and its associated carbon costs (0.008 RMB) are significantly higher than other electrodes which is due to its higher wear and emissions intensive extraction of aluminum metal.
- Aluminum electrode also causes the highest dielectric fluid consumption (299.7 ml), GHG emissions (734.3 g CO₂), direct dielectric cost (1.106 RMB) and carbon cost (0.075 RMB), due to its rapid erosion and higher debris generation necessitates faster flushing and increasing dielectric fluid consumption than copper and brass electrodes.
- Analysis of overall GHG emissions from the EDM process revealed that dielectric fluid consumption is the largest contributor to the emissions, followed by EC. Copper electrode, owing to its higher electrical and

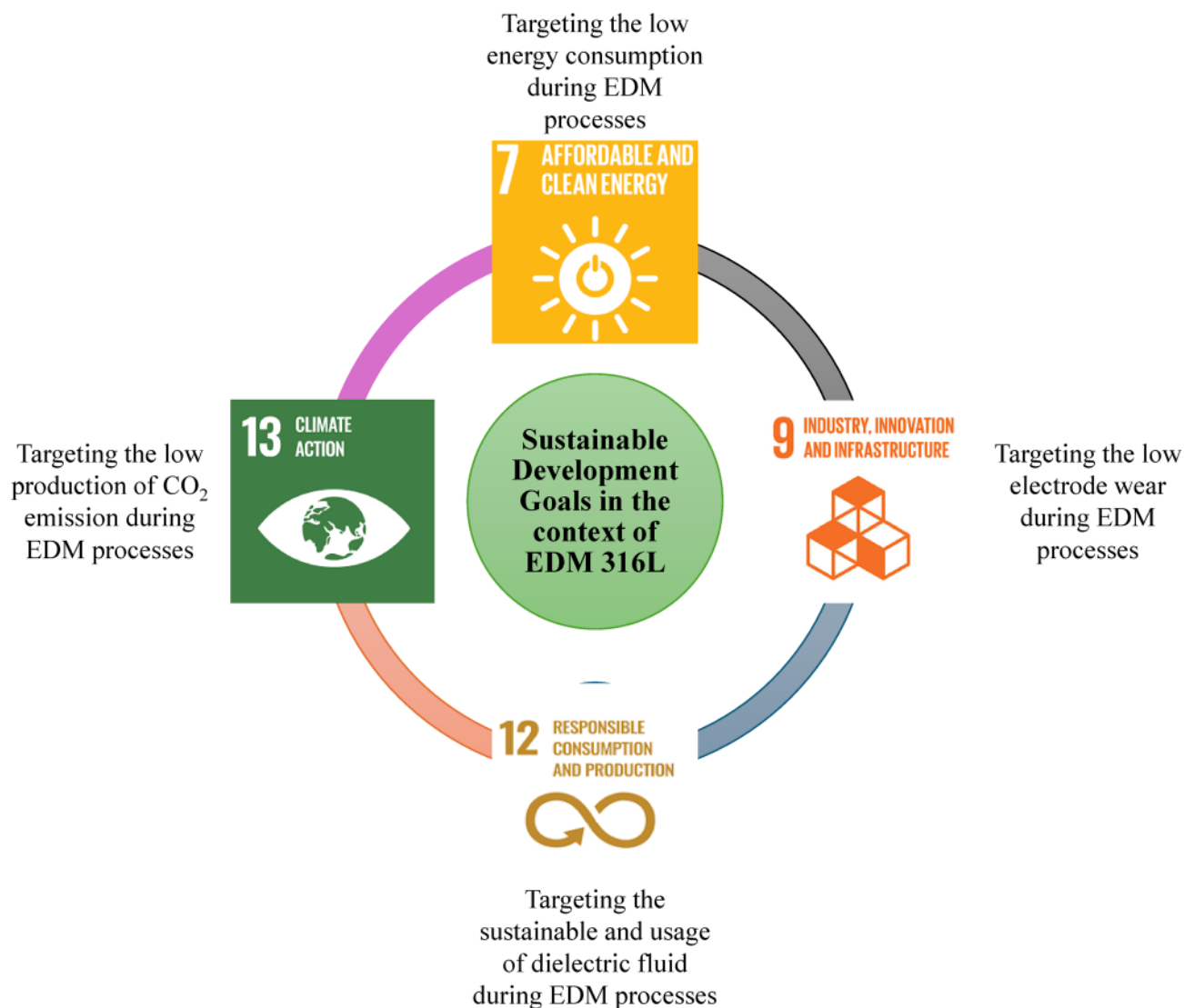


Fig. 16. SDGs for current study targeting low EC, less material consumption, favoring sustainable usage of dielectric, and reducing less CO₂ emissions.

thermal conductivity along with its higher melting point, result in the generation of minimal total GHG emissions and associated carbon cost during the EDM process. Aluminum and brass electrodes generate GHG emissions (and associated carbon cost) of 20.98% ~ 30.90% and 58.70% ~ 80.64%, respectively, then the copper electrode.

- Regression based ANOVA results revealed I_p as the topmost factor with the highest contribution to EC, while P_r remains the most significant machining variable for EW and dielectric fluid consumption.
- The SDGs relevant to this study—specifically SDGs 7, 9, 12, and 13—are closely connected to promoting sustainable production. These goals not only encourage minimizing raw material consumption but also inspire young researchers to focus on reducing CO₂ emissions during manufacturing processes while considering the broader impact of climate action on all living species. Furthermore, the use of sustainable and recyclable dielectric materials supports these objectives effectively during the EDM of SS316L.

Limitations/future research

In this study, the GHG emissions of dielectric fluid are considered at their production (extraction and refining) stage. The evaporation and combustion of kerosene oil during the EDM process also releases toxic aerosol emissions, including fine particulates matter from erosion of electrode and workpiece materials. Kerosene oil also contains volatile organic compounds (VOCs), which, upon evaporation, react with other pollutants in the atmosphere and produce ozone on the ground level. The emissions of kerosene oil due to its combustion and evaporation at the machining phase are not considered in this study.

Data availability

The data relating to experimental findings is already reported within the paper, and it can also be available from the corresponding author upon a reasonable request.

Received: 28 June 2025; Accepted: 13 October 2025

Published online: 18 November 2025

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Author contributions

Conceptualization, M.A. Ali.; Methodology, M.A. Ali, and M.H. Raza.; Data curation, S. Ehsan.; Software, M.A. Ali, and M.H. Raza.; Validation, M.A. Ali and M.H. Raza.; Visualization, M.A. Ali, M. Sana, and M.U. Farooq.; Formal analysis, M.A. Ali, M.H. Raza and S. Ehsan.; Investigation, M.A. Ali, M. Sana, and S. Ehsan.; Writing—original draft preparation, M.A. Ali, and M.H. Raza.; Writing—review and editing, M.A. Ali, M.H. Raza, M. Sana, M. Jawad, M.U. Farooq, and A.A. Adediran; Project administration; M.A. Ali. Resources; S. Ehsan. Funding acquisition, S. Ehsan and A.A. Adediran. All authors have read and agreed to the published version of the manuscript.

Funding

Authors do not receive any direct funding to cover the article processing charges.

Declarations

Competing interests

The authors declare no competing interests.

Consent for publication

All authors agreed upon the current version of the submission for publication.

Additional information

Correspondence and requests for materials should be addressed to M.A.A. or A.A.A.

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