

Comparison of Sustainability Index Single Wall Carbon Nano Tubes (SWCNT) Powder Mixed Electric Discharge Machining (PMEDM) With Rotary Tool using Various Non-Edible Oils as a Dielectric Fluid

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Abstract

The present study reveals the sustainability index for powder mixed electrical discharge machining with rotary tools waste vegetable oil (WVO), Jatropha Curcas oil (JCO), Kusum oil and castor oil as a dielectric fluid. Result shows that all the four non-edible oils make the process more sustainable as compared to hydro carbon-based oil. Lastly, the result reveals that Castor oil, WVO, JCO & Kusum oil shows lower sustainability index values (SI) 1.93, 6.27%, 1.96% and 2.38% respectively as compared to conventional hydro carbon based EDM oil and hence making the process more efficient along with cost, safe for environment and good for user/operator health.

Keywords: Non-edible oils, MRR, Sustainability Index (SI), EDM oil.

Abbreviations

SWCNT:	Single Wall Carbon Nano-Tubes
WVO:	Waste Vegetable Oil
JCO:	Jatropha Curcas Oil
I _p :	Peak current
T _{on} :	Time for Pulse ON
T _{off} :	Time for Pulse OFF
P _c :	Powder particles concentration
TR:	Rotation of tool
MRR:	Rate of Material Removal
PMEDM:	Powder Mixed Electrical Discharge Machining
SI:	Sustainability Index

INTRODUCTION

Over recent decades, electrical discharge machining (EDM) has come-up as a reliable unconventional method for processing the materials which are hard-to-machine. Its precision in creating intricate shapes has made it indispensable in fields such as biomedical devices, automotive manufacturing, mold and die production, and aerospace components [1]. EDM operates as a non-contact thermal process where material is eroded through repeated sparks generated between electrodes amid dielectric breakdown. These sparks, reaching temperatures of 8000–12000 K, form a plasma channel in the working gap that melts and vaporizes workpiece material [2, 3]. Though EDM offers low material removal rates (MRR), it remains popular for superalloys, composites, and ceramics, with efficiency gains achieved by optimizing input parameters [4]. Researchers have enhanced basic EDM setups through innovations like specialized tool electrodes [5], advanced pulse generators [6], ultrasonic

vibration of tools, workpieces, or dielectrics [7-9], tool or workpiece rotation [10,11], and dry or near-dry machining [12,13]. Among these, micro/nano powder-mixed EDM (PMEDM) stands out for delivering superior performance. Adding fine powder particles refines the electric field distribution in the discharge zone [14]. In 1981, early work showed that mixing 4 g/l graphite powder into the dielectric boosted MRR and cut tool wear rate (TWR) when machining mild steel [15]. Smaller particles yielded smoother surfaces and thicker recast layers as reported by Fong and Chen [16]. Kansal et al. [17] found that machining with graphite PMEDM process provide better MRR, TWR, and surface roughness (SR). Peças and Henriques investigated that improved crater dimensions, recast layer thickness (RLT) and surface roughness by using silicon PMEDM process [18]. Prabhu and Vinayagam [19] during the machining on Inconel 825 achieved finer finishes, improved morphology, and fewer microcracks with multi-walled carbon nanotubes (MWCNT). Mai et al. [20] found that 66% shorter machining times and 0.09 μm SR improvement with carbon nanotubes (CNT) PMEDM process. Izman et al. [21] and Sari et al. [22], and Mohal et al. [23] observed SR, RLT, MRR, and energy wear ratio (EWR) better while machining on alloys like Ti6Al4V, AISI-H13, and Al-10%SiCp respectively. Baseri and Sadeghian [24] found that better MRR and SR and TWR using TiO₂ PMEDM technique. Bajaj et al. [25] highlighted SR reductions, MRR increases, and better topography using MWCNT PMEDM with tool rotation process. In manufacturing industries, particularly EDM as the fourth most-used process after grinding, milling, and turning, contributes heavily to pollution [26]. PMEDM is highly effective with hard materials but presents sustainability concerns, such as dielectric waste from non-recyclable powders, blocked filters, and difficulties with disposal [27-29]. Sustainable manufacturing provides better energy efficiency, operator safety and health, cost savings, and waste minimization [30-32]. In the PMEDM process, significant obstacles to sustainable manufacturing include the blending of nano powder particles and the creation of debris during machining, which is unavoidable. The sustainability issues associated with the PMEDM process can only be somewhat alleviated by utilizing cost-effective, eco-friendly, and biodegradable dielectric fluids. It has been noted that non-edible and waste vegetable oils serve as viable alternatives to hydrocarbon oil, thereby improving the sustainability aspects of the EDM process [33-35]. Mali et al. [36] reported 32% MRR gains with WVO and 8% EWR reductions with blended used vegetable oil as compared to hydrocarbon oil. Palm oil biodiesel increased MRR by 38% and reduced machining cost as compared to machining with kerosene [37]. GG Reddy et al. [38] found that sunflower oil's improved MRR, operator health and environmental safety but also higher TWR and SR. S. Das et al. [39] investigated that machining time, SR and MRR improved significantly by 50–65%, 17% & 22% respectively with neem oil than kerosene. Bajaj et al. [40] achieved 57% MRR and 55% SR improvements by using Kusum oil as dielectric fluid along MWCNT process with tool rotation. Bajaj et al. [41] observed that by using Jatropha Curcas Oil (JCO) as dielectric with MWCNT powder and tool rotation improved the MRR by, SR by 50%, sustainability index by 9.92% better morphology and safety in relation to EDM oil [41]. Machining by WVO's as dielectric fluid provided better the machining performance and sustainability as compared to conventional EDM reported by Bajaj R. et al. [42]. Singla et al. [43] investigated that the PMEDM process with non-edible oils improved the material removal rate (MRR), surface roughness (SR), microhardness, corrosion resistance and biocompatibility for medical implants. Figure 1 indicates the various significant research done in the area of PMEDM/EDM techniques using hydrocarbon based/edible/non-edible oils as a dielectric fluid.

Experimental setup of rotary SWCNT-mixed PMEDM using castor oil dielectric for machining Inconel 625 figure 1. Table 1 shows the properties of various dielectric fluids (edible and non-edible). Inconel 625 and pure copper electrode of 10 mm diameter, selected as workpiece and tool material respectively. while key PMEDM performance factors included peak current, pulse ON

time, pulse OFF time, powder particles concentration, and rotary tool with their range selected by pilot test shown in table 2. Tool rotation speed was regulated via an Arduino controller, achieving up to 2500 rpm maximum. To minimize powder consumption and experimental costs, a compact acrylic tank (30×22×13 cm) contained the process, while pre-sonicated SWCNT-mixed non-edible (highly viscous) oils served as the dielectric fluid. A gear pump ensured proper circulation of the highly viscous non-edible at a consistent flow rate of 3.5 L/min throughout testing.

Table 1: Thermo-physical properties of various dielectric fluids [44]

Type		Viscosity (cm ² /S)	Thermal Conductivity (W/m.K)	Flash Flash Point (°C)	Density (gm/cm ³)	Specific Heat (kJ/KgK)
Edible Oil	Non-Edible Oil					
	Kerosene	1.219	0.128	38	0.802	2.01
	Hydrocarbon Oil (35°C)	0.25	0.14	101	0.81	2.5
	EDM Oil (40°C)	4	0.134	110	0.824	2.03
	Waste Vegetable Oil (35°C)	0.402	0.22	225	0.924	1.67
Sunflower Oil		0.085	0.159	250	0.92	2.24
Peanut Oil		0.11	0.144	283	0.914	2.05
	Neem Oil	4.3	0.15	214	0.868	1.962
	Kusum Oil (40°C)	40	0.168	204	0.862	1.96
	Jatropha curcas oil (40°C)	35.8	0.174	290	0.904	2.76
Canola Oil (40°C)		5.8	0.157	330	0.92	1.910
Coconut Oil		55	0.321	295	0.91	1.6
Palm Oil (27°C)		4.57	0.147	148	0.875	2.03
	Pongamia Pinnata (35°C)	40.2	0.22	225	0.924	NA

	Blended Used VO (35°C)	31.7	0.11	234	0.790	NA
	Castor Oil	15.25	0.180	145	0.955	1.97

Table 2: Input process variables and their ranges

Variable	Symbol	Level		
		Low (-1)	Medium (0)	High (+1)
Peak Current (A)	I_p	3	5	7
Time for Pulse ON (μs)	T_{on}	100	150	200
Time for Pulse OFF (μs)	T_{off}	40	70	100
Powder Particle	P_c	0.15	0.3	0.45
Concentration (g/l)				
Tool Rotation (RPM)	TR	400	600	800

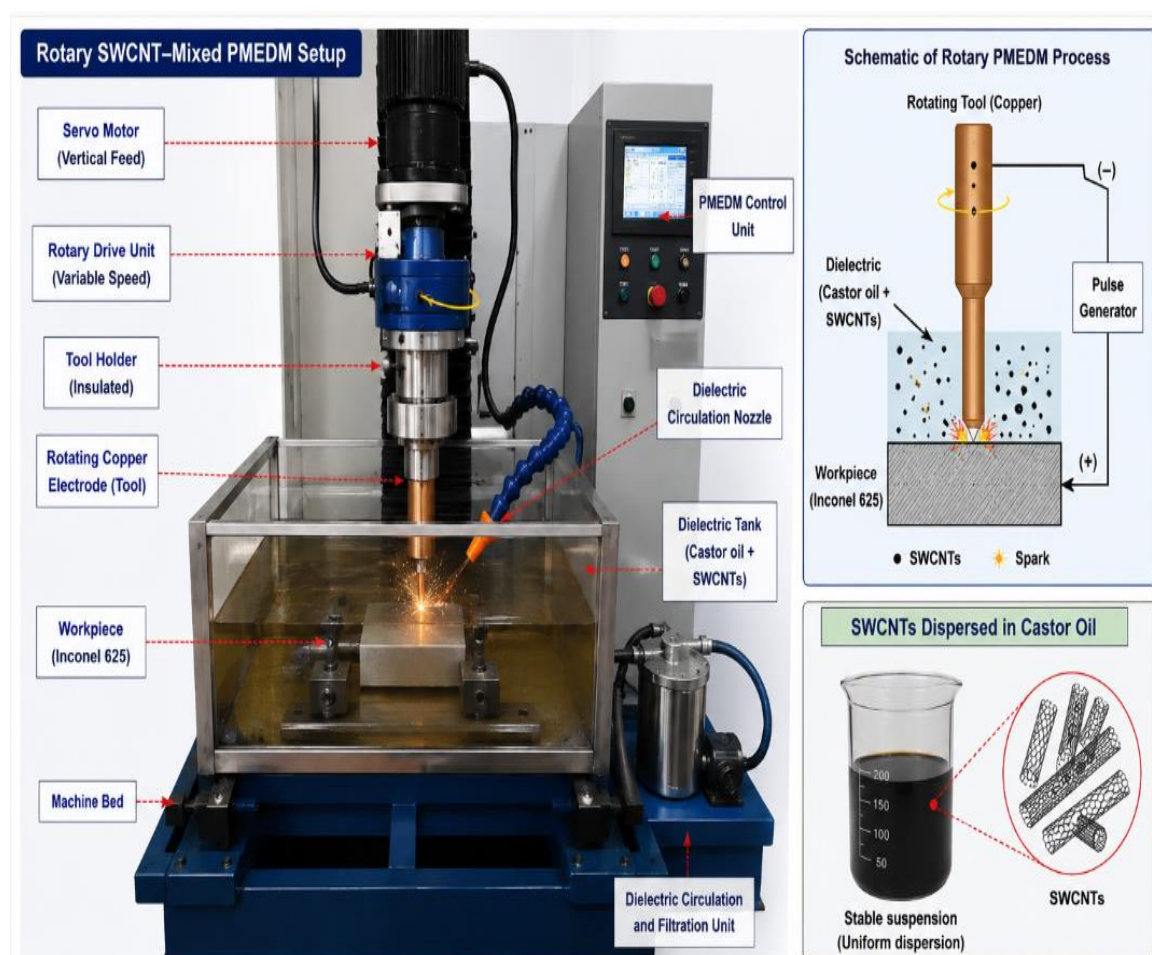


Figure 1: Experimental setup of rotary SWCNT-mixed PMEDM using castor oil dielectric for machining Inconel 625 [45]

Table 3 compared the cost effectiveness & thermal and physical properties of the non-edible oils (Castor Oil, JCO, Kusum oil) with EDM oil.

Table 3: Cost wise effectiveness and Thermal & physical properties of WVO, JCO, Kusum oil and EDM oil

Attributes	EDM Oil	JCO	Kusum Oil	WVO	Castor Oil
Price (₹)	91	41	60	0	71
Viscosity at (40°C)	4	35.8	40	9.55	15.25
Density (gm/ml)	0.824	0.904	0.862	0.893	0.955
Specific Heat (kJ/Kg K)	2.03	2.76	1.96	1.96	1.97
Thermal Conductivity (W/m K)	0.134	0.174	0.168	0.2	0.180
Dielectric Constant (27°C)	2.135	3.6	1.9	2.86	4.7
Breakdown Voltage (kV)	45	10	60	30	24.04
Flash Point (°C)	110	290	204	180	145
Biodegradability	Low	High	High	High	High

All tests maintained a consistent 150µm depth of cut, generating an electric field of 10^5 – 10^7 V/m when applying 80–320 V across electrodes. The powder particles mixed dielectric modifies the fluid's thermo-physical properties, expanding the spark gap to 50–150µm [46], which produces shallower craters on the machined surface and improves overall surface finish quality. To ensure process stability, freshly prepared dielectric fluid—ultrasonically treated—was used for each experimental run listed in Table 2. Material removal rate (MRR) determined by measuring volumetric material loss using the following calculation:

$$MRR = \frac{W_i - W_f}{\rho * t} * 1000 \quad \dots\dots\dots(i)$$

Result & Discussions

On the basis of the input parameters of all three non-edible oils (WVO, JCO, Kusum oil) in table 4 the optimum values of MRR (mm³/min) predicted as well as experimental shown in figure 2.

Table 4: Optimum values of MRR with their input parameters for all three non-edible oils

Parameters	WVO	JCO	Kusum Oil	Castor Oil
I _p (A)	7	7	7	7
T _{on} (µs)	175	166	159	174.6
T _{off} (µs)	40	38	46	40
P _c (gm/l)	0.313	0.315	0.309	0.313
TR (rpm)	590	615	720	590.8

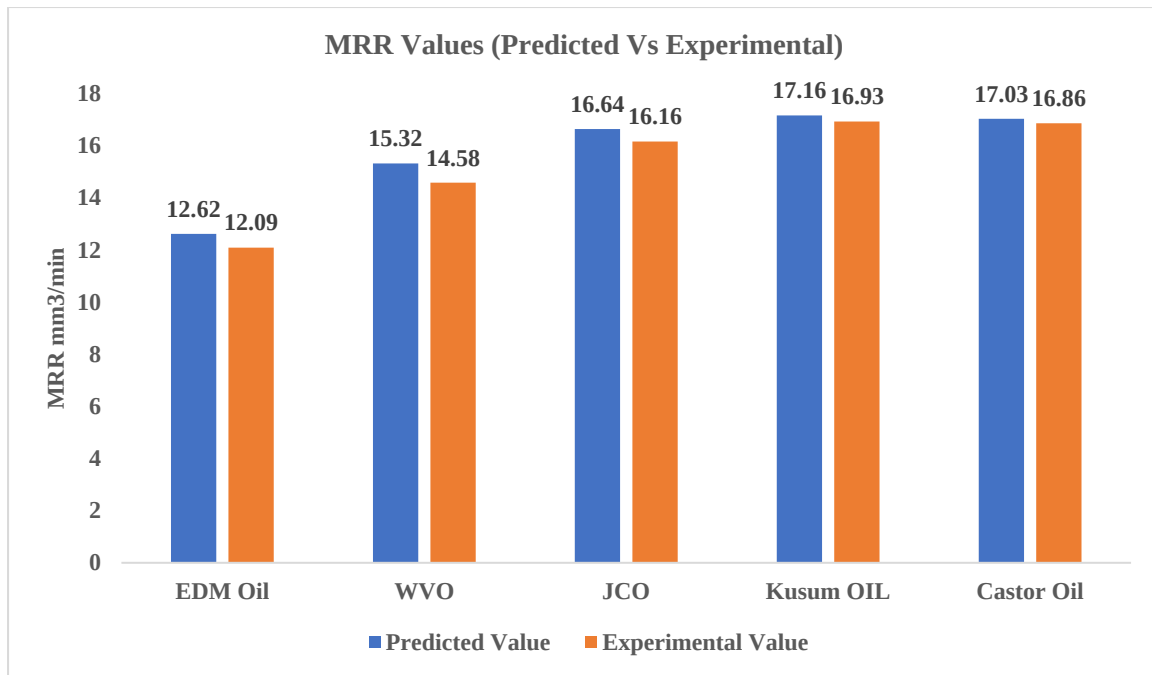


Figure 2: Comparison of Predicted and Experimental Values of MRR for all three non-edible oils

Sustainability Assessment

Manufacturing sustainability involves reducing costs, energy use, and negative environmental/operator health impacts while upholding product quality through reuse, reduce, and recycle principles [46-47].

Energy Consumption based Sustainability Index (SI_{EC}):

It calculated in terms of rupees (₹) by the following equation

$$SI_{EC} = E_c \times C_e \quad \dots\dots\dots(ii)$$

Where: E_c = Energy consumed during machining by EDM machine in kWhr;

C_e = Cost of electricity consumed during machining in ₹/kWhr

Sustainability Index based on Dielectric Fluid Consumption (SI_{DC}):

$$SI_{DC} = \frac{C_{DFPL} \times V_{DF} \times T_m}{T_{DFLC}} \quad \dots\dots\dots(iii)$$

Where: C_{DFPL} = Cost of dielectric fluid per liter in ₹

V_{DF} = Volume of dielectric fluid used for per experiment

T_m = Machining time in minutes

T_{DFLC} = Dielectric fluid life cycle

Sustainability Index based on Operator's Health and Environmental Safety (SI_{OE}):

$$SI_{OE} = (1 + C_p) \times \alpha \times T_m \quad \dots\dots\dots(iv)$$

Where: C_p = Penalty constant, ratio of assigned values to maximum values of parameters

α = Unit value in ₹/hr, which is constant.

The sustainability index for PMEDM assesses environmental safety and societal impact—considering factors like aerosol/toxic fume emissions and operator skin health risks—via a qualitative scoring system (Table 5) where 0 indicates risk free, 1 very low risk, 2 medium level risk, and 3 high level risks to either environment/atmosphere or user/operator health.

Table 5: Penalty Constant Analysis EDM Oil, WVO, JCO & Kusum Oil

Dielectric	Fire Risk	Toxic Fumes	Skin Problems	Fumes Generation	Dust Generation	Reuse of Dielectric	Total	C _p
EDM Oil	3	3	3	3	0	1	13	0.72
WVO	0	1	0	3	0	1	5	0.28
JCO	0	1	0	3	0	1	5	0.28
Kusum Oil	0	1	0	3	0	1	5	0.28
Castor Oil	0	1	0	3	0	1	5	0.28

Table 6 presents the comprehensive sustainability index, integrating energy consumption, dielectric usage, and environmental safety metrics and percentage reduction.

Table 6: Comparison of SI for PMEDM process WVO, JCO, Kusum Oil with EDM Oil

Dielectric	Optimum MRR (mm ³ /min)	Time taken for Machining (T _m) in mins	SI _{EC} (₹)	SI _{DC} (₹)	SI _{OE} (₹)	SI _{Total} (₹)	%age Reduction in SI
EDM Oil	12.09	16.8	1.41	1455	0.48	1456.9	-
WVO	14.58	11.7	1.24	1364	0.25	1365.5	6.27
JCO	16.13	10.6	1.12	1427	0.23	1428.4	1.96
Kusum Oil	16.93	9.7	1.03	1421	0.21	1422.3	2.38
Castor Oil	16.86	9.8	1.32	1427	0.26	1428.8	1.93

CONCLUSIONS

The present work reveals that the non-edible oils (Castor oil WVO, JCO and Kusum oil) provide better MRR in relation to EDM oil. Further, the sustainability index (SI) analysis result exposes that cost effective non-edible oils (Castor oil, WVO, JCO & Kusum oil) as dielectric is good alternative in relation to hydro based EDM oil in terms of machining performance, consumption of dielectric and operator health and environmental conditions.

Non-edible oils (Castor oil, WVO, JCO and Kusum oil) provide reduction in SI by 1.93%, 6.27%, 1.96% and 2.38% respectively as compared to hydrocarbon based EDM oil.

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