Journal of
Polymer & Composites

ISSN: 2321-2810 (Online)
ISSN: 2321-8525 (Print)
Volume 14, Special Issue 1, 2026
DOI (Journal): 10.37591/JoPC

https://journals.stmjournals.com/jopc

Research JoPC

Optimization of Sustainable Electrochemical Machining Parameters for Polymer based Materials Using AHP Integrated TOPSIS Method

S. Chandrasekhar[1,*], M. V. Ramesh[2], Arief Sheik[3], K. Srirama murthy[4], K.S.B.S.V.S. Sastry[5] and Shaik Sohail[6]

Abstract

The current paper describes the use of the AHP-TOPSIS method to optimize process parameters in sustainable electrochemical machining of polymer composites. Combine lightweight polymer matrices with reinforcing particles or fibers such as TiB_2, SiC, or Al_2O_3, offering high strength-to-weight ratio, corrosion resistance, and design flexibility, making them ideal for aerospace and automotive applications. Non-conductive and heterogeneous nature poses challenges during electrochemical machining, as it affects current distribution and material removal behavior, requiring careful optimization of process parameters to achieve uniform machining quality. Results show that AHP integrated with TOPSIS effectively handled multiple-response objectives for parameters such as electrolyte concentration, voltage, and current. AHP assigned 72.35% weight to specific energy consumption, 19.32% to overcutting, and 8.33% to material removal rate. TOPSIS identified optimal levels as 3 moles electrolyte concentration, 14 V, and 2 A. Interaction plots revealed current as the most influential factor, followed by electrolyte concentration and voltage. Microscopic analysis of polymer composites confirmed uniform hole radius with nano burrs at the edge, caused by current and tool insulation issues. Confirmation experiments showed a 3% improvement in closeness coefficient over initial settings. Overall, the AHP-TOPSIS approach enhanced sustainable machining performance of polymer composite and can be applied to optimize other processes with multiple responses by adjusting response weights.

Keywords:-Polymer composites, electrochemical machining, AHP-TOPSIS method, sustainable machining

***Author for Correspondence**
S. Chandrasekhar

[1,5]Associate Professor, Department of Mechanical Engineering, Sri Vasavi Engineering College, Tadepalligudem, Andhra Pradesh, India
[2]Professor, Department of Mechanical Engineering, Sri Vasavi Engineering College, Tadepalligudem, Andhra Pradesh, India
[3,4]Assistant Professor, Department of Mechanical Engineering, Sri Vasavi Engineering College, Tadepalligudem, Andhra Pradesh, India
[6]UG Student, Department of Mechanical Engineering, Sri Vasavi Engineering College, Tadepalligudem, Andhra Pradesh, India

Received Date: October 14, 2025
Accepted Date: November 15, 2025
Published Date: February 10, 2026

Citation: S. Chandrasekhar, M. V. Ramesh, Arief Sheik, K. Srirama murthy, K.S.B.S.V.S. Sastry and Shaik Sohail. Optimization of Sustainable Electrochemical Machining Parameters for Polymer based Materials Using AHP Integrated TOPSIS Method. Journal of Polymer & Composites. 2026; 14(Special Issue 1): S1048–S1059p.

INTRODUCTION

The manufacturing sector plays a major role in the global economy. In India, it has grown significantly through the *Make in India* campaign, contributing 29–30% to GDP Mehta and John Rajanet al. [1]. However, this growth has led to rising energy consumption and CO_2 emissions. Since manufacturing consumes large amounts of natural resources, efforts are focused on improving efficiency by reducing energy and material use with minimal environmental impact Gamage J.R. et al.[2, 3]. discussed the "Cooperative Effort on Process Emissions in Manufacturing," which investigates the environmental impact of manufacturing processes through their primary and secondary emissions. Electrochemical machining is a unconventional process, widely used to manufacture helicopter engines, gun barrels, projectiles, and turbine blades Pavel and Tzimaset al. [4].ECM offers several advantages over conventional machining, including no tool wear, moderate material removal rate, high surface finish, and suitability for hard-to-cut materials and complex shapes. The resulting surfaces are free from distortion, residual stress, heat-affected zones, burrs, and scratches Xu and Wanget al. [5], thereby enhancing component service life. The electrochemical dissolution process produces large amounts of sludge containing metal ions, nitrates, acids, and heavy metals, creating disposal issues. Electrolytes such as NaCl and $NaNO_3$ form insoluble hydroxides that settle as sludge. To ensure safety, skin contact with electrolytes must be avoided, and interlocked covers should prevent the process from starting when open Rajurkar et al.[6]. Few studies have addressed sustainability in ECM. Skinn B.T. et al. [7] described a recycling ECM system combining machining and electro-winning units, where pulse and pulse-reverse power improve accuracy and electro-winning enables metal recovery. This approach offers benefits such as material reclamation, reduced landfill, elimination of sludge, and lower energy use for filtration, centrifugation, and transport. H.K. Tcinshoff, R. Eggerl, F. Klocke et al. [8, 9] discussed strategies to reduce emissions, highlighting sodium nitrate electrolyte for its low cost and reduced harmfulness when freshly mixed. However, the process also generates toxic byproducts like chromates, nitrates, and ammonia during ECM. These compounds attach to metal hydroxides in the ECM slurry. H. El-Hofy and H. Youssef [9] highlighted ECM's environmental hazards and safety measures, noting that electrolysis generates explosive hydrogen gas. Proper local exhaust is required to keep hydrogen below its flammability limit and remove mist from the breathing zone.Maintaining the inter-electrode gap in ECM is challenging, as conductivity changes generate gas bubbles that shrink the gap. This results in uneven electric fields, accumulation of byproducts, and electrolyte boiling, which lower the material removal rate and machining accuracy.In pulsed power supply, material dissolves during the pulse-on time, while byproducts and gas bubbles are removed during pulse-off, helping maintain the inter-electrode gap and improve efficiency. Rajurkar et al. [10] reported that using pulsed power with $NaNO_3$ improves dimensional accuracy and reduces sludge compared to DC supply with NaCl, though it lowers MRR.

Balancing energy efficiency, accuracy, and surface quality remains a challenge for sustainability Mortazavi and Ivanov. Mortazari and Ivanovet al. [11, 12] proposed sustainability indicators for ECM covering energy, waste, environment, safety, and cost. Kozak et al. [13]. noted ECM consumes 2–7 × 10^5 J/cm², higher than turning (1.7–3 × 10^5 J/cm²), limiting its industrial use and highlighting the need for sustainability assessment.The push for energy-efficient machine tools is growing, but high costs often lead industries to prefer process optimization methods Bagabera and Yusoff et al. [14]. Multi-response optimization helps balance conflicting responses to achieve optimal process settings and is well-documented for reducing cost and environmental impact in conventional machining. Among these, the TOPSIS method ranks alternatives based on distance from ideal solutions Yadav et al. [15, 17] applied RSM-enabled TOPSIS to machining hardened AISI 4140 steel, reducing cutting energy and improving efficiency. Most researchers assign equal weights to responses in multi-response optimization. In practice, however, weights should reflect industry needs or process requirements. Bhattacharyya et al [21, 22]. applied AHP for weighting and TOPSIS for optimization in turning EN 353 steel, showing that AHP-based weighting outperforms entropy and equal-weight methods in achieving better performance. Literature on sustainability assessment of ECM for aluminum composites shows notable gaps. No experimental studies report on specific energy consumption, overcut, or MRR, nor on trade-offs between energy, quality, and cost. This paper addresses these gaps by applying AHP-integrated TOPSIS to optimize machining parameters for AA6061-TiB_2 composites, aiming to minimize energy use and overcut while maximizing MRR.

EXPERIMENTAL WORK

AA6061 alloy was used as the matrix material, containing magnesium and silicon as main elements. TiB_2 particulates were synthesized in-situ via a mixed salt method using K_2TiF_6, KBF_4, and molten aluminum at 850^0C is mixed with pre heated salts to form the TiB_2 phase, the molten composite is poured in cast-iron die to produce solid composite for machining Chandrasekhar et al. [18, 23]. The composite was fabricated into a 0.5-mm sheet for investigation. Experiments were conducted on an ECM setup at Sona College of Technology, Salem, containing a machining unit and control systems for tool feed, pulsed power, and electrolyte supply shown in Figure 1. The pulsed system operated at 20 V, 30 A, 65% duty cycle, and 50 Hz, with adjustable parameters. Electrolyte flow was regulated by a pump and filtered to remove debris. A constant 50 µm inter electrode gap was used, with Z-axis tool feed controlled by a stepper motor and 8051 microcontroller using feedback from a current sensor. This feed control system is critical in ECM, tool–workpiece contact causes short circuits, leading to excess current, heat, workpiece damage, and reduced machining efficiency and surface quality.

Current, voltage, and electrolyte concentration were chosen as machining parameters, while specific energy consumption, material removal rate, and overcut were considered responses. A 500 µm copper cylindrical tool and $NaNO_3$ electrolyte (flow rate 10 L/min) were used. Material removal rate was calculated as mass loss per machining time, and overcut was measured with a metallurgical microscope as half the difference between hole and tool diameters. Specific energy consumption, defined as electrical energy per unit volume removed, was obtained from voltage X current X time of machining. Process parameters and levels are shown in Table 1, with experiments based on an L27 layout. Response values were calculated as described and listed in Table 2.

AHP Integrated -TOPSIS Method

Most investigators assign equal weights in multi-response optimization, but sustainable machining requires prioritizing sustainability-related responses. AHP is effective for estimating response weights based on decision-maker judgment, while TOPSIS enables trade-offs where poor results in one response can be combined with good results in another. Here, specific energy consumption and overcut are "smaller-the-better" responses, while material removal rate is "larger-the-better." AHP begins by structuring the problem hierarchically, followed by pairwise comparisons, normalization, weight calculation, and consistency checking. TOPSIS involves creating and normalizing a decision matrix, applying weights, identifying positive and negative ideal solutions, calculating separation measures, and finally determining the closeness coefficient to rank alternatives.

Step 1 Pair-Wise Comparison Based on The Geometric Average of Expert's Opinion

The responses are evaluated and created the pair-wise comparison matrix by estimating the relative importance of different responses in order to fulfill the goal. Saaty's nine-point reference scale (illustrated in Table 3) is adopted for creating the pair-wise comparison matrix. Geometric average of the experts' opinion is considered forthe comparison.

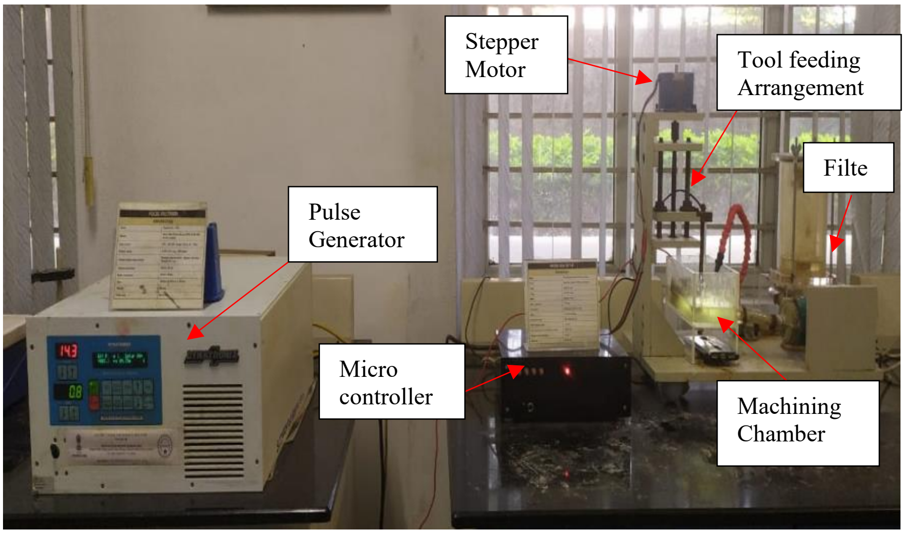

Figure 1. Micro electro chemical machining setup at sona college of technology -Salem.

Table 1. Process Parameters and Their Levels.

Process parameters	Units	Levels		
		Level 1	*Level 2*	*Level 3*
EC	Moles/litter	1	2	3
Voltage	Volts	14	16	18
Current	Amps	2	3	4

Table 2. Experimental observations.

Trial No.	Levels			Responses		
	Electrolyte concentration	*Voltage*	*Current*	*SECX 10^5 (J/cm^2)*	*ROC (µm)*	*MRR (mg/min)*
1	1	14	2	5.873	50.556	0.029
2	1	14	3	8.254	50.5652	0.031
3	1	14	4	10.265	50.5722	0.037
4	1	16	2	6.204	50.5658	0.028
5	1	16	3	8.672	50.575	0.032
6	1	16	4	10.716	50.5822	0.044
7	1	18	2	6.409	50.5685	0.029
8	1	18	3	8.899	50.5778	0.038
9	1	18	4	10.913	50.585	0.043
10	2	14	2	5.726	50.5315	0.033
11	2	14	3	8.032	50.571	0.04
12	2	14	4	9.969	50.5778	0.048
13	2	16	2	6.035	50.5715	0.039
14	2	16	3	8.417	50.5808	0.048
15	2	16	4	10.377	50.588	0.062
16	2	18	2	6.218	50.574	0.035
17	2	18	3	8.613	50.5835	0.049
18	2	18	4	10.532	50.5905	0.056
19	3	14	2	5.577	50.5668	0.033
20	3	14	3	7.810	50.5762	0.042
21	3	14	4	9.672	50.583	0.043
22	3	16	2	5.866	50.577	0.037
23	3	16	3	8.163	50.5862	0.048
24	3	16	4	10.038	50.5932	0.055
25	3	18	2	6.028	50.5795	0.04
26	3	18	3	8.327	50.589	0.057
27	3	18	4	10.151	50.5958	0.056

Table 3. Saaty's 9-point scale of relative importance [19].

Scale	Definition
1	'i' and 'j' are equally important
3	'i' is slightly more important than 'j'
5	'i' is important than 'j'
7	'i' is very strongly important than 'j'
9	'i' is extremely important than 'j'
2,4,6,8	In-between values

Assuming n responses in order to create a pair-wise comparison matrix $S_n \times {}_n$and this is represented in equation (1). In pair wise comparison the response (Si) is compared with response (Sj). In order to decide the elements of this matrix, first give the suitable relative importance to every single row response (S1, S2, ..., Sn) by equating with response of every single column response (S1, S2, ….., Sn). In this matrix, the value of s_{ij}= 1 for i = j, in other words a response compared with same response 1 is assigned.

Although, the value of other elements of the matrix (if i ≠ j) are considered as the inverse of the value of corresponding element e.g. s_{12}= 1/s_{21}. As a result, the main diagonal entries of the matrix ($S_n \times {}_n$) are all 1, upper half of the entries are determined by comparing the respective responses the and lower half entries are inverse of the corresponding elements.

Responses (j) S_1 $S_2 S_j$ S_n

$$S_{n\times n} = \begin{matrix} S_1 \\ S_2 \\ S_i \\ S_n \end{matrix} \begin{pmatrix} 1 & S_{12} & S_{1j} & S_{1n} \\ S_{21} & 1 & S_{2j} & S_{2n} \\ S_{i1} & S_{i2} & 1 & S_{in} \\ S_{n1} & S_{n2} & S_{nj} & 1 \end{pmatrix} \quad (1)$$

Step 2. Normalization of Aggregate Score Matrix then Computation of Weight of Responses

The relative normalized weight (wj) of each response is calculated by the ratio of geometric average (GMi) of corresponding row in the (S_{nxn}) and the sum of the geometric average of entire the rows (equation (2) and equation (3)).

$$\mathrm{GM}_i = \left[\prod_{j=1}^{n} s_{ij} \quad\right]^{1/m} \quad (2)$$

$$w_j = \frac{\mathrm{GM}_i}{\sum_{i=1}^{n} \mathrm{GM}_i} \quad (3)$$

Step 3. Consistency Checking

The consistency ratio (CR) is the ratio of consistency index (CI) and random inconsistency index (RI) and it is described in the equation 4.

The consistency index (CI) is estimated by using the equation (5), where λmaxis the maximum Eigen value of the matrix. λmaxis calculated by using the average value of the sum of the matrix multiplication of the pair-wise comparison matrix and weight vectors and dividing by the relative normalized weight of the corresponding response.

$$CR = \frac{CI}{RI} \quad (4)$$

$$CI = \frac{\lambda_{max}}{n-1} \quad (5)$$

where RI value is selected from the Table 4 based on the number of responses. Generally, a CR value of 0.10 or smaller is considered as acceptable. Thereby, the informed judgment attributable to the knowledge of the expert concerning the problem under investigation.

Table 4. Random inconsistency index (RI) (Saaty, 2008) [19].

Number of Responses (n)	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Random inconsistency index (RI)	0.0	0.0	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49

Step 4. Creation of the Decision Matrix

Create the decision matrix X = {r_{ij}}, where r_{ij}denotes the value of the j thresponsein the ith experimental trail;i = 1, 2, …, m; j = 1, 2, …, n. All the responses are calculated and displayed as per the equation 6.

$$r_{ij} = \begin{pmatrix} X_{11} & X_{12} & \dots & X_{1n} \\ X_{21} & X_{22} & \dots & X_{2n} \\ \vdots & \vdots & \vdots & \vdots \\ X_{m1} & X_{m2} & \dots & X_{mn} \end{pmatrix} \qquad (6)$$

Step 5 Normalization of the Matrix

In this step, the output responses are normalized using the following equation (7). Nevertheless, the output responses have different units, they get normalized with the help of multiplication.

$$r_{ij} = \frac{x_{ij}}{\sqrt{\sum_{i=1}^{m} (x_{ij})^2}} \qquad (7)$$

Step 6 Calculation of the Weighted Normalized Decision Matrix

The weighted normalized matrix to the responses can be constructed by the weight to each response obtained from AHP method. These weights areusually multiplied with the normalized output values of the matrix. Theweighted normalized matrix V can be represented as

V= $w_j * r_{ij}$;wherei = 1, 2, …, m; j = 1, 2, …, n and V can be represented in equation 8

$$V = \begin{pmatrix} w_1 r_{11} & w_2 r_{12} & \dots & w_n r_{1n} \\ w_1 r_{21} & w_2 r_{22} & \dots & w_n r_{2n} \\ \vdots & \vdots & \vdots & \vdots \\ w_1 r_{m1} & w_2 r_{m2} & \dots & w_n r_{mn} \end{pmatrix} \qquad (8)$$

Step 7. Attain the Positive Ideal and Negative Ideal Solutions

As per principle, the TOPSIS mainly identifies that the selectedalternatives should have the nearby and utmost distance. Hence, calculating the relative proximity of an experimental trailswith the optimum solution would give positive ideal solutionand negative ideal solution. The positive idealand negative ideal solution for a specific attribute may be either maximum or minimum value among the alternative values. The ideal alternativesto the best performance are signified as A+ and theworst performance are signified as A− and it is represented in the equation 9 and 10.

$$A^{+} = \{V_1{}^{+}, V_2{}^{+} \dots\dots\dots V_n{}^{+}\} \qquad (9)$$

$$A^{-} = \{(min_i\, V_{ij}\, j \in J), (max_i\, V_{ij}\, j \in J^1) i = 1,2, \dots, m\}$$

$$A^{-} = \{V_1{}^{-}, V_2{}^{-} \dots\dots\dots V_n{}^{-}\} \qquad (10)$$

where *J* = { *j*= 1, 2, ___, *n* | *j* related with the −higher −the −better attribute}, J^- = { *j*= 1, 2, ___, *n* | *j* associated with the −smaller −the −better attribute}

Step 8. Calculation of the Separation Measures

Theperformance of criteria can be computed from the distance between the score for respective alternative and the matrixof positive and negative ideal solution. Best alternativedistance can be obtained from A^+ values and worst alternativesdistances from A^-. The separation measure values of S_i^+ and S_i^-areobtainedfrom the equation 11 and 12.

$$S_i^+ = \sqrt{\sum_{j=1}^{n}\left(V_{ij} - V_j^+\right)}^2 \quad (11)$$

$$S_i^- = \sqrt{\sum_{j=1}^{n}\left(V_{ij} - V_j^-\right)}^2 \quad (12)$$

Step 9. Estimation of the Closeness Coefficient

Closenesscoefficient (CC) for each experimental run can be calculated from the equation13.The value of relative closeness replicates the relative dominance of the alternatives. Greater closeness coefficient indicates that the alternative relatively better among others, whereas smaller values designates that the alternative is relatively worst among other alternates.

$$CC = \frac{S_i^-}{(S_i^+ + S_i^-)} \quad (13)$$

where i=1,2,3….m; $0 \leq CC \leq 1$

RESULTS AND DISCUSSION

AHP Method

By using the AHP method (Saaty,2008) [19], the relative normalized weight, consistency ratio, consistency index, and weightage of the responses are evaluated. The AHP method gives out the weightage for SEC, overcut and MRR are 0.7235, 0.1932and 0.0833 respectively. The consistency analysis shows that the calculated CR value is less than the permissible value of 0.10, which confirms that there is a good consistency in the judgment made by the decision-maker while assigning values in the pairwise comparison matrix.

TOPSIS Method

By using the TOPSIS method Kumar et al. [16], the weighted normalized matrix to the responses is constructed by using the weights obtained from AHP, equal, and entropy weighting method. Further, the positive and negative ideal solutions, separation measures, and closeness coefficient for each trial is calculated and tabularized in Table 5. As per the procedure for TOPSIS, the greater value of the closeness coefficient designates that the corresponding experimental trial is comparatively better while lesser values exhibit that the corresponding experimental trial is worst among other experimental trials.

As exposed in Table 5, the experimental trail 19 (T-19) has the greater closeness coefficient value. The corresponding machining parameters are 3 moles of electrolyte concentration, 14 V of applied voltage, and 2 A of current. This ECM parametric setting offersthe greater machining rate in addition to the minimum specific energy consumption and overcutting. Based on the AHP-TOPSIS method, the preference of sustainable machining parameter levels can be made in the following order of choice

T-19 > T-22> T-10 > T-25 > T-13 > T-1> T-16 > T-4 > T-7 > T-20 > T-11 > T-23 > T-26 >T-2 > T-14 > T-17 > T-5 > T-8 > T-21 > T-24 > T-12 > T-27 > T-15 > T-18> T-3 > T-6 > T-9.

The AHP-TOPSIS method combines all machining responses into a single response. The optimized parameters improve machining efficiency with sustainability.

Figure 2 shows the comparison of specific energy consumption and radial overcut for different trials. Trial T-19 recorded the lowest energy consumption with parameters of 3 moles electrolyte concentration, 14 V voltage, and 2 A current.

Trial T-10 showed the least radial overcut with parameters of 2 moles electrolyte concentration, 14 V voltage, and 2 A current.

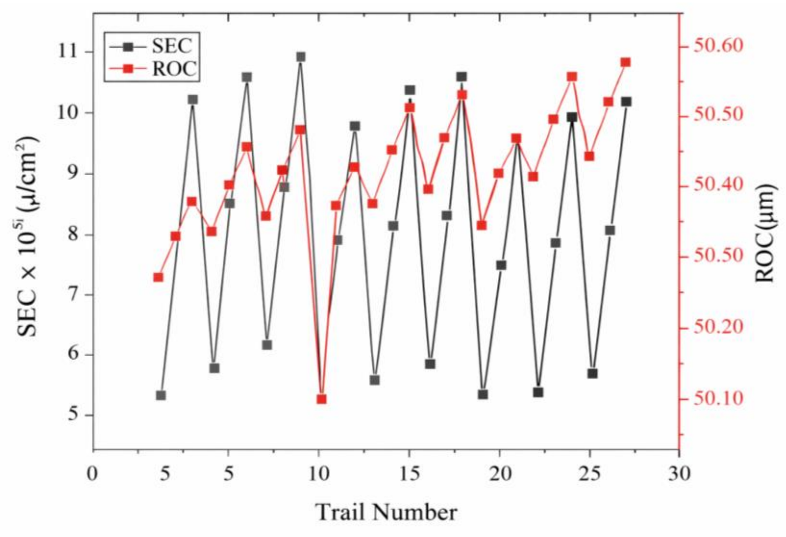

Figure 2. Shows the comparison of specific energy consumption and radial overcut for different trials.

Table 5. Positive and negative ideal solution and Closeness coefficient.

Trial No.	Positive ideal solution (S^+)	Negative ideal solution(S^-)	Closeness coefficient (CC)	Rank
1	0.0133	0.0835	0.86264	6
2	0.0459	0.0441	0.48960	14
3	0.0783	0.0112	0.12554	25
4	0.0165	0.0780	0.82574	8
5	0.0526	0.0372	0.41416	17
6	0.0855	0.0068	0.07376	26
7	0.0185	0.0746	0.80090	9
8	0.0558	0.0336	0.37547	18
9	0.0888	0.0056	0.05933	27
10	0.0111	0.0859	0.88540	3
11	0.0416	0.0479	0.53550	11
12	0.0730	0.0173	0.19180	21
13	0.0115	0.0809	0.87540	5
14	0.0474	0.0420	0.46966	15
15	0.0796	0.0155	0.16287	23
16	0.0147	0.0778	0.84104	7
17	0.0506	0.0389	0.43454	16
18	0.0822	0.0122	0.12932	24
19*	0.0108*	0.0884*	0.89093*	1*
20	0.0378	0.0517	0.57739	10
21	0.0683	0.0213	0.23773	19
22	0.0105	0.0837	0.88827	2
23	0.0433	0.0462	0.51623	12
24	0.0740	0.0176	0.19250	20
25	0.0112	0.0811	0.87900	4
26	0.0457	0.0442	0.49162	13
27	0.0759	0.0164	0.17760	22

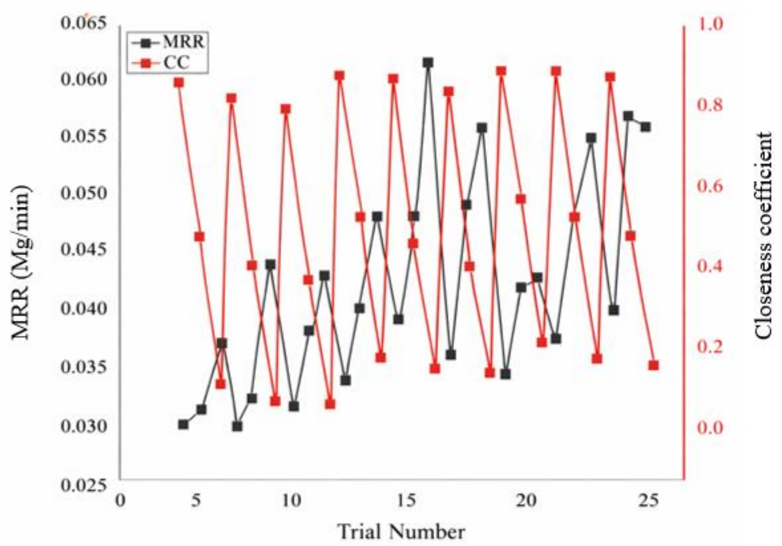

Figure 3. Comparisons of material removal rate and closeness coefficient.

Figure 3 shows that trial T-15 achieved the highest material removal rate with parameters of 2 moles electrolyte concentration, 16 V voltage, and 4 A current. In electrochemical machining, higher current increases material removal, while moderate voltage and electrolyte concentration further support it. Figure 3 also indicates that trial T-19 has the highest closeness coefficient, making its parameters (3 moles electrolyte concentration, 14 V voltage, and 2 A current) the optimal set for sustainable machining.

In ECM, the applied voltage drives DC current between the electrodes, causing anodic dissolution at the workpiece and hydrogen gas formation at the cathode. The voltage also charges the electrode surface, attracting dipoles and opposite ions from the electrolyte, which forms an electrical double layer. This layer, considered a drawback under constant potential, increases workpiece polarization and accelerates dissolution, leading to overcutting around the hole.

The AHP-TOPSIS method shows that 14 V is the optimal voltage for sustainable machining. This low voltage provides sufficient anodic dissolution with minimal heat, reducing overcut and maintaining hole circularity. In this study, a pulsed power supply (20 V, 30 A capacity) with adjustable settings was used, fixed at 65% duty cycle and 50 Hz. The pulsed supply limits current density at the machining zone, further lowering overcut and improving hole quality. Additionally, using 14 V helps reduce specific energy consumption.

Sodium nitrate electrolyte helps prevent stray corrosion and ensures better tool shape replication, which preserves hole cylindricity. The AHP-TOPSIS method shows that a 3-mole concentration offers the best sustainable machining performance. As noted by Lienhard et al. [22], higher electrolyte concentration increases conductivity and ion availability, leading to faster machining, but it has little effect on overcut, cylindricity, or energy consumption. In contrast, lower concentration increases resistance, reducing material removal, though it improves machining quality by lowering overcut and cylindricity deviation. The pulsed power supply also contributes to reducing the removal rate.

The AHP-TOPSIS method identifies 2 A as the optimal current for sustainable machining. Although higher currents can increase dissolution and machining rate by raising electrolyte temperature and conductivity (as per Joule’s law), they reduce hole cylindricity, increase overcut, and raise specific energy consumption. For micro-machining, where hole quality is critical, higher current is not suitable. Thus, using 2 A with a pulsed power supply ensures controlled overcutting, lower energy use, and better sustainability.

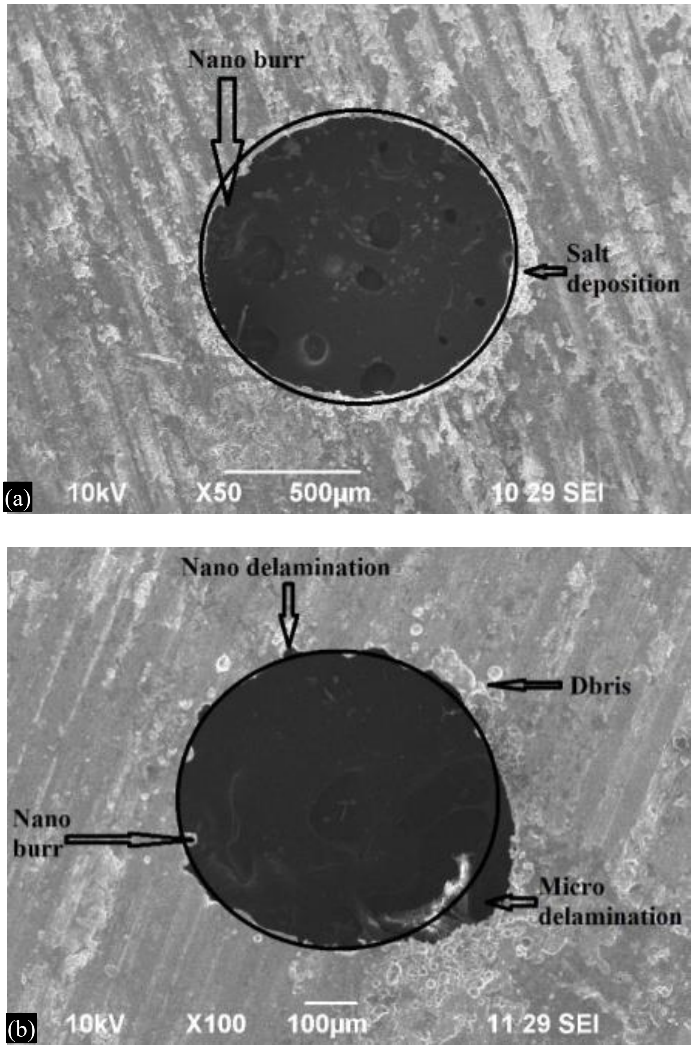

Figure 4. (a)Micrograph of drilled hole (3 moles-14 Volts-2 Amps)
(b) Micrograph of drilled hole (1 moles-18 Volts-4 Amps)

Figure 4 aexemplifies the scanning electron microscopic assessment of a micro hole drilled At the optimum parameters (T-19: 3 moles electrolyte, 14 V, 2 A), Figure 4a shows that the hole radius is nearly uniform, with only nano-sized burrs at the edge due to lack of tool insulation, along with some salt and debris deposits. In contrast, Figure 4b for trial T-9 (1 mole electrolyte, 18 V, 4 A) reveals micro delamination, multiple nano burrs, nano delamination, and random debris deposition. The higher current and voltage worsen hole quality by causing delamination and burrs, while also increasing specific energy consumption. Thus, the optimal parameters improve hole quality and reduce energy use, supporting sustainable machining.

A confirmation experiment was conducted using the optimized electrochemical machining parameters to verify their accuracy and evaluate performance improvement over the initial settings. The Taguchi predictor in Minitab 19 was used to estimate the closeness coefficient for the optimized combination of electrolyte concentration, voltage, and current, giving a predicted value of 0.9405. The confirmation test was then performed for the optimal parameters, with results shown in Table 6.

From Table 6, the closeness coefficient for the optimal run is 0.8909, which is over 3% higher than the initial setting (T-1). This confirms that the AHP-TOPSIS method provides the best performance among all parameter combinations.

Table 6. Confirmation test

Parameter	**Initial setting**	**Prediction by Taguchi predictor-Minitab-19**	**Experimental**
	1Mole-14Volts-2Amps	*1Mole-14Volts-2Amps*	*1Mole-14Volts-2Amps*
Specific Energy Consumption x 10^5(J/cm^2)	5.873	--	5.577
Radial over cut (μm)	50.556	--	50.5668
Material Removal Rate(mg/min)	0.029	--	0.033
Closeness Coefficient	0.8629	0.9405	0.8909
Percentage Improvement in Closeness Coefficient			3.14 %

In this method, AHP assigns weights to responses such as energy consumption, overcut, and material removal based on expert judgment, and the closeness coefficient depends on these weights. The obtained parameters are valid for sustainable machining, though different weight assignments may be required for economic machining or higher precision.

CONCLUSION

The application of the AHP-TOPSIS method was described for optimizing the process governing parameters during sustainable electrochemical machining of polymer composites. From the experimental investigation the following notable conclusions are arrived.

1. The AHP integrated with TOSIS method, has been effectively used to handle the multiple-response objective system for optimizing the process governing parameters such as electrolyte concentration, applied voltage and current in sustainable ECM of polymer composites.
2. The AHP method yielded the weight for SEC, over cut and rate of material removal is 0.7235, 0.1932 and 0.0833 respectively, in order to obtain the greater machining efficiency within the sustainable frame. The consistency ratio for weight assignment is 0.056 and this value is less than the permissible value of 0.10, which confirms that there is a good consistency in the judgment made by the decision maker while assigning values in developing the pair wise comparison matrix.
3. The TOSIS method effectively ranked the various experimental trails and offered the optimum level of process governing parameters as 3 moles of electrolyte concentration, 14 V of applied voltage, and 2 A of current.
4. The interaction plot exemplified that the increase in electrolyte concentration rise the average coefficient closeness value whereas an increment in applied voltage and current reduce the average closeness coefficient value. Further, the interaction plot also illustrated that the current has the utmost effect on the closeness coefficient, followed by electrolyte concentration and voltage.
5. The microscopic view of hole generated by optimal process governing parameters depicted that the radius of the hole is approximately equal through the periphery. Further, the edge of the hole has nano size burr which is formed the effect current due to the lack of insulation throughout the tool.
6. The Confirmation experiment demonstrated that the optimal experimental trail has 3% improvement of coefficient closeness value than the initial parametric setting.
7. Analysis of result showed that the AHP integrated TOPSIS method has improved the ECM efficiency within the sustainable frame,as expected for the current manufacturing scenario.
8. Furthermore, this method could be used to optimize any machining process with multiple responses by varying the weight of each responses based on the objective function.

REFERENCES

1. Mehta,Y. and Rajan, A.J.,“Manufacturing sectors in india: outlook and challenges”, Proc. Eng.2017,174, 90 – 104.

2. Gamage,J.R., Anjali K.M.D., Harrison,C.and Harrison, D., "Ascertaining life cycle inventory data for electrical discharge machining", Proc. CIRP,2016, 41,908 – 913.
3. Kellens,K.,Dewulf, W., Overcash, M., Hauschild, M.Z. and R.Duflou.J.R., "Methodology for systematic analysis and improvement of manufacturing unit process life-cycle inventory (UPLCI)—CO_2PE! initiative (cooperative effort on process emissions in manufacturing). Part 1: Methodology description", Int.J. Life Cy. Asses.,2012,17(1),69–78.
4. C. Pavel, C.C. and Tzimas,E.,"Raw materials in the European defense industry", EUR 27542 ENEuropean Commission,2016, DOI: 10.2790/0444.
5. Xu, Z.Y. and Wang, Y.D., "Electrochemical machining of complex components of aero-engines:Developments, trends, and technological advances", Chinese J. Aeronaut.2019, https://doi.org/10.1016/j.cja.2019.09.016.
6. Rajurkar, K.P.,Hasidim., Pariti,J. and Reddy, G.C., "Review of sustainability issues in non-traditional machining processes", Proc. Manuf., 2017,7, 714–720.
7. Skinn,B., Lucatero, S., Snyder, S., Taylor, E.J., Hall, T.D., McCrabb, H., Garich.,H. and Inman,M.E., "Sustainable electrochemical machining for metal recovery, elimination of waste, and minimization of water usage", ECS Transactions,2016,72(35),1-20; DOI: 10.1149/07235.0001ecst.
8. Tcinshoff, H.K., Eggerl, R. and Klocke, F.,"Environmental and safety aspects of electrophysical and electrochemical processes", CIRP Ann., 1996, 45(2), 553–568.
9. El-Hofy,H. and Youssef, H.,"Environmental hazards of nontraditional machining". In: Proc. 4th IASME / WSEAS Int. C. Ener. Env., 2009, pp.140–145. Cambridge (UK).
10. Rajurkar, K.P.,Zhu,D. and Wei,B.,"Minimization of machining allowance in electrochemical machining", CIRP Ann., 1998, 47(1), 165–168.
11. Mortazavi,M. and Ivanov,A.,"Sustainability of micro electrochemical machining: discussion",Int. Con. Sus. Des. Manuf.,2017,203-210,DOI:https://doi.org/10.1007/978- 3-319- 57078-5_20.
12. Mortazavi,M. and Ivanov,A., "Sustainable μECM machining process: indicators and assessment",J. Clean. Prod.,2019, 235,1580–1590.
13. Kozak, J., Ross, R.F. and Rozenek, M., "An investigation of SEC in electrochemical machining". Elect. Chem. Soc.,1996,95 (19),279–289.
14. Bagabera, S.A. and Yusoff,A.R.,"Energy and cost integration for multi-objective optimization in a sustainable turning process". Measurement,2019; 136, 795–810.
15. Park, H. S., Nguyen, T. T. and Dang, X. P.,"Multi-Objective Optimization of Turning Process of Hardened Material for Energy Efficiency," Int. J. Prec. Eng. and Manuf.,2016, 17(12), 1623–1631.
16. Kumar,R., Bilga,P.S.andSingh,S.,"Multi objective optimization using different methods of assigning weights to energy consumption responses, surface roughness and material removal rate during rough turning operation", J. Clean. Prod.,2017, 164,45–57.
17. Yadav, S.K., Joseph, D. and Jigeesh, N.,"A review on industrial applications of TOPSIS approach", Int. J. Ser. Op. Manag., 2018, 30(1),23–38.
18. Chandrasekhar, S. and Prasad N. B. V., "Optimization of the Electrochemical machining parameters in drilling of AA6061-TiB_2 in-situ composites produced by K_2TiF_6-KBF_4 reaction system", IOP Conf. Series: Mat Sci and Eng 2018; 390: doi:10.1088/1757- 899X/390/1/012006.
19. Saaty, T. L., "Decision Making with the Analytic Hierarchy Process," Int. J. Ser. Sci.,2008, 1(1), 83–98.
20. Wang, M., Peng, W.,Yao, C. and Zhang,Q.,"Electrochemical machining of the spiral internal turbulator", Int. J. Adv. Manuf. Tech., 2010, 49,(9), 969–973.
21. Bhattacharyya, B. and Munda, J.,"Experimental investigation on the influence of Electrochemical machining parameters on machining rate and accuracy in micromachining domain", Int. J. Mach. Tool. Manuf., 2003,43(13),1301–1310.
22. Lienhard, J. H.,"A Heat Transfer Textbook", 2nd ed.; PrenticeHall: Englewood Cliffs, NJ, 1987.
23. S. Chandrasekhar and N. Prasad, "Multi-response optimization of electrochemical machining parameters in the micro-drilling of AA6061-TiB2in situ composites using the Entropy–VIKOR method," Proceedings of the Institution of Mechanical Engineers. Part B, Journal of engineering manufacture, vol. 234, no. 10, pp. 1311–1322, Apr. 2020, doi: https://doi.org/10.1177/0954405420911539.

