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OPTIMIZATION OF FACE MILLING PARAMETERS IN GREEN MACHINING USING THE TAGUCHI METHOD

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Abstract

Green machining has become an important manufacturing approach for reducing environmental impacts while maintaining machining performance. Minimum Quantity Lubrication (MQL) using biodegradable coconut oil offers an effective alternative to conventional flood cooling by minimizing cutting fluid consumption while ensuring adequate lubrication. This study optimizes face milling parameters of S45C medium-carbon steel under coconut oil-based MQL using the Taguchi method. Experiments were conducted on a conventional milling machine with a 10 mm four-flute carbide end mill. Cutting speed (16.33, 22.45, and 31.09 m/min), feed per tooth (0.042, 0.061, and 0.090 mm/tooth), and axial depth of cut (0.5, 0.8, and 1.2 mm) were arranged using a Taguchi L27 orthogonal array. Surface roughness (Ra) was analyzed using the Smaller-the-Better Signal-to-Noise ratio and Analysis of Variance (ANOVA). The optimum parameters were cutting speed = 31.09 m/min, feed per tooth = 0.042 mm/tooth, and axial depth of cut = 0.5 mm, yielding the highest S/N ratio despite not producing the lowest experimental Ra, indicating the most robust condition. ANOVA showed feed per tooth as the most influential factor (39.42%), followed by cutting speed (11.39%) and axial depth of cut (4.87%). These findings confirm that coconut oil-based MQL enhances surface quality and supports sustainable machining.

Keywords: Coconut oil, Face milling, Minimum Quantity Lubrication (MQL), Surface roughness, Taguchi method.

INTRODUCTION

Manufacturing industries continuously demand machining processes that produce high-quality components while minimizing environmental impact (Parray et al., 2025; Usley et al., 2025). Conventional flood cooling improves machining performance but increases production costs and creates environmental and health concerns due to excessive cutting fluid use (Mikell P. Groover, 2020) driving growing interest in sustainable machining alternatives. Minimum Quantity Lubrication (MQL) addresses these limitations by supplying only a small amount of lubricant directly into the cutting zone, reducing friction, cutting temperature, and lubricant consumption while maintaining machining performance (Rahman et al., 2021; Savković et al., 2020). Among biodegradable lubricants, virgin coconut oil is particularly attractive for its excellent lubricity, biodegradability, renewability, and high flash point, making it a promising substitute for mineral-based cutting fluids (Arsene et al., 2021; Fernando et al., 2019; Kazeem et al., 2022).

Despite these advances, several research gaps remain. Most previous studies focused on aluminum and titanium alloys, while S45C medium-carbon steel under coconut oil-based MQL remains largely unexplored, and its distinct mechanical and thermal characteristics mean optimum parameters from those studies cannot be directly applied. Furthermore, although Taguchi optimization and MQL have each been studied extensively, few studies integrate coconut oil-based MQL with a Taguchi L27 design, ANOVA, and confirmation experiments to comprehensively evaluate cutting speed, feed per tooth, and axial depth of cut on S45C surface roughness.

The novelty of this study therefore lies in integrating biodegradable coconut oil-based MQL with a Taguchi L27 design, ANOVA, and confirmation experiments to op timize face milling of S45C medium-carbon steel, providing experimentally validated guidelines beyond the aluminum and titanium alloys examined in prior work. Specifically, this study aims to determine the significance of cutting speed, feed per tooth, and axial depth of cut;

identify the optimum conditions for minimizing surface roughness; quantify each parameter's statistical contribution; and validate the predicted optimum through confirmation experiments, thereby supporting practical, sustainable machining applications.

LITERATURE REVIEW

The Taguchi method combined with Analysis of Variance (ANOVA) has been widely applied to optimize machining parameters using a reduced number of experimental trials while identifying the most influential factors. For lightweight alloys, (Rahman et al., 2021; Savković et al., 2020) both reported feed per tooth as the dominant factor governing surface roughness in face milling of Al7075 and Ti6Al4V, respectively, with cutting speed exerting only a moderate secondary effect. However, both studies were limited to aluminum and titanium alloys, whose machining behavior differs considerably from medium-carbon steels. The effectiveness of Taguchi optimization has also been extended to carbon and tool steels. (Sulaiman et al., 2022) confirmed feed per tooth as the most influential parameter on surface roughness in dry milling of Al6061, while (Beyza avci et al., 2025) reached a similar conclusion for CNC milling of hardened AISI D2 tool steel. For S45C medium-carbon steel specifically, (Thi Kim Lien et al., 2023) identified feed per tooth as the dominant parameter affecting surface roughness but did not employ any Minimum Quantity Lubrication (MQL) strategy.

Minimum Quantity Lubrication using vegetable-based lubricants has received growing attention as a sustainable alternative to conventional flood cooling. (Arsene et al., 2021)) demonstrated that corn oil-based MQL in hard turning of AISI D2 steel reduced tool wear and improved surface roughness compared with dry and flood-cooled conditions, while (Afonso et al., 2022) showed that vegetable oil MQL improved surface quality in milling relative to dry machining. Broader reviews by (Berman, 2024; Kazeem et al., 2022; Khan et al., 2025) consistently confirm that vegetable-based cutting fluids offer strong lubricity, biodegradability, and oxidation stability, positioning them as promising substitutes for mineral-based fluids across a wide range of machining operations.

(Touggui et al., 2021) found that nano-enhanced MQL reduced cutting force and improved surface finish in turning of AISI 304 stainless steel, while (Metla et al., 2025) reported that MQL could reduce cutting fluid consumption by more than 99% compared with flood cooling without compromising machining performance. (Parray et al., 2025) further showed that MQL suppresses Built-Up Edge (BUE) formation and improves surface quality in stainless steel machining. These studies, however, focused on lubrication performance in general and did not examine face milling optimization of S45C steel under coconut oil-based MQL specifically. From a broader sustainability perspective, hybrid Taguchi-based optimization approaches have been shown to improve process efficiency while supporting green machining objectives (Ihsan et al., 2025), and comprehensive reviews of cutting fluid application in micro-milling confirm that MQL based on biodegradable lubricants is central to environmentally sustainable machining strategies (Kuram et al., 2024). Complementary evidence from carbide tool wear behavior in steel milling (Lubis et al., 2023) and comprehensive reviews of MQL applications in machining processes (Usley et al., 2025) reinforce the relevance of lubrication strategy to both surface integrity and tool life, underscoring that appropriate combinations of cutting parameters and lubricant delivery conditions are essential to achieving stable, low-friction cutting conditions.

Although Taguchi-ANOVA optimization and MQL have each been extensively studied between 2020 and 2025, no identified study within this period has integrated coconut oil-based MQL with a Taguchi L27 orthogonal array, ANOVA, and confirmation experiments to comprehensively evaluate cutting speed, feed per tooth, and axial depth of cut on the surface roughness of S45C medium-carbon steel. This gap forms the basis for the present study, which extends the fundamental milling principles established by (Mikell P. Groover, 2020) to a statistically validated, environmentally sustainable optimization framework for face milling of S45C steel under coconut oil-based MQL.

METHOD

Experiment Setup

The experiments were conducted on S45C steel using a Dahlih-U2 conventional milling machine (3-phase, 380 V, 50 Hz, 3.7 kW motor; table travel of 850 mm (X), 360 mm (Y), and 450 mm (Z); spindle speed adjustable across 18 discrete steps from 70 to 1300 rpm; feed rate adjustable from 13 to 700 mm/min) and a 10 mm four-flute carbide end mill. Image 1 shows the complete experimental setup used for the face milling experiments under minimum quantity lubrication conditions. The minimum quantity lubrication system operated at an air pressure of 5 bar with a lubricant flow rate of 100 ml/h. Virgin coconut oil was atomized using compressed air and delivered through a nozzle positioned approximately 30 mm from the cutting zone at a 45° spray angle toward the cutting zone to ensure effective lubrication and cooling during machining**.** The minimum quantity lubrication operating conditions used in this study were selected based on previous studies demonstrating that an air pressure of approximately 5 bar and a lubricant flow rate between 50 and 150 ml/h provide effective lubrication and cooling under milling operations (Arsene et al., 2021; Fernando et al., 2019; Parray et al., 2025). To prevent bias from progressive tool wear, a fresh cutting insert was used at the start of each experimental replication series.

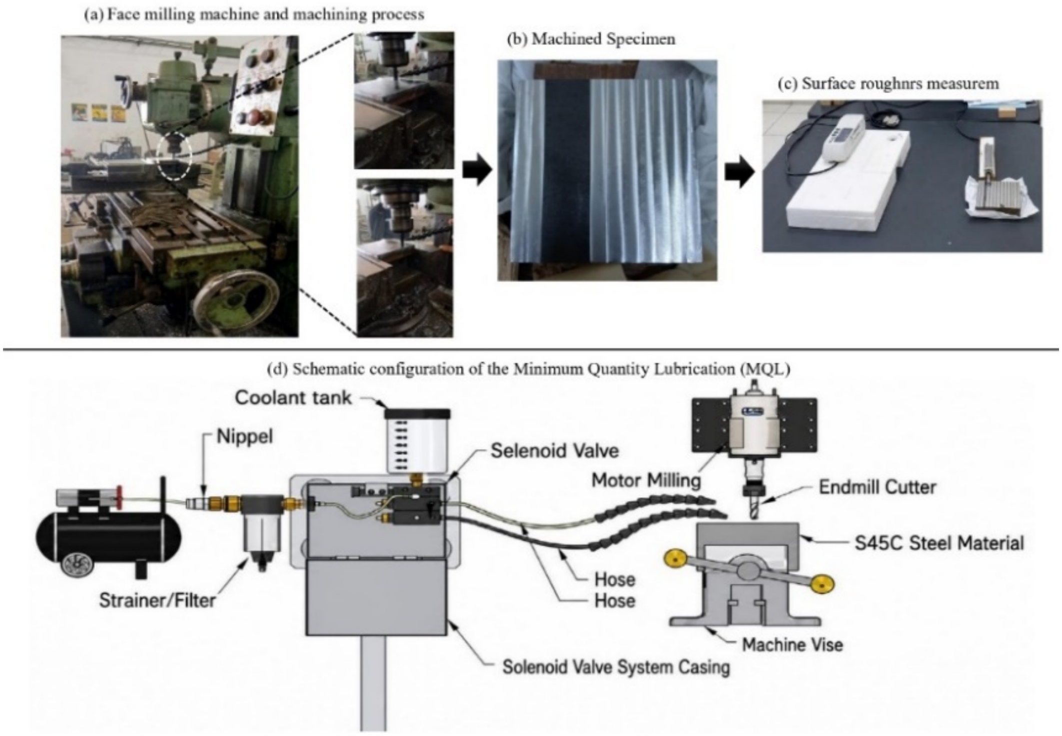

Image 1. Experimental setup consisting of; (a) the face milling process on a conventional milling machine, (b) machined specimen, (c) surface roughness measurement using a portable roughness tester. (d) the schematic configuration Minimum Quantity Lubrication

Workpiece and Tool Materials

The workpiece, cutting tool, and biodegradable lubricant used in this study are presented in Image 2. The workpiece (Image 2a) was S45C medium-carbon steel (100 × 100 × 25 mm), selected for its excellent balance of strength, toughness, and machinability; each specimen was cleaned and securely clamped before machining. The cutting tool (Image 2b) was a 10 mm diameter four-flute coated carbide end mill with flat-end geometry, chosen for its high hardness, wear resistance, and cutting-edge stability under MQL conditions. The lubricant (Image 2c) was virgin coconut oil (brand Barco; viscosity 27.15 cSt, density 0.913 g/cm³), selected for its lubricity, biodegradability, and renewability, and was supplied through the MQL system using compressed air.

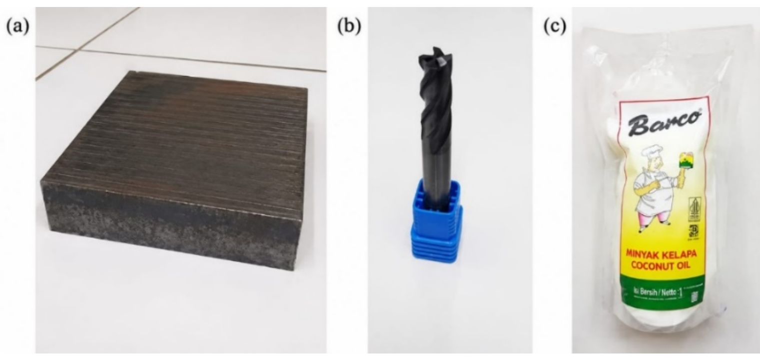

Image 2. Materials used in the experiments: (a) S45C medium-carbon steel workpiece (100 mm x 100 mm x 25 mm); (b) 10 mm diameter four-flute coated carbide end mill; (c) Coconut oil used as the biodegradable lubricant for the MQL system.

Experimental Design

The machining parameters and their corresponding levels are presented in Table 1. The experiments were designed using the Taguchi L27 orthogonal array. Three machining parameters were investigated: cutting speed (vc), feed per tooth (fz), and axial depth of cut (ax). Surface roughness (Ra) was selected as the response variable.

Table 1. Machining Parameters and Their Levels

Factor	Symbol	Unit	Level 1	Level 2	Level 3
Cutting speed	vc	(m/min)	16.33	22.45	31.09
Feed per tooth	fz	(mm/tooth)	0.042	0.061	0.090
Axial depth of cut	ax	(mm)	0.5	0.8	1.2

The machining parameter levels were selected based on the Dahlih-U2 machine's capability, the carbide end mill manufacturer's recommendations, and previous MQL face-milling studies, representing stable cutting conditions for S45C steel while minimizing excessive tool wear and chatter.

Surface Roughness Measurement

Surface roughness of the machined S45C specimens was measured using a calibrated portable surface roughness tester (Accretech Handysurf), in accordance with ISO 4287 and ISO 4288, using a cutoff length of 0.8 mm and an evaluation length of 4 mm (Image 3). Three measurements were taken at the start, middle, and end of each machined pass, and the average value was used as the response for the Taguchi and ANOVA analyses. Before each measurement, the specimen surface was cleaned of chips and residual oil using compressed air and a clean cloth to remove contaminants that could affect measurement accuracy.

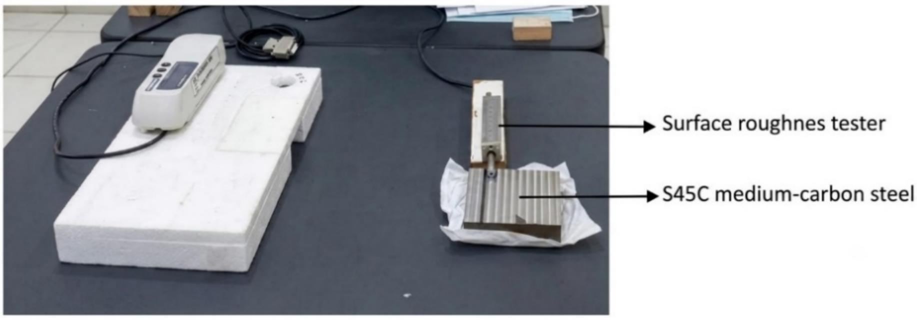

Image 3. Surface roughness measurement of the machined S45C specimen using a portable surface roughness tester.

Statistical Analysis

The experimental data were analyzed using the Taguchi optimization approach. Since the objective of this study was to minimize surface roughness, the Smaller-the-Better quality characteristic was adopted for calculating the Signal-to-Noise (S/N) ratio.

The Signal-to-Noise (S/N) ratio was determined using:

$$S/N = -10\log\left(\frac{1}{n}\sum_{i=1}^{n} y_i^2\right) \quad (1)$$

where:

- n is the number of observations,
- yi is the measured surface roughness value.

Analysis of Variance (ANOVA) was subsequently performed using Minitab statistical software to determine the significance and percentage contribution of each machining parameter. A significance level of 95% (α = 0.05) was adopted to evaluate the influence of cutting speed (vc), feed per tooth (fz), and axial depth of cut (ax) on surface roughness.

RESULTS AND DISCUSSION

Surface Roughness Results

The surface roughness (Ra) values obtained from the 27 face milling experiments are presented in Table 2. The experiments were conducted using the Taguchi L27 orthogonal array to evaluate the effects of cutting speed (vc), feed per tooth (fz), and axial depth of cut (ax) on the surface roughness of S45C medium-carbon steel under Minimum Quantity Lubrication (MQL) conditions.

Table 2. Experimental Design Matrix and Surface Roughness Results

No	Cutting speed (vc)	Feed per tooth (fz)	Axial depth of cut (ax)	Ra measurement result
1	16.33	0.042	0.5	0.300
2	16.33	0.042	0.8	0.440
3	16.33	0.042	1.2	0.470
4	16.33	0.061	0.5	0.340
5	16.33	0.061	0.8	0.450
6	16.33	0.061	1.2	0.500
7	16.33	0.090	0.5	0.590
8	16.33	0.090	0.8	0.640
9	16.33	0.090	1.2	0.720
10	22.45	0.042	0.5	0.720
11	22.45	0.042	0.8	0.310
12	22.45	0.042	1.2	0.400
13	22.45	0.061	0.5	0.300
14	22.45	0.061	0.8	0.530
15	22.45	0.061	1.2	0.560
16	22.45	0.090	0.5	0.590
17	22.45	0.090	0.8	0.630
18	22.45	0.090	1.2	0.670
19	31.09	0.042	0.5	0.420
20	31.09	0.042	0.8	0.370
21	31.09	0.042	1.2	0.410
22	31.09	0.061	0.5	0.390
23	31.09	0.061	0.8	0.360
24	31.09	0.061	1.2	0.400
25	31.09	0.090	0.5	0.470
26	31.09	0.090	0.8	0.460
27	31.09	0.090	1.2	0.540

The lowest experimental surface roughness (Ra = 0.300 μm) occurred at vc = 16.33 m/min, fz = 0.042 mm/tooth, and ax = 0.5 mm. However, Taguchi optimization identified vc = 31.09 m/min, fz = 0.042 mm/tooth, and ax = 0.5 mm as the optimum combination based on the highest S/N ratio, since this method selects the most robust condition against experimental variation rather than simply the lowest observed value.

Signal-to-Noise (S/N) Ratio Analysis

The Taguchi method was applied using the Smaller-the-Better characteristic, since lower Ra indicates better performance; the S/N response is presented in Table 3, with the corresponding Main Effects Plot in Image 4.

Feed per tooth (fz) exhibited the largest Delta value, followed by cutting speed (vc) and axial depth of cut (ax), confirming it as the most influential parameter consistent with(Gunjal et al., 2021; Rahman et al., 2021; Savković et al., 2020). The optimum combination (vc = 31.09 m/min, fz = 0.042 mm/tooth, ax = 0.5 mm) produced the highest S/N ratio, indicating that high cutting speed, low feed per tooth, and shallow axial depth of cut jointly promote stable, high-quality face milling of S45C steel under coconut oil-based MQL.

Table 3. Response Table for Signal-to-Noise Ratio (Smaller-the-Better)

Level	Cutting speed (vc)	Feed per tooth (fz)	Axial depth of cut (ax)
1	6.421	7.672	7.175
2	6.008	7.594	6.878
3	7.509	4.671	5.885
Delta	1.502	3.000	1.291
Rank	2	1	3

The combined effects of the three parameters on surface roughness are illustrated in Image 4.

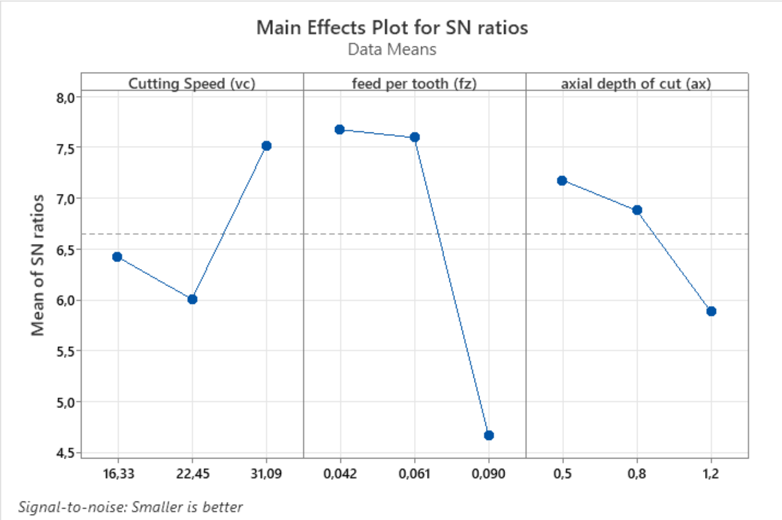

Image 4. Main Effects Plot for S/N Ratio

Higher cutting speed improved surface finish by reducing built-up edge formation and stabilizing chip removal, whereas increasing feed per tooth raised surface roughness due to larger feed marks. Axial depth of cut had only a slight influence, as the tested depths remained within the machine's stable cutting region.

Analysis of Variance (ANOVA)

Analysis of Variance (ANOVA) was performed to evaluate the statistical significance of each machining parameter affecting surface roughness. The ANOVA results are summarized in Table 4.

Table 4. Analysis of Variance (ANOVA) for Surface Roughness (Ra)

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Cutting speed (vc)	2	0.04654	0.02370	2.57	0.102
Feed per tooth (fz)	2	0.16116	0.080581	8.90	0.002
Axial depth of cut (ax)	2	0.01992	0.009959	1.10	0.352
Error	20	0.18116	0.009058		
Total	26	0.40879			

The statistical analysis indicates that feed per tooth (fz) significantly affects surface roughness, with a P-value of 0.002, which is lower than the significance level of 0.05. Therefore, feed per tooth (fz) is considered the most significant machining parameter.

Meanwhile, cutting speed (vc) and axial depth of cut (ax) produced P-values greater than 0.05, indicating that their effects were statistically less significant within the investigated parameter range. The percentage contribution of each machining parameter obtained from the ANOVA analysis is presented in Table 5.

Table 5. Percentage Contribution of Machining Parameters Based on ANOVA

Factor	Adj SS	Contribution (%)
Cutting Speed (vc)	0.04654	11.39
Feed per tooth (fz)	0.16116	39.42

Axial Depth of Cut (ax)	0.01992	4.87
Error	0.18116	44.32
Total	0.40879	100

These percentage contributions confirm feed per tooth as the dominant source of surface irregularities, followed by a moderate effect from cutting speed via chip formation and built-up edge reduction, while axial depth of cut remained within a stable machining region. The remaining 44.32% reflects experimental error and uncontrolled variables such as machine vibration, tool condition, and measurement uncertainty.

Effect of Machining Parameters on Surface Roughness

Cutting speed (vc) ranked second in influence (Table 3), and although its ANOVA effect was not statistically significant (Table 4–5), increasing vc still tended to improve surface finish by reducing built-up edge (BUE) formation and stabilizing chip flow a more stable tool–workpiece interaction produced a smoother surface. This is consistent with (Rahman et al., 2021; Savković et al., 2020), who reported similar improvements at higher cutting speeds in Ti6Al4V and Al7075, respectively indicating that this effect is not limited to non-ferrous alloys and also extends to S45C steel under coconut oil-based MQL

Surface roughness increased with feed per tooth (fz) because larger feed values produced wider feed marks and a greater theoretical scallop height, consistent with fz being the dominant parameter identified in Tables 3–5. This aligns with the surface generation mechanism in milling and with (Rahman et al., 2021; Savković et al., 2020), and, more directly, with (Thi Kim Lien et al., 2023), the only prior study on S45C steel, which likewise found fz dominant — though under dry/conventional cooling. The present results show this dominance persists even under coconut oil-based MQL, confirming that lubrication strategy does not change the underlying scallop-height mechanism.

Axial depth of cut (ax) had the smallest influence among the three parameters (Table 3–5), with no statistically significant effect within the investigated range. Similar to previous face milling studies, shallow axial depths of cut primarily affected material removal rate rather than surface quality — consistent with (Rahman et al., 2021; Savković et al., 2020), hallow axial depths did not generate sufficient cutting force or vibration to affect surface quality. This minor effect held across markedly different materials (Ti6Al4V, Al7075, and now S45C steel), suggesting ax is comparatively material-independent relative to fz and vc. Overall, surface quality was governed mainly by fz and vc, as illustrated in the main effects plot for means (Image 5).

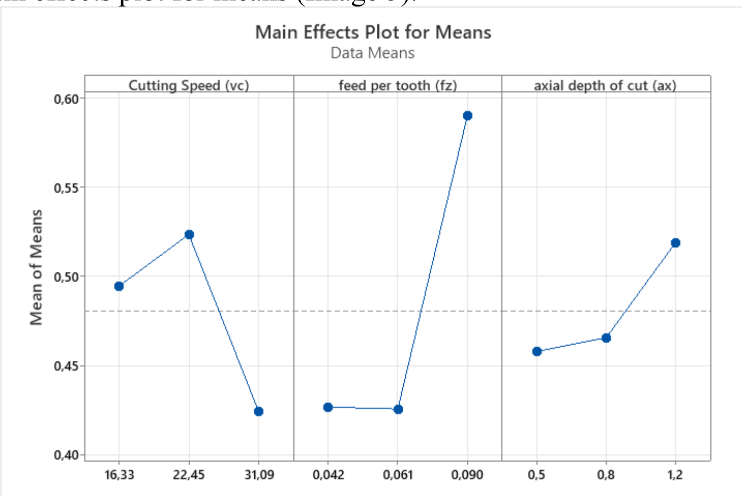

Image 5. Effect of machining parameters on surface roughness

Verification Experiment of Optimal Machining Parameters

The predicted Signal-to-Noise (S/N) ratio at the optimum machining condition was determined using the Taguchi additive model. The optimum parameter combination obtained from the Signal-to-Noise (S/N) ratio analysis was vc3 – fz1– ax1, corresponding to a cutting speed of 31.09 m/min, feed per tooth of 0.042 mm/tooth, and axial depth of cut of 0.5 mm. The predicted Signal-to-Noise (S/N) ratio was calculated based on the overall mean Signal-to-Noise (S/N) ratio and the contribution of each selected factor level.

Table 6. Verification experiment results of optimal machining parameters

Response	Predicted value	Confirmation experiment
Cutting speed, vc (m/min)	31.09	31.09
Feed per tooth, fz (mm/tooth)	0.042	0.042
Axial depth of cut, ax (mm)	0.5	0.5
Signal-to-Noise (S/N) ratio (dB)	9.242	7.535
Surface roughness, Ra (μm)	0.345	0.420

The predicted response was validated through a confirmation experiment at the optimum condition (vc = 31.09 m/min, fz = 0.042 mm/tooth, ax = 0.5 mm), which produced Ra = 0.420 μm and an S/N ratio of 7.535 dB, versus the predicted Ra = 0.345 μm and S/N ratio of 9.242 dB (Table 6). The 0.075 μm (≈21.7%) deviation is acceptable for practical machining, since the Taguchi additive model estimates the optimum from average factor effects rather than all sources of variability (tool wear, vibration, material heterogeneity, MQL droplet distribution). Both results consistently point to the same optimum condition, confirming that the Taguchi approach reliably identifies robust, sustainable face milling parameters for S45C steel under coconut oil-based MQL.

Green Machining Performance

Beyond the statistical optimization of surface roughness, the environmental dimension of this study central to its green machining framing established in the Introduction — warrants explicit discussion. The use of coconut oil-based MQL supports sustainable manufacturing by substantially reducing cutting fluid consumption compared with conventional flood cooling, while still maintaining satisfactory machining performance, consistent with (Arsene et al., 2021; Metla et al., 2025; Parray et al., 2025). Combined with the optimized parameters identified in this study (vc = 31.09 m/min, fz = 0.042 mm/tooth, ax = 0.5 mm), this approach minimizes environmental pollution and lubricant waste while delivering good surface quality, demonstrating that coconut oil-based MQL and Taguchi optimization together offer an effective pathway toward sustainable face milling.

CONCLUSION

This study successfully addressed the four objectives set out in the Introduction. Cutting speed, feed per tooth, and axial depth of cut were shown to have significantly different levels of influence on surface roughness, with feed per tooth (fz) confirmed as the most influential parameter (39.42% contribution), followed by a moderate effect from cutting speed (vc, 11.39%) and a minor effect from axial depth of cut (ax, 4.87%). The optimum condition for minimizing surface roughness was identified as vc = 31.09 m/min, fz = 0.042 mm/tooth, and ax = 0.5 mm, which produced the most robust performance according to the Signal-to-Noise ratio. This predicted optimum was subsequently validated through a confirmation experiment, which achieved Ra = 0.420 μm — an acceptable deviation from the predicted value of 0.345 μm, thereby confirming the reliability of the Taguchi-based optimization approach.

The main contribution of this study is providing experimentally validated, statistically supported optimization of face milling parameters for S45C steel under coconut oil-based MQL, a combination previously underexplored beyond aluminum and titanium alloys, thereby advancing understanding of machining behavior under environmentally friendly lubrication.

From an industrial perspective, the findings offer practical guidelines for manufacturers seeking better surface quality while reducing cutting fluid consumption and environmental impact, showing that biodegradable coconut oil MQL can match flood-cooling performance while supporting cleaner, more sustainable manufacturing.

This study was limited to S45C steel, three machining parameters, and surface roughness as the response. Future research should examine additional responses such as tool wear, cutting force, and energy consumption across different biodegradable lubricants and workpiece materials.

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