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Development and Performance Evaluation of an Eco-Friendly Cutting Fluid using Aloe Vera for Sustainable Turning Operations

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Development and Performance Evaluation of an Eco-Friendly Aloe Vera-Based Cutting Fluid for Sustainable Turning of Mild Steel

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Highlights

- Aloe vera cutting fluid cut average turning temperature by 10.9% versus oil.
- Chip thickness fell 7.2% and the chip reduction coefficient fell 3.7% with aloe vera.
- Factorial and RSM models explained over 91% of the temperature variance.
- Depth of cut was the dominant factor for both temperature and chip compression.
- The biodegradable fluid needs no hazardous-waste disposal, unlike mineral oil.

Abstract

An aloe vera-based cutting fluid was developed and tested as an eco-friendly alternative to petroleum-based fluids for turning mild steel. Conventional water-soluble cutting fluids cool and lubricate effectively, but most do not biodegrade and have been linked to skin and respiratory problems in machine operators. Fresh aloe vera gel was extracted, blended, filtered, and mixed with water at a 30:70 ratio to produce the experimental fluid, then tested against a conventional water-soluble oil emulsion (15% oil, 85% water) under identical turning conditions with a tungsten-coated carbide tool. Twenty-seven trials were run per fluid across a three-level, three-factor (3^3) design varying cutting speed, feed rate, and depth of cut. Each trial recorded cutting temperature, chip thickness, and the chip reduction coefficient (ζ); flank wear was tracked separately under a toolmaker's microscope. Minitab handled factorial regression, response surface methodology, and analysis of variance. The aloe vera fluid outperformed the conventional fluid on every response measured: cutting temperature fell by 10.9%, chip thickness by roughly 7%, and ζ by about 3.7%, with the advantage held across the full tested range. Flank wear accumulated roughly 33% more slowly under aloe vera. Twelve regression models, factorial and response-surface, fitted the data well for temperature and chip thickness (R^2 above 91%) and moderately for ζ (R^2 65–73%). These results point to aloe vera-based cutting fluid as a viable, biodegradable, low-cost substitute for petroleum-based fluids in turning, worth testing across a broader range of cutting speeds, feeds, and workpiece materials before drawing firmer conclusions.

Keywords

Aloe vera; Cutting fluid; Sustainable machining; Turning; Biodegradable lubricant; Response surface methodology

1. Introduction

Turning generates heat mainly through plastic deformation of the workpiece and friction at the tool-chip and tool-workpiece interfaces. Once that heat crosses a certain threshold, tool wear accelerates, surface finish suffers, and the whole process becomes less stable. Manufacturers have addressed this for decades with petroleum-based cutting fluids, which cool and lubricate effectively but carry a real cost on the other end: improperly disposed fluid contaminates soil and water, and operators who work around these liquids daily are exposed to skin irritation and respiratory problems (Sokovic & Mijanovic, 2001; Debnath et al., 2014).

The scale of that cost is not trivial. A single machine shop running conventional water-soluble coolants can generate hundreds of liters of spent fluid per year, most of which is classified as hazardous industrial waste once it has picked up tramp oil, metal fines, and bacterial growth over its service life. Treating and disposing of that waste through licensed facilities is a recurring operating cost, and in regions without accessible treatment infrastructure, informal disposal into drains or open ground is common, with consequences for soil and groundwater quality that extend well beyond the factory boundary. Occupational exposure compounds the problem: prolonged skin contact with mineral oil emulsions is a well-documented cause of contact dermatitis among machinists, and fine coolant mist inhaled during high-speed operations has been linked to respiratory sensitization in longitudinal workplace studies. None of this is unique to any one country, but it falls hardest on small and medium-sized manufacturers who lack the capital to install closed-loop filtration, biocide dosing, and fluid-monitoring systems that larger operations use to extend fluid life and reduce disposal frequency.

Sustainable manufacturing has pushed this issue higher up the research agenda. Industries are expected to cut their environmental footprint without giving up productivity or part quality, and cutting fluid selection sits squarely inside that trade-off (Debnath et al., 2014). Vegetable oils, plant-based lubricants, and water-based biodegradable fluids have all drawn attention as replacements for mineral oil emulsions, since they can offer comparable lubrication with a smaller ecological cost (Shashidhara & Jayaram, 2010; Lawal et al., 2012). Their lubricity comes from fatty acid molecules that adsorb onto metal surfaces and form a boundary film, reducing friction at the tool-chip interface (Belluco & De Chiffre, 2004; Lawal et al., 2012). Vegetable oils such as palm, coconut, soybean, and castor oil have shown encouraging results on tool wear and cutting force in earlier studies (Ojolo et al., 2008; Lawal et al., 2013; Kuram et al., 2010), though poor oxidation stability, temperature-sensitive viscosity, and a short shelf life still limit how far they have moved into industrial practice (Shashidhara & Jayaram, 2010; Lawal et al., 2012).

The mechanism behind that lubrication deserves a closer look, since it is central to how any plant-derived fluid, including the one tested here, is expected to work. Fatty acid chains in vegetable oils carry a polar carboxyl group at one end that bonds chemically to the metal surface, while the long hydrocarbon tail orients away from the surface and forms a low-shear-strength boundary layer a few molecules thick. That layer keeps the tool and chip from making full metal-to-metal contact even under the high pressures generated in the cutting zone, which is why these fluids can reduce friction even at concentrations and delivery pressures too low to sustain a full hydrodynamic oil film. This boundary-lubrication effect is measurable in surface roughness and thrust force even when vegetable oil was diluted well below typical mineral-oil concentrations (Kuram et al., 2010), and a similar pattern was reported under minimum quantity lubrication with a vegetable-oil-based fluid in turning of alloy steel (Khan et al., 2009). The practical limitation is chemical rather than tribological: unsaturated fatty acid chains oxidize readily at the temperatures generated during cutting, which is what drives the short shelf life and gum formation that has kept many vegetable oils out of continuous industrial use despite their favorable friction behavior.

Aloe vera is a comparatively unexplored candidate. It is inexpensive, widely cultivated across South and Southeast Asia including Bangladesh, and its gel is naturally high in water content with a mucilaginous, polysaccharide-rich structure that could plausibly reduce friction at a sliding interface. Hartono et al. (2018) tested aloe vera gel as a cutting fluid using response surface methodology and reported it as a workable, environmentally friendly alternative to oil-based fluids in turning. Premkumar et al. (2024) combined aloe vera with coconut oil for turning EN-31 steel and found the blend performed well, though that formulation was oil-based rather than water-based. Marichelvam et al. (2022) developed a separate eco-friendly fluid for turning AISI 1010 steel, reinforcing the broader case for plant-derived alternatives. What is missing from this body of work is a straightforward water-based aloe vera formulation (gel and water, nothing else) evaluated across a full design-of-experiments matrix on mild steel, with cutting temperature, chip thickness, and chip reduction coefficient all measured and modelled statistically. Most sustainable-machining studies to date have concentrated on surface roughness, cutting force, and flank wear; chip-formation

behavior under a biodegradable fluid has received comparatively little attention (Shaw, 2005; Boothroyd & Knight, 2006).

This study addresses that gap. A cutting fluid made from 30% fresh aloe vera gel and 70% water was formulated and tested against a conventional water-soluble oil emulsion (15% oil, 85% water) during turning of mild steel with a tungsten-coated carbide tool. The specific objectives were to: (i) formulate a biodegradable aloe vera-based cutting fluid; (ii) compare its machining performance against the conventional fluid under identical conditions; (iii) quantify how cutting speed, feed rate, and depth of cut affect cutting temperature, chip thickness, and chip reduction coefficient (ζ) under each fluid; (iv) compare tool wear across dry, conventional, and aloe vera conditions; and (v) build and evaluate factorial and response-surface regression models for each response using Minitab. The aim throughout is not to declare aloe vera fluid a finished commercial product, but to establish, with controlled experimental data, whether it holds up as a viable and more sustainable alternative within a defined machining envelope.

2. Materials and methods

2.1 Workpiece material and cutting tool

Mild steel was used as the workpiece material throughout the study. Its moderate hardness and predictable machinability make it a practical choice for isolating fluid effects, since it produces measurable responses across all output variables without wearing the tool out before data collection is complete. Its relevant mechanical and physical properties are summarized in Table 1. Continuous chip formation at the cutting conditions used here sustains contact between the insert rake face and the chip. That is the zone where most cutting heat is generated and where the cutting fluid has the clearest opportunity to reduce friction and interface temperature.

Table 1. *Mechanical and physical properties of the mild steel workpiece.*

Property	Value	Unit
Carbon content	0.15–0.30	wt%
Tensile strength	400–550	MPa
Yield strength	250–350	MPa
Hardness	120–160	HB
Density	7.85	g/cm³
Thermal conductivity	~50	W/m·K
Melting point	~1370–1400	°C

All turning trials used a tungsten-coated carbide insert (square SNMG geometry) mounted in a square turret holder, chosen for its widespread use in steel turning and its transferability to industrial practice. A fresh cutting edge was used for each experimental configuration. The insert's Vickers hardness (1500–1800 HV) and thermal hardness retention to roughly 900 °C are well above the mechanical and thermal loads generated in this study, so the tool retained its integrity throughout testing. The tungsten carbide (WC-Co) substrate also carries a transverse rupture strength of 1400–2000 MPa and an elastic modulus of 550–600 GPa, both well above the corresponding properties of the mild steel workpiece; the high elastic modulus in particular limits tool deflection under cutting force, which helps keep the depth of cut consistent across the 54 experimental runs rather than drifting as the tool engages the workpiece. Fig. 1 shows the coated insert used throughout the trials, including the wear marks on its cutting corners after use.



Fig. 1. *Tungsten-coated carbide square insert (SNMG geometry) used in the turning trials.*

2.2 Turning machine and fluid delivery

Experiments were carried out on a DC1660-E geared-head precision lathe. Cutting speed was set through the gearbox's speed range, feed rate through the carriage feed mechanism, and depth of cut through the cross-slide; all three were verified before each run (Fig. 2, Fig. 3). The workpiece was held in a three-jaw chuck and supported by the tailstock to limit deflection under cutting force.



Fig. 2. *DC1660-E geared-head precision lathe: speed and feed control panel.*



Fig. 3. *DC1660-E conventional centre lathe, full machine view.*

Cutting fluid was delivered to the tool-chip interface through a pressurized spray system fed by an air compressor (Fig. 4, Fig. 5), with a flow meter and pressure gauge to keep the delivery rate constant across runs, since an uncontrolled change in flow rate would have introduced an extra variable into the comparison.



Fig. 4. *Pressurized cutting-fluid delivery system with flow meter and pressure gauge.*



Fig. 5. *Air compressor used to pressurize the cutting-fluid delivery system.*

2.3 Preparation of cutting fluids

The aloe vera fluid was prepared from fresh Aloe barbadense leaves, washed to remove surface contamination, then cut lengthwise so the inner gel could be scraped away from the leaf skin. The gel was blended to a uniform consistency and filtered to remove fibrous matter that could clog the delivery nozzle, then mixed with water to give a final concentration of 30% gel to 70% water by volume. Higher gel concentrations were tried but proved too viscous for consistent delivery through the spray nozzle; 30% retained enough gel content for a measurable lubricating film while staying pumpable at room temperature. Fluid was prepared fresh on the day of testing and used within a few hours, since the polysaccharide and saponin components responsible for lubrication degrade over time without preservatives. The preparation sequence, from leaf collection through gel extraction, blending, filtering, and final dilution, is summarized in Fig. 6.

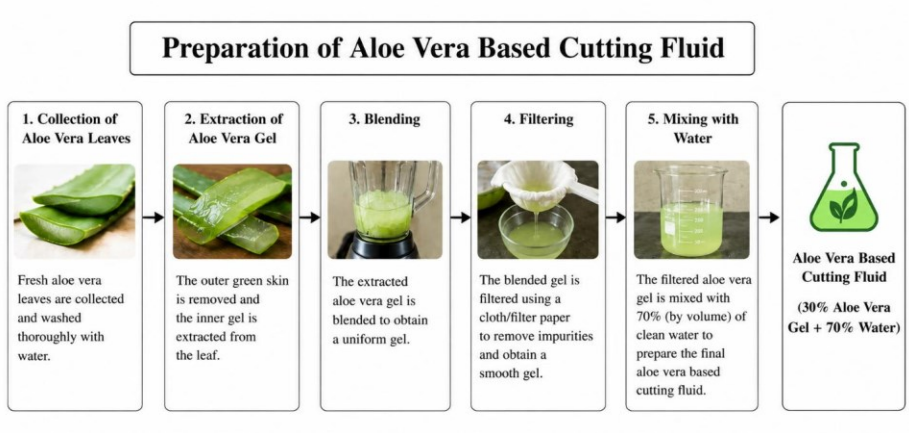


Fig. 6. *Preparation sequence for the aloe vera-based cutting fluid.*

The conventional fluid was a commercial water-soluble cutting oil diluted to 15% oil and 85% water by volume, a standard dilution for general-purpose steel turning. Table 2 summarizes both formulations. The aloe vera fluid relies on its natural polysaccharide structure for lubrication and its water content for cooling; the conventional fluid achieves the same two functions through an emulsified oil-in-water system. Testing both cutting fluids under identical machining conditions isolates fluid chemistry as the variable responsible for any performance difference.

Table 2. *Cutting fluid formulations compared in this study.*

Property	Aloe vera-based fluid	Conventional fluid
Composition	30% aloe vera gel, 70% water	15% water-soluble oil, 85% water
Lubricating agent	Natural polysaccharides, saponins	Emulsified petroleum-derived oil
Cooling agent	Water (70%)	Water (85%)
Preparation	Manual extraction, blending, filtering	Direct dilution with water
Environmental impact	Biodegradable, non-toxic	Requires controlled disposal

2.4 Machining parameters and experimental design

Cutting speed, feed rate, and depth of cut were selected as the input factors, each tested at three levels spanning a practical operating range for mild steel with a coated carbide tool (Table 3). A full 3^3 factorial design produced 27 experimental runs per fluid (54 runs in total), chosen over a fractional design because it estimates all main effects and two- and three-way interactions without confounding, which matters here since interaction effects (for example, how the influence of speed on temperature might shift with depth of cut) could plausibly differ between the two fluids. Run order was randomized within each fluid configuration to limit systematic bias from gradual tool wear or ambient temperature drift over a testing session. Minitab 22 generated the design matrix and carried out all subsequent regression, ANOVA, and RSM analysis.

Table 3. *Machining parameters and levels.*

Parameter	Symbol	Level 1 (Low)	Level 2 (Mid)	Level 3 (High)	Unit
Cutting speed	A	185	265	315	RPM
Feed rate	B	0.10	0.16	0.21	mm/rev
Depth of cut	C	0.5	1.0	1.5	mm

2.5 Measurement of temperature, chip thickness, and chip reduction coefficient

Cutting temperature was measured with the tool-work thermocouple method: the electrical potential generated at the dissimilar-metal junction between tool and workpiece was recorded as a voltage and converted to temperature using a calibration equation specific to this tool-workpiece pairing,

$$T = 111.45 + 50.11V - 0.0505V^2$$

where T is temperature in °C and V is the measured voltage in millivolts. The quadratic form accounts for the way the junction's Seebeck coefficient shifts with temperature, and the same equation was applied across all 54 runs for comparability.

Chip thickness was measured with a digital slide caliper on chips collected under steady-state cutting, not at the start or end of a cut, where tool engagement produces unrepresentative geometry. Several measurements were taken along each chip's length and averaged, which reduces the noise introduced by chip curl and segmentation. The chip reduction coefficient, ζ, is the ratio of measured chip thickness (t_2) to the theoretical uncut chip thickness (t_1) for the given feed rate and tool geometry:

$$\zeta = t_2 / t_1$$

Values above 1 confirm chip compression along the shear plane, which is the expected outcome in turning; a lower ζ indicates a higher effective shear plane angle and, generally, less friction at the tool-chip interface.

2.6 Tool wear measurement

Flank wear was chosen as the wear criterion since it dominates in turning mild steel with coated carbide tools under these conditions and can be measured without damaging the insert. Wear was tracked with a Carl Zeiss toolmaker's microscope at 2-minute intervals over a 10-minute cutting period per configuration, with the insert cleaned and remounted in the same orientation between readings. The ISO flank wear limit of VB = 0.3 mm served as the tool-life reference, and the slope of the wear curve in its steady-state region gave the average wear rate for each condition. Measurements were taken with the Carl Zeiss toolmaker's microscope shown in Fig. 7.



Fig. 7. *Carl Zeiss toolmaker's microscope used for flank wear measurement.*

2.7 Statistical analysis

Data were analyzed in three stages using Minitab 22: factorial regression, analysis of variance, and response surface methodology. Factorial regression estimated main effects and interactions for each response, with terms judged significant at $p < 0.05$. RSM then fitted a second-order polynomial including squared terms, capable of representing curvature that the linear-plus-interaction factorial model cannot. Model adequacy was judged using R^2, adjusted R^2, and predicted R^2 and residuals were checked for normality, constant variance, and the absence of systematic patterns. Variance inflation factors were checked across all terms to rule out multicollinearity distorting the coefficient estimates.

Fitting both a factorial and an RSM model to the same 27-run dataset is only valid because each factor was tested at three levels rather than two. A two-level factorial design can estimate only linear main effects and interactions; it has no way to detect whether a response curves upward or downward between the low and high settings. Testing depth of cut, feed rate, and cutting speed at low, mid, and high levels gives the regression enough degrees of freedom to estimate the quadratic term for each factor directly from the same run matrix, without needing a separate center-point or augmented design such as a central composite arrangement. The trade-off is fewer replicate degrees of freedom for pure error compared to a design built specifically for RSM, which is part of why the predicted R^2 values reported in Section 3.6 run somewhat below the ordinary R^2 values for every model: the design was built to serve two analytical purposes at once, and it does both reasonably well without being optimal for either taken alone.

2.8 Health, safety, and environmental considerations

Eye protection was worn throughout, and chip collection followed complete spindle stop. The aloe vera fluid presented no known chemical hazard under normal handling and was disposed of through the general wastewater system, consistent with its biodegradability. The conventional fluid, containing emulsified petroleum-derived oil, was handled with nitrile gloves and disposed of following the institution's protocol for water-miscible metalworking fluids. Mild steel swarf was collected in the designated metal waste container; the modest chip volume generated across 54 short-duration runs did not create a handling hazard.

3. Results and discussion

3.1 Overview

Across all 27 matched run combinations, the aloe vera fluid returned lower values than the conventional fluid for every response measured (Fig. 8, Fig. 24). The clearest gap was in temperature: aloe vera averaged 475.74 °C against 533.89 °C for oil, a reduction of about 10.9%. Chip thickness under aloe vera was roughly 7% lower, and the mean chip reduction coefficient about 3.7% lower. Both fluids showed the expected pattern of rising temperature and chip thickness as cutting speed and depth of cut increased toward their upper levels, and the aloe vera advantage held across that entire range rather than appearing only at mild conditions. Twelve regression models in total (factorial and RSM, for three responses, under two fluids) were fitted in Minitab. Temperature and chip thickness models were highly adequate (R^2 consistently above 91%); ζ models were more moderate (R^2 in the 65–73% range). ζ is simply harder to model, since chip compression depends on more than the three controlled factors here.

3.2 Cutting temperature

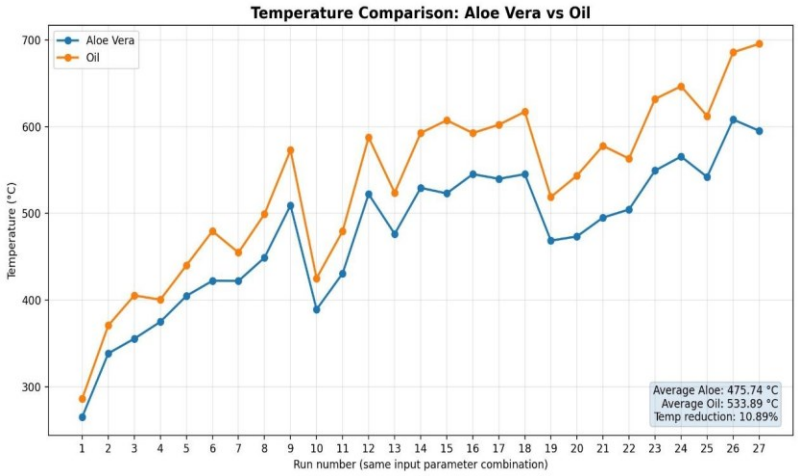


Fig. 8. *Cutting temperature across the 27 matched run combinations, aloe vera-based fluid vs. conventional oil-based fluid.*

Heat in orthogonal turning comes mainly from plastic deformation in the primary shear zone and friction at the rake face; a cutting fluid's job is to remove that heat convectively and to reduce the frictional component through lubrication. The aloe vera fluid outperformed oil on both counts. At the mildest parameter combinations, both fluids produced temperatures in the 265–410 °C range; at the most aggressive combinations of speed and depth of cut, oil climbed to nearly 700 °C while aloe vera peaked near 607 °C. The gap widened, rather than narrowed, under harsher conditions.

The factorial model centered at 471.93 °C for aloe vera versus 529.37 °C for oil; the RSM model centered at 500.70 °C versus 558.60 °C. In both models and both fluids, depth of cut, feed rate, and cutting speed were all significant at $p = 0.000$, with depth of cut dominant, consistent with established turning theory: a deeper cut increases the volume of material sheared per unit time and therefore the total heat generated. RSM improved on the factorial fit by roughly 3–5 percentage points in R^2 for both fluids (Table 5), driven by a significant quadratic depth-of-cut term, meaning temperature does not rise linearly with depth of cut across the tested range (Fig. 9, Fig. 10).

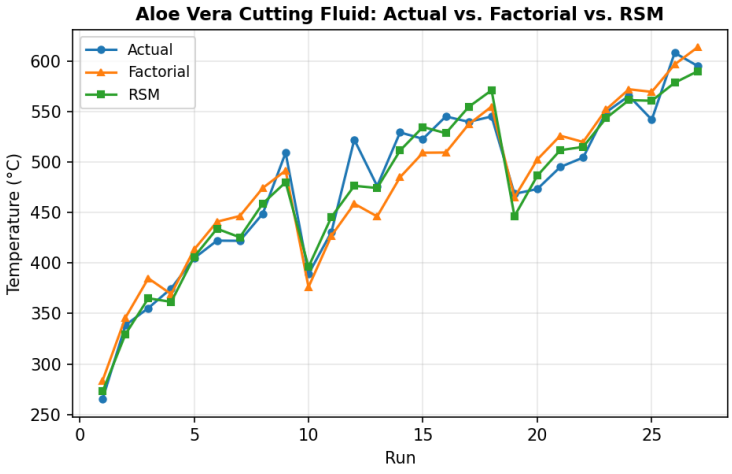


Fig. 9. *Aloe vera-based fluid: actual cutting temperature vs. factorial and RSM model predictions.*

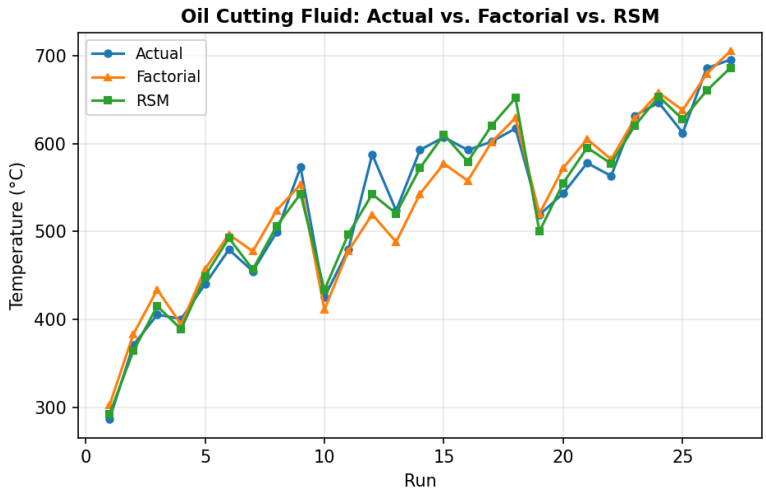
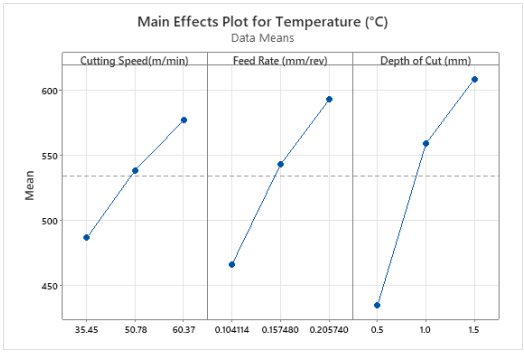


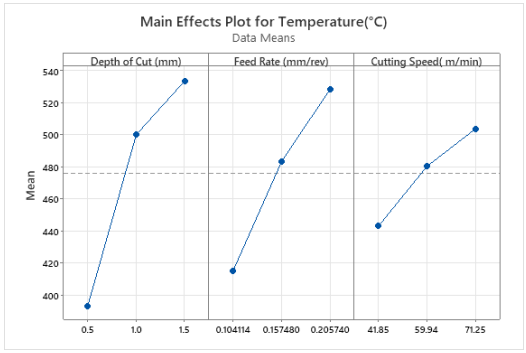
Fig. 10. *Conventional oil-based fluid: actual cutting temperature vs. factorial and RSM model predictions.*

The physical explanation likely rests on two mechanisms working together. The aloe vera formulation's 70% water fraction gives it a specific heat capacity and thermal conductivity closer to pure water than the oil emulsion achieves, so more heat is carried away per unit volume delivered. The gel's polysaccharide matrix then contributes a secondary effect: a thin boundary film at the tool-chip interface that lowers rake-face friction, which reduces the heat generated at the secondary shear zone on top of the cooling benefit.

The main effects plot for temperature (Fig. 11) shows the response mean at each factor level for depth of cut, feed rate, and cutting speed. Depth of cut produces the steepest slope for both fluids, feed rates the second steepest, and cutting speed the shallowest, matching the significance ordering reported above.



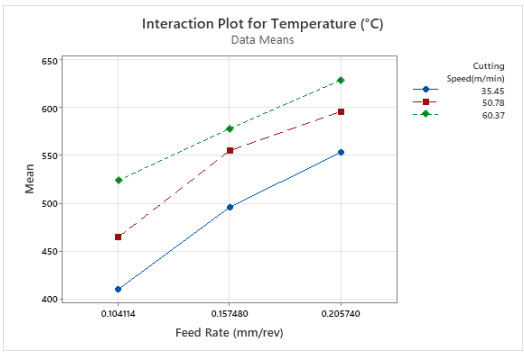
(a) Oil-based fluid



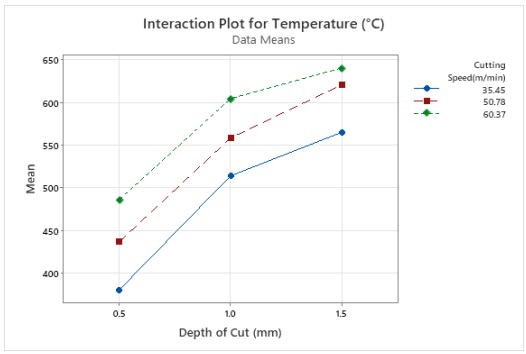
(b) Aloe vera-based fluid

Fig. 11. *Main effects plot for cutting temperature.*

The interaction plot for temperature (Fig. 12) shows the factor-level lines for depth of cut, feed rate, and cutting speed running close to parallel across their range, for both fluids, which is the visual counterpart of the finding that no two-way or three-way interaction reached significance for temperature (Section 3.6).



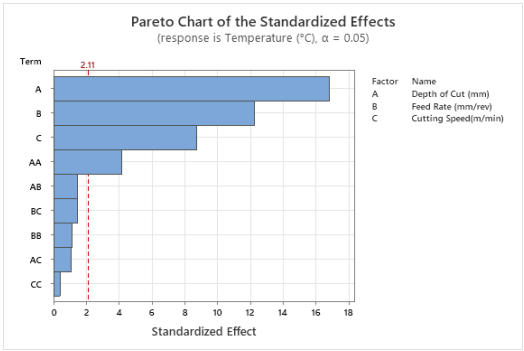
(a) Oil-based fluid



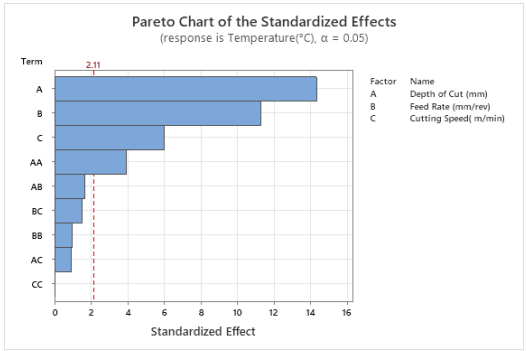
(b) Aloe vera-based fluid

Fig. 12. *Interaction plot for cutting temperature.*

The Pareto chart of standardized effects for the RSM temperature model (Fig. 13) gives the same ranking a formal significance cutoff: depth of cut, feed rate, cutting speed, and the depth-of-cut squared term all cross the α = 0.05 reference line, while every interaction term falls short of it.



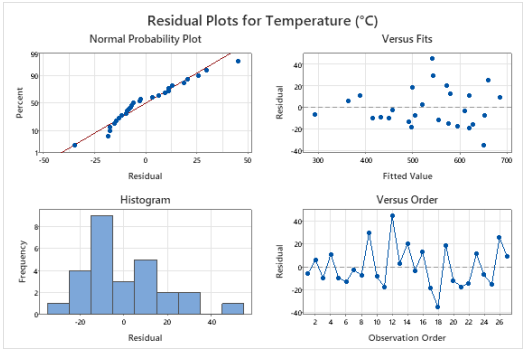
(a) Oil-based fluid



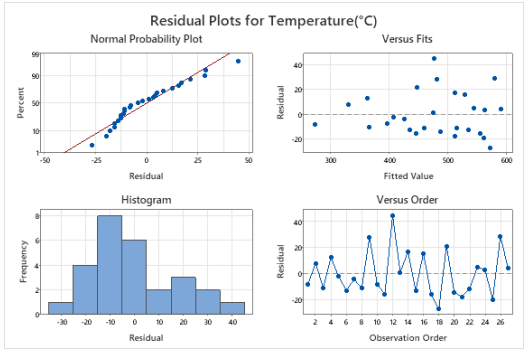
(b) Aloe vera-based fluid

Fig. 13. *Pareto chart of standardized effects for the RSM temperature model (α = 0.05).*

Residual diagnostics for the temperature RSM model (Fig. 14) support the model's adequacy for both fluids: the normal probability plot tracks the reference line closely aside from mild deviation at one flagged high-residual run, the residuals-versus-fitted-value plot shows an even scatter with no funnel or curvature, and the residuals-versus-order plot shows no directional drift across the run sequence.



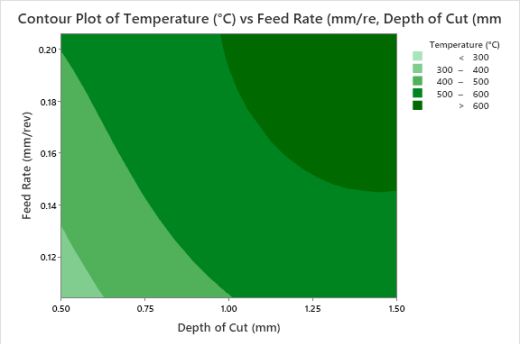
(a) Oil-based fluid



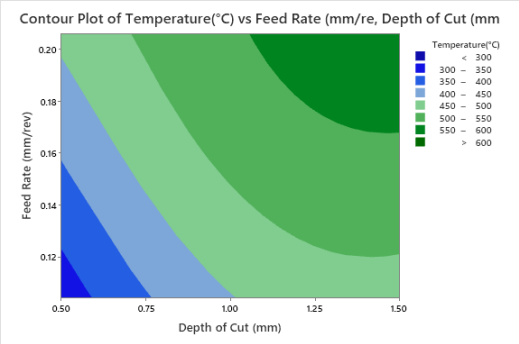
(b) Aloe vera-based fluid

Fig. 14. *Four-in-one residual diagnostic plots for the RSM temperature model.*

The contour plot of temperature against feed rate and depth of cut (Fig. 15) shows the practical operating window implied by the model: the lowest-temperature region sits clearly at the lower-left corner (shallow depth of cut, low feed rate) for both fluids, and the shade bands run in an almost parallel diagonal pattern, consistent with the absence of a significant two-way interaction for this response.



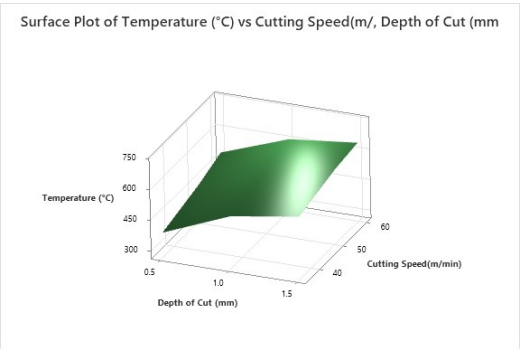
(a) Oil-based fluid



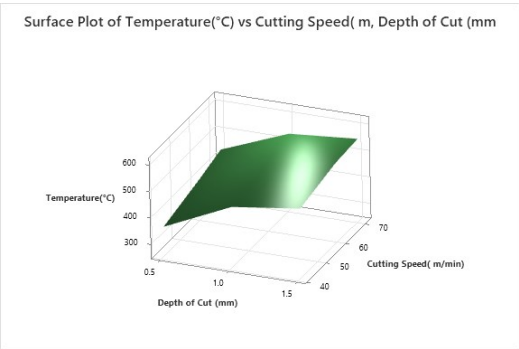
(b) Aloe vera-based fluid

Fig. 15. *Contour plot of cutting temperature versus feed rate and depth of cut (cutting speed held at its centre-point level).*

The response surface of temperature against cutting speed and depth of cut (Fig. 16) shows a gently curved, rising sheet rather than a flat plane, visualizing the significant depth-of-cut quadratic term reported above.



(a) Oil-based fluid



(b) Aloe vera-based fluid

Fig. 16. *Response surface of cutting temperature versus cutting speed and depth of cut (feed rate held at its centre-point level).*

3.3 Chip thickness

Chip thickness reflects how much the workpiece material compresses as it crosses the shear plane during cutting; better lubrication shortens the tool-chip contact length, raises the shear plane angle, and produces a thinner chip for the same uncut thickness. The factorial center value for chip thickness dropped from 0.4066 mm under oil to 0.3772 mm under aloe vera, a 7.24% reduction; the RSM models gave 0.4002 mm and 0.3727 mm, a 6.87% reduction. Feed rate was the dominant factor for chip thickness in both fluids ($p = 0.000$), which follows directly from its role in setting uncut chip thickness per revolution; depth of cut was the second most significant factor. Under aloe vera, cutting speed approached significance in the RSM model ($p = 0.091$). That is not conclusive, but it is consistent with the gel's lower viscosity allowing faster re-application to the cutting zone between revolutions.

The reduction is attributable to the same boundary-lubrication mechanism discussed for temperature: polysaccharide compounds in the gel adsorb onto the rake face, lower the friction coefficient, and raise the shear plane angle by Merchant's circle of forces, producing a thinner chip. Lower cutting temperatures compound this indirectly, since a cooler interface limits the softening of workpiece material in the secondary shear zone.

Model adequacy for chip thickness followed the same pattern established for temperature: strong fits for both fluids, with aloe vera again returning a marginally tighter residual spread (Table 4). Depth of cut and feed rate together accounted for the overwhelming majority of explained variance in both the factorial and RSM decompositions. The depth-of-cut × cutting-speed interaction reached significance for the oil-based fluid ($F = 5.26$, $p = 0.033$) and approached significance for aloe vera ($F = 4.13$, $p = 0.056$), a milder version of the same interaction that was more strongly significant for ζ (Section 3.4). That gradient is informative in its own right: chip thickness is driven mainly

by additive main effects with only a modest interaction contribution, while chip compression, captured by ζ, depends on that same depth-of-cut × cutting-speed interaction much more heavily.

Across every matched run, aloe vera produced a thinner chip than oil (Fig. 17). The mean chip thickness came out to 0.377 mm under aloe vera against 0.408 mm under oil, a 7.62% reduction, and the gap holds at both the low and high ends of the cutting range rather than narrowing under harsher conditions, consistent with a genuine lubrication effect at the tool-chip interface rather than a difference that only shows up at mild settings.

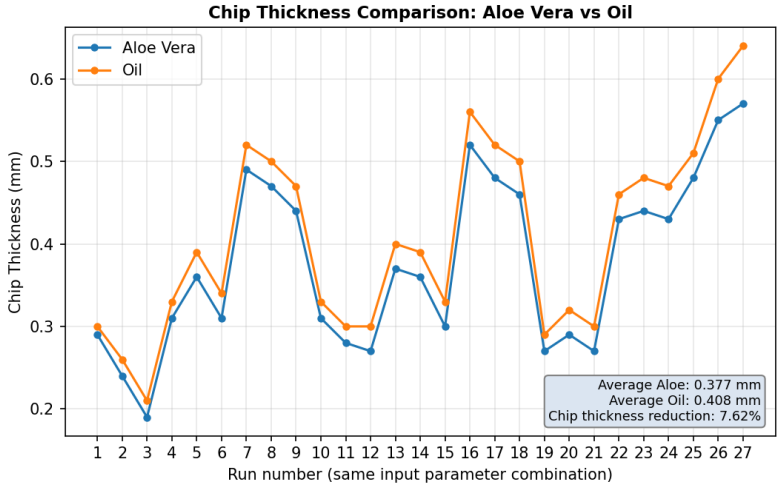


Fig. 17. *Chip thickness across all 27 matched run combinations, aloe vera-based fluid vs. conventional oil-based fluid.*

Both the factorial and RSM models track the actual chip thickness values closely across the full run sequence for both fluids (Fig. 18, Fig. 19), including the sharp rises and drops between parameter combinations. The RSM curve sits slightly nearer the actual line than the factorial curve at several points for both fluids, consistent with RSM's marginally higher R^2 for this response (Table 4).

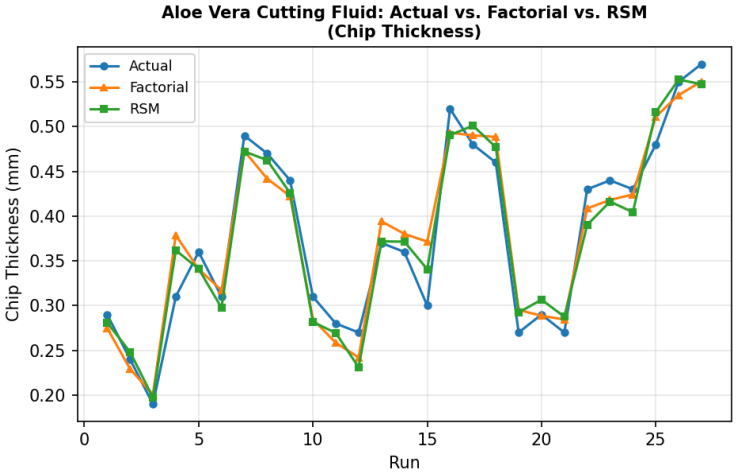


Fig. 18. *Aloe vera-based fluid: actual chip thickness vs. factorial and RSM model predictions across 27 runs.*

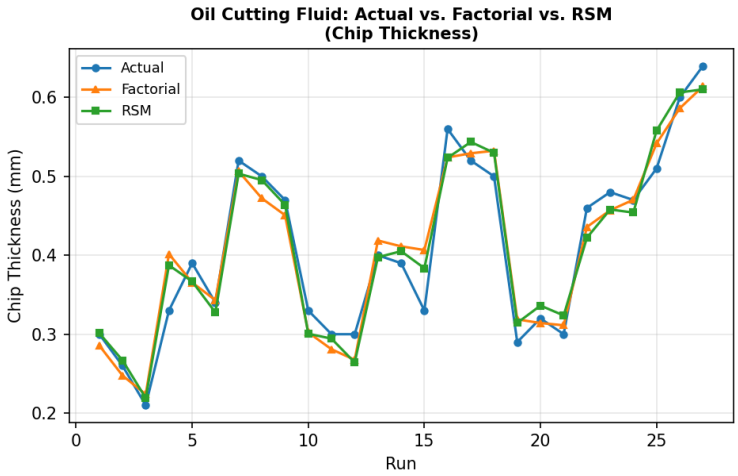
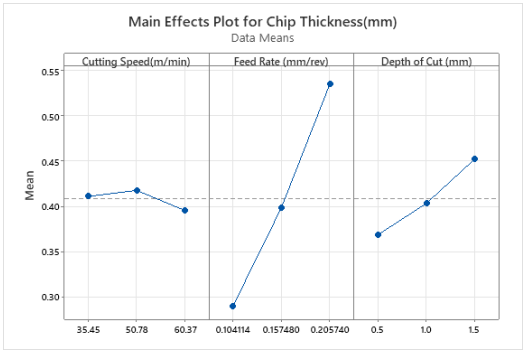


Fig. 19. *Conventional oil-based fluid: actual chip thickness vs. factorial and RSM model predictions across 27 runs.*

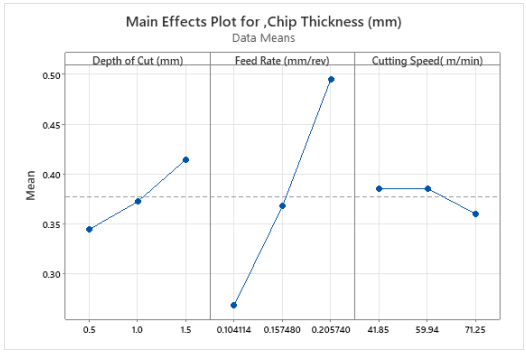
Table 4. *Chip thickness regression model adequacy — oil vs. aloe vera.*

Model indicator	Oil	Aloe vera
Factorial R^2	93.17%	92.94%
Factorial adj. R^2	90.65%	90.34%
Factorial pred. R^2	84.82%	84.08%
Factorial S (residual error)	0.0347 mm	0.0324 mm
RSM R^2	94.24%	94.56%
RSM adj. R^2	91.19%	91.68%
RSM pred. R^2	84.57%	85.44%
RSM S	0.0337 mm	0.0301 mm

The main effects plot for chip thickness (Fig. 20) shows a markedly steeper slope for feed rate than for depth of cut or cutting speed in both fluids, the visual counterpart of the F-value gap between feed rate and the other two factors.



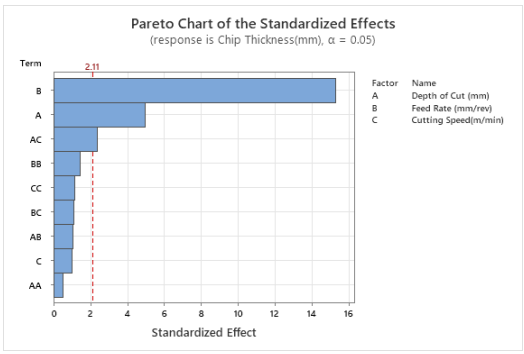
(a) Oil-based fluid



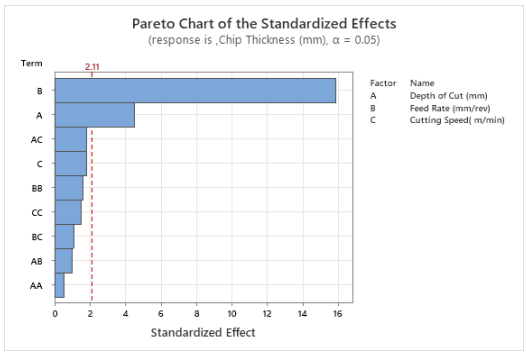
(b) Aloe vera-based fluid

Fig. 20. *Main effects plot for chip thickness.*

The Pareto chart for the RSM chip thickness model (Fig. 21) places feed rate as the dominant term, followed by depth of cut, with the depth-of-cut × cutting-speed interaction the only other term approaching or crossing the significance threshold.



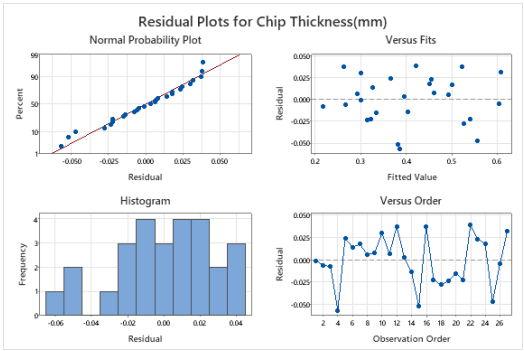
(a) Oil-based fluid



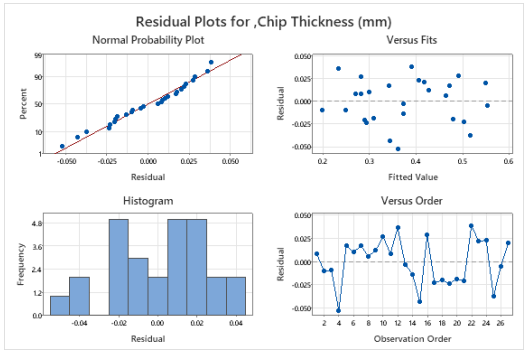
(b) Aloe vera-based fluid

Fig. 21. *Pareto chart of standardized effects for the RSM chip thickness model (α = 0.05).*

Residual diagnostics for the chip thickness RSM model (Fig. 22) show a well-behaved pattern for both fluids: an approximately linear normal probability plot, an even spread of residuals against fitted values, and no systematic trend across run order.



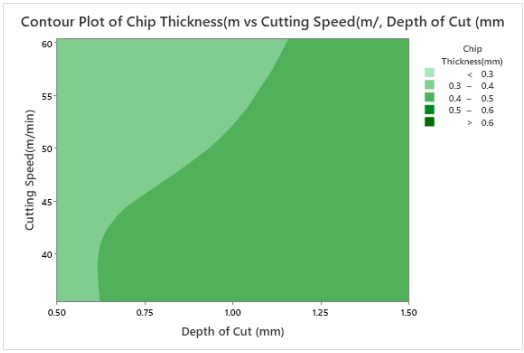
(a) Oil-based fluid



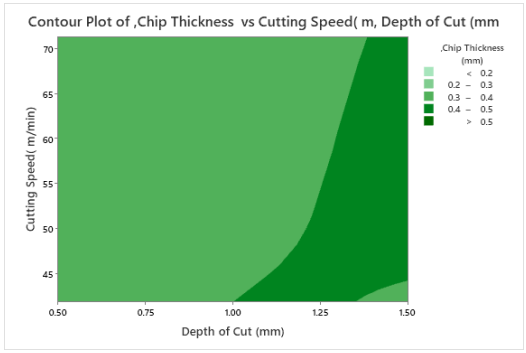
(b) Aloe vera-based fluid

Fig. 22. *Four-in-one residual diagnostic plots for the RSM chip thickness model.*

The contour plot of chip thickness against cutting speed and depth of cut (Fig. 23) is the most informative view of this response, since the slight curvature in its shade-band boundaries is the visual signature of the depth-of-cut × cutting-speed interaction discussed above.



(a) Oil-based fluid



(b) Aloe vera-based fluid

Fig. 23. *Contour plot of chip thickness versus cutting speed and depth of cut (feed rate held at its centre-point level).*

3.4 Chip reduction coefficient

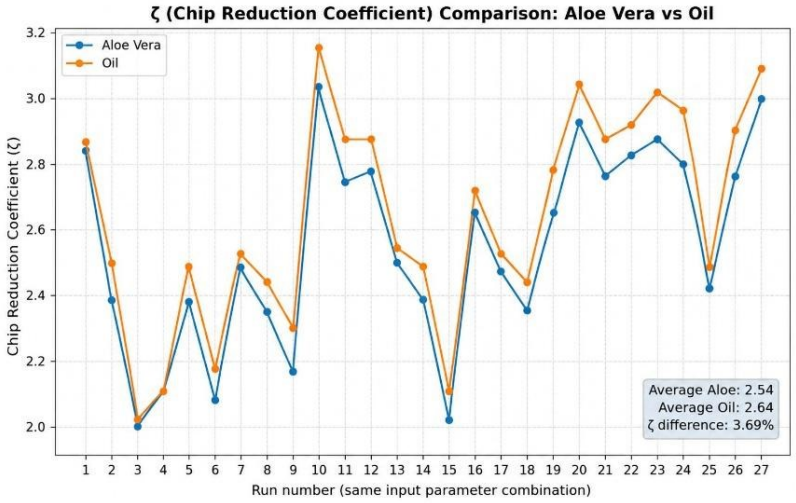


Fig. 24. *Chip reduction coefficient (ζ) across the 27 matched run combinations, aloe vera-based fluid vs. conventional oil-based fluid.*

The mean ζ was 2.54 under aloe vera versus 2.64 under oil, a 3.69% reduction that is smaller in percentage terms than the temperature or chip thickness gaps, but directionally consistent across the full run sequence. Factorial center values were 2.5590 (aloe vera) versus 2.6457 (oil); RSM centers were 2.5260 versus 2.6180. Depth of cut was again the most significant factor ($p = 0.000$) in both fluids, and the depth-of-cut by cutting-speed interaction was also significant, which makes physical sense: at greater depths, higher cutting speed raises contact pressure and sliding velocity simultaneously, intensifying friction and chip compression. Aloe vera's boundary film appears to partly offset that interaction, since its ζ stayed lower even at the more aggressive parameter combinations (Fig. 25, Fig. 26).

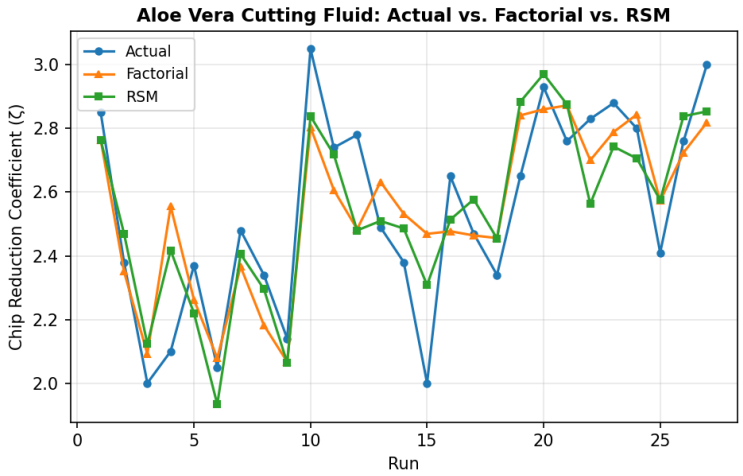


Fig. 25. *Aloe vera-based fluid: actual ζ vs. factorial and RSM model predictions.*

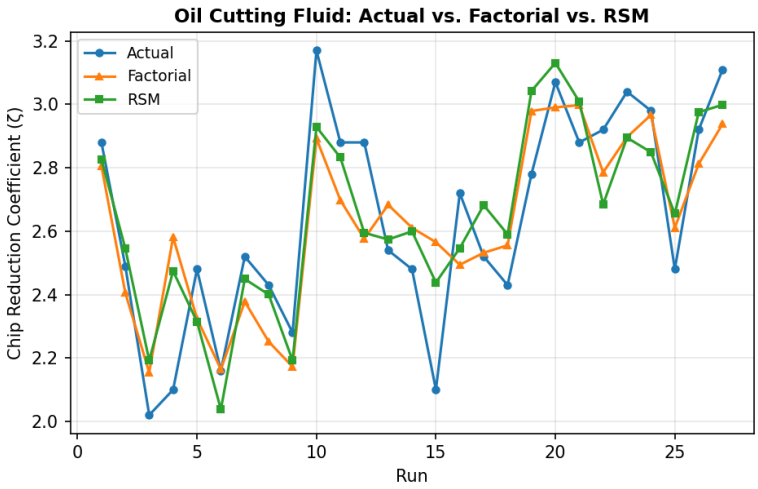
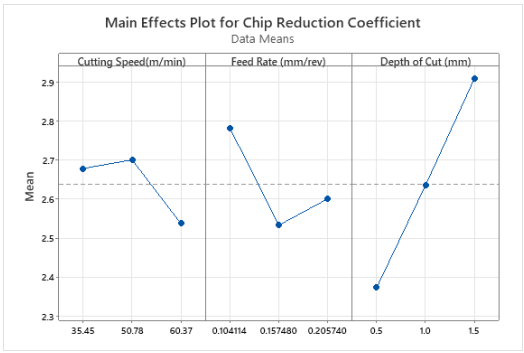


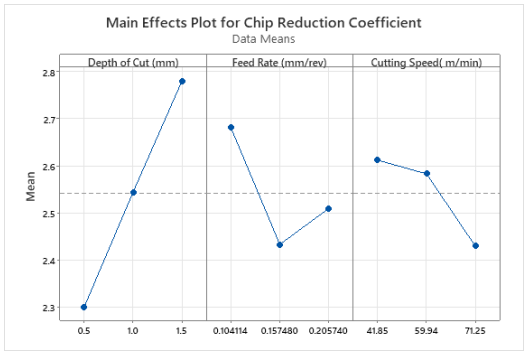
Fig. 26. *Conventional oil-based fluid: actual ζ vs. factorial and RSM model predictions.*

ζ was harder to model than the other two responses: R^2 sat in the 65–73% range compared with over 91% for temperature and chip thickness (Table 6). Chip compression is sensitive to variables outside the three controlled factors here, including tool wear state, local strain hardening, and minor variation in tool-chip contact conditions, none of which were captured in this design. This is consistent with what published turning studies generally report for ζ modelling, and it should be weighted accordingly rather than treated as a weakness unique to this dataset.

The main effects plot for ζ (Fig. 27) shows depth of cut with a clearly steeper slope than feed rate or cutting speed for both fluids, matching its position as the only factor significant at p = 0.000 in the ANOVA decomposition.



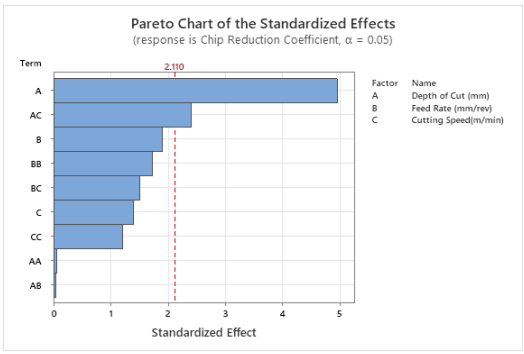
(a) Oil-based fluid



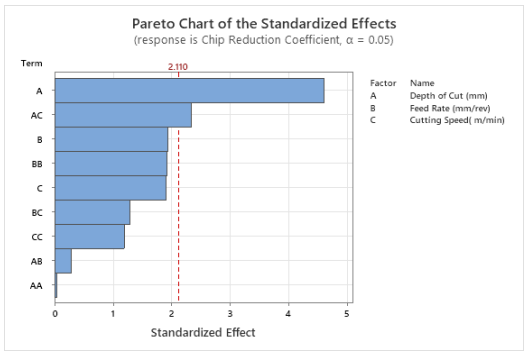
(b) Aloe vera-based fluid

Fig. 27. *Main effects plot for chip reduction coefficient (ζ).*

Only two terms cross the significance line for ζ in the Pareto chart (Fig. 28): depth of cut and its interaction with cutting speed. Feed rate falls just short of the threshold for both fluids, consistent with the model's comparatively low R^2.



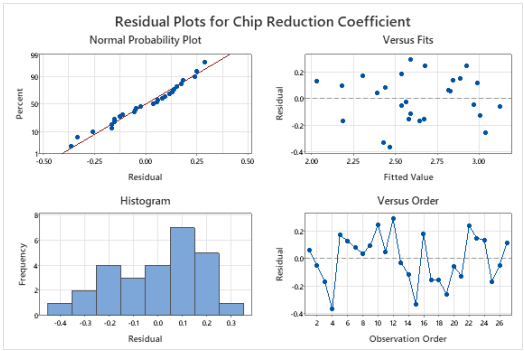
(a) Oil-based fluid



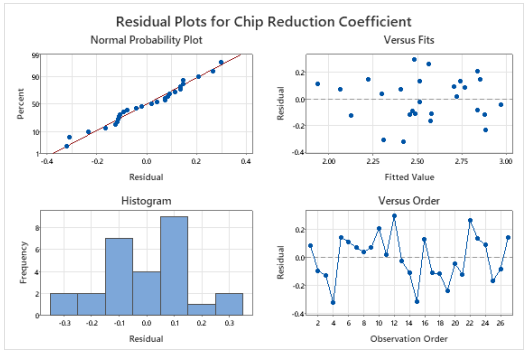
(b) Aloe vera-based fluid

Fig. 28. *Pareto chart of standardized effects for the RSM ζ model (α = 0.05).*

Residual diagnostics for the ζ model (Fig. 29) show more scatter than the temperature or chip thickness models, consistent with the lower R^2 reported above, but no systematic pattern against fitted values or run order that would indicate a missing model term rather than ordinary process noise.



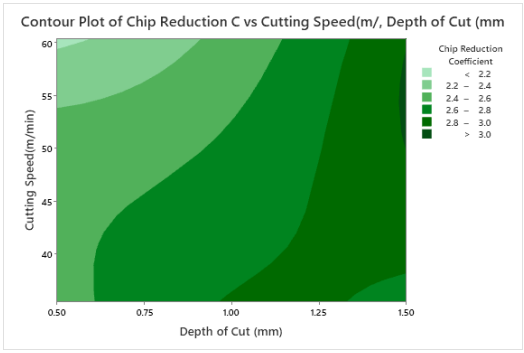
(a) Oil-based fluid



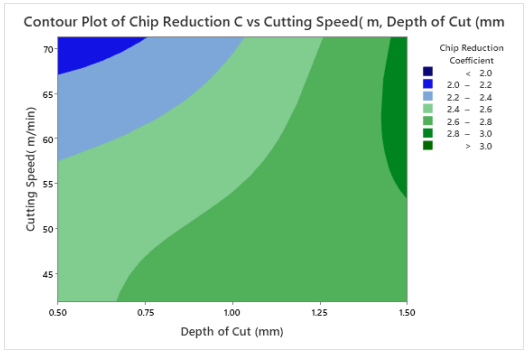
(b) Aloe vera-based fluid

Fig. 29. *Four-in-one residual diagnostic plots for the RSM ζ model.*

The contour plot of ζ against depth of cut and cutting speed (Fig. 30) shows visibly curved shade-band boundaries rather than straight lines, the clearest visual confirmation among the three responses of a real factor interaction, matching the significant depth-of-cut × cutting-speed term.



(a) Oil-based fluid



(b) Aloe vera-based fluid

Fig. 30. *Contour plot of chip reduction coefficient versus depth of cut and cutting speed (feed rate held at its centre-point level).*

3.5 Tool wear

Flank wear was tracked at 2-minute intervals over a 10-minute cutting period for the aloe vera fluid and the conventional oil-based fluid, at a fixed parameter setting held constant across the interval (Section 2.6). Both wear

curves rose steadily across the full test with no distinct running-in stage at the start and no sharp acceleration toward the end, consistent with steady-state flank wear progression rather than early tool failure (Fig. 31).

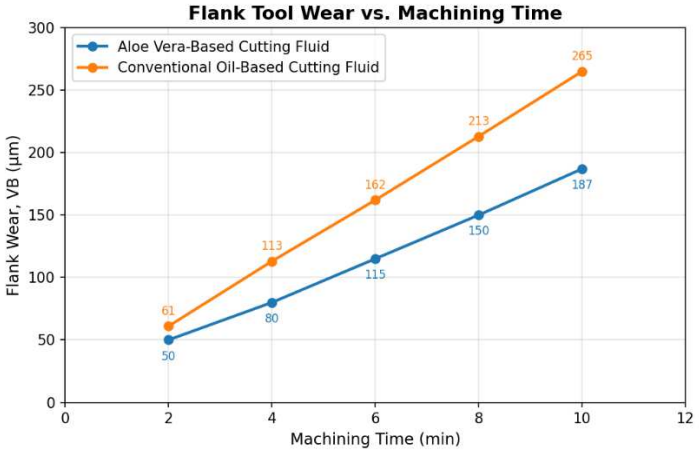


Fig. 31. *Flank wear accumulation over a 10-minute cutting period, aloe vera-based fluid (Tool Wear AVG) vs. conventional oil-based fluid (Tool Wear WS).*

At the first interval (2 min), the two fluids were only 11 µm apart (50 µm under aloe vera versus 61 µm under oil). By the final interval (10 min) that gap had widened to 78 µm (187 µm versus 265 µm), meaning the two wear curves diverge progressively rather than staying offset by a fixed amount. Over the full test, aloe vera accumulated 137 µm of flank wear against 204 µm for oil, an average wear rate of roughly 13.7 µm/min versus 20.4 µm/min, about 33% slower under aloe vera. At the 10-minute mark, flank wear under aloe vera was 29% lower than under oil. Neither fluid reached the ISO flank wear limit of VB = 0.3 mm within the test window, but the oil curve's steeper trajectory suggests it would cross that limit sooner under extended cutting; this study did not run cutting to tool failure, so that projection is an extrapolation from the observed slope rather than a measured tool-life figure.

This pattern is consistent with, and plausibly explained by, the temperature results in Section 3.2: lower tool-chip interface temperature under aloe vera would be expected to slow the diffusion and oxidation wear mechanisms that dominate flank wear in carbide tooling at these cutting conditions, since both mechanisms are thermally activated. The two measurements were not designed to formally establish causation between the temperature reduction and the wear-rate reduction, since tool wear was measured at a single fixed parameter combination rather than across the full 3^3 design used for the other three responses, but the direction of both results is consistent with established tool-wear theory and with each other.

3.6 Effect of machining parameters and interactions

Depth of cut was the most influential parameter for temperature and ζ across both fluids, following from its direct effect on engaged cutting-edge length and material removal rate. Feed rate, by contrast, dominated chip thickness specifically, and ranked second for temperature. Cutting speed had the weakest individual effect on temperature and ζ in this study, a result that can look counterintuitive until the speed range is considered: at the levels tested, higher speed's extra heat generation was partly offset by the shorter tool-chip contact time that comes with faster chip movement. Cutting speed mattered more through its interaction with depth of cut on ζ than as a main effect on its own. No two- or three-way interaction was significant for temperature in either fluid ($p > 0.05$), meaning the three main effects drive temperature largely independently of one another. For chip thickness, the depth-of-cut × cutting-speed interaction was significant for oil and close to significant for aloe vera (Section 3.3), a milder version of the same interaction that dominates ζ.

For process optimization, these patterns point in a specific direction: reducing depth of cut offers the biggest lever for cutting temperature, feed rate is the key variable for chip thickness control, and ζ management needs attention to both depth of cut and its interaction with cutting speed. Aloe vera's advantage held across all these parameter combinations

without requiring any change to machine settings, which matters for shops that cannot always run conservative parameters.

3.7 Statistical model adequacy

Table 5 and Table 6 summarize model performance for temperature and ζ, respectively; chip thickness followed the same pattern as temperature, with factorial and RSM R^2 between 92.9% and 94.6% for both fluids and a consistently lower residual error under aloe vera. Across all twelve fitted models, aloe vera returned a lower residual standard error than oil, so its regression fit sits tighter around the data, a sign of somewhat more consistent machining behavior rather than simply a better average.

Table 5. *Temperature regression model adequacy — oil vs. aloe vera.*

Model indicator	Oil	Aloe vera
Factorial R^2	93.55%	91.62%
Factorial S (residual error)	30.04	28.35
RSM R^2	96.90%	95.69%
RSM adj. R^2	95.26%	93.40%
RSM pred. R^2	91.89%	88.07%
RSM S	22.02	21.50

Table 6. *ζ regression model adequacy — oil vs. aloe vera.*

Model indicator	Oil	Aloe vera
Factorial R^2	65.10%	65.22%
Factorial S	0.2320	0.2169
RSM R^2	72.29%	73.20%
RSM adj. R^2	57.62%	58.81%
RSM S	0.2185	0.2013

One limitation applies across all twelve models: because the same 27-run, three-level design was used to fit both the factorial and the response-surface models (Section 2.7), the design carries fewer replicate degrees of freedom for pure error than a design built specifically for response-surface work, which inflates the variance of individual coefficient estimates without invalidating the broad comparisons. The findings here should be read at the level of clear trends (which factors are significant, which responses show consistent fluid-to-fluid differences) rather than as precise values for every coefficient.

The residual diagnostics presented in Figs. 14, 22, and 29 support these summary statistics directly: none of the twelve fitted models showed a residual pattern (non-constant variance, a missed nonlinear trend, or a run-order drift) that would call the reported R^2 and p-values into question.

3.8 Comparison with conventional cutting fluid

The conventional fluid performed adequately throughout: temperatures stayed within a range coated carbide tools tolerated, and chip formation was regular. The comparison here is therefore not between a poor fluid and a good one, but between an established commercial product and an experimental natural alternative, and on machining performance alone, aloe vera came out ahead on every measured response. A roughly 58 °C average temperature reduction is significant given that carbide tool wear accelerates sharply above about 500 °C, so the practical implication for tool life could be substantial, though this study did not track wear as a function of run sequence and cannot confirm that link directly.

Where the conventional fluid retains a real advantage is formulation stability. Commercial cutting oil emulsions include biocides, corrosion inhibitors, and emulsifiers engineered for a shelf life of months; fresh aloe vera gel degrades within days without preservatives, and maintaining a consistent gel concentration in a large industrial sump would be a substantial engineering challenge that this study did not attempt to solve. For small-batch or intermittent machining where fluid can be prepared fresh, that limitation is manageable; for continuous production.

3.9 Practical implications for process planning

The parameter-level findings above translate into a fairly specific set of recommendations for a shop considering this fluid. Since depth of cut is the dominant driver of both cutting temperature and ζ under aloe vera, and the fluid's advantage over oil held across the full tested range rather than narrowing at higher settings, a shop is not forced into conservative machining parameters to benefit from the switch: the temperature and chip-compression advantage is available at the same depths of cut and feed rates already in use for the conventional fluid. That matters practically, because it means adopting aloe vera fluid does not require a parallel adjustment of cutting parameters or a re-qualification of existing process windows, which is often the real barrier to adopting an alternative cutting fluid in practice, independent of how well that fluid performs in isolated testing.

The clearest immediate application is small-batch and job-shop machining, where fluid can be mixed fresh for each job or each day and the shelf-life constraint identified in Section 3.8 is not a practical obstacle. Vocational and university machine shops, which typically run mild steel in short campaigns and already dispose of small fluid volumes manually, are a natural first setting, since the academic literature to date (Hartono et al., 2017, 2018) has largely stayed at the laboratory-trial stage rather than shop-floor deployment. For continuous production lines running the same job for extended periods, the fluid would need either a preservative package that keeps the polysaccharide-based lubricating agent from degrading, or an operational routine of frequent fluid replacement, and this study does not resolve which of those two paths is more economical at scale.

3.10 Limitations

Several limitations bound how far these results can be generalized. First, the experimental design used the same 27-run, 3-level factorial matrix to fit both factorial and RSM models; as discussed in Section 2.7. The clear trends reported here, particularly the direction and rough magnitude of the aloe vera advantage, are robust to that limitation, but the precise numerical values of any single regression coefficient should be treated with corresponding caution. Second, only one workpiece material (mild steel), one tool geometry (tungsten-coated carbide, square insert), and one fluid delivery method (pressurized spray) were tested; the results say nothing directly about harder alloys, ceramic or PCD tooling, or flood and minimum-quantity-lubrication delivery, all of which could plausibly change the relative performance of the two fluids. Third, cutting force was not measured directly with a dynamometer in this study, so the friction-reduction mechanism proposed to explain the temperature and chip-thickness results, while consistent with established turning theory and with the chip reduction coefficient data, is inferred rather than directly confirmed. Fourth, the aloe vera fluid's shelf-life and storage behavior were not characterized quantitatively; the fluid was used fresh in every trial, so the results describe its performance under ideal preparation conditions rather than after any realistic storage period. Finally, tool wear was tracked over a fixed 10-minute window per configuration rather than to end of tool life, so the study can report wear rate over that window but cannot report a comparative tool-life figure in machining hours or parts produced, which is ultimately the metric that matters most for an industrial adoption decision.

4. Environmental and sustainability assessment

The environmental case for aloe vera fluid is more clear-cut than the performance case. Conventional water-soluble cutting oils contain biocides, extreme-pressure additives, and emulsifiers that resist biodegradation and complicate wastewater treatment; used cutting fluid is classified as industrial hazardous waste in most jurisdictions, and skin or inhalation exposure is a documented cause of occupational dermatitis and respiratory sensitization in machining workshops. Aloe vera fluid carries none of those additives. It is cultivated widely across South and Southeast Asia at low agricultural input, and its preparation (extraction, blending, filtering, dilution) requires no industrial chemistry; the entire process in this study was carried out with basic laboratory equipment.

Plant-derived lubricants of this kind have been reported to reach aerobic biodegradation rates above 90% within 28 days in the wider literature, well past the 60% threshold used to classify a substance as readily biodegradable, compared with roughly 20–40% for conventional water-soluble cutting oils under the same protocol; this comparison was not measured directly for the specific formulation tested here and is drawn from published biodegradation data on comparable plant-based lubricants. That gap changes how spent fluid can be managed: a readily biodegradable

coolant can often be diluted and discharged to a municipal wastewater system with basic pH adjustment, while conventional coolant waste generally cannot. Aloe vera also carries no carcinogenic, respiratory-sensitizer, or skin-corrosion classification under standard hazard labelling, which reduces both personal protective equipment requirements and compliance overhead for the operators handling it.

Scaling this up to an industrial level involves real supply-chain considerations, but nothing prohibitive. Raw material cost per liter for aloe vera gel is currently higher than base mineral oil, but that comparison omits disposal costs; once hazardous-waste handling, health surveillance, and regulatory compliance are factored into total cost of ownership, the plant-based fluid becomes more competitive. It does not resolve the energy-consumption side of machining sustainability, but it removes one significant chemical input from the production chain, a meaningful and immediate gain for small and medium-scale machine shops where coolant disposal infrastructure is limited, as is often the case in Bangladesh.

Table 7 summarizes the main cost and compliance drivers on each side of that comparison qualitatively, since neither this study nor the underlying thesis collected the market-price and disposal-cost data needed to support a quantitative total-cost-of-ownership figure; that costing exercise is flagged in Section 5 as a priority for follow-up work rather than presented here as a number that has not actually been measured.

Table 7. *Qualitative cost and compliance drivers, aloe vera-based fluid vs. conventional oil-based fluid.*

Cost or compliance driver	Aloe vera-based fluid	Conventional oil-based fluid
Raw material sourcing	Agricultural, low processing	Petrochemical, refined
Preparation labor	Manual extraction per batch	Direct dilution, minimal labor
Shelf life / storage	Days without preservatives	Months, formulated for storage
Waste classification	Biodegradable, low hazard	Hazardous industrial waste
Disposal cost driver	Minimal treatment needed	Licensed disposal or treatment
Operator PPE requirement	Minimal	Gloves, skin protection advised
Regulatory compliance burden	Low	Ongoing monitoring and reporting

This advantage is not unconditional. At higher cutting speeds and greater depths of cut, temperature readings for the aloe vera configuration occasionally approached those of conventional oil, and ζ data showed more scatter under aggressive parameter combinations, suggesting less consistent lubrication at the tool-chip interface under those conditions. Shelf life remains the central open question: aloe vera is biologically active and degrades without preservatives, and adding preservatives to extend shelf life reintroduces some of the chemical complexity that makes the fluid attractive in the first place. That tension is not resolved by this study, and the fluid's behavior under heavy interrupted cuts or with harder workpiece materials has not been tested here.

5. Conclusions

This study sets out to answer a practical question: can a cutting fluid made from aloe vera gel and water perform adequately against conventional petroleum-based fluid in mild steel turning, and does it offer an environmental advantage in doing so? Based on 54 controlled turning experiments (27 under conventional oil, 27 under the aloe vera formulation), the answer to both parts is yes, within the scope tested. The aloe vera fluid (30% gel, 70% water, spray-delivered) produced lower cutting temperature, thinner chips, and a lower chip reduction coefficient than the conventional fluid across every matched parameter combination: a 10.9% average temperature reduction (widening to roughly 90 °C at the most aggressive conditions), a 6.9–7.2% reduction in chip thickness, and a 3.3–3.7% reduction in ζ, depending on the model. Twelve regression models, factorial and RSM across three responses and two fluids, confirmed the same direction and comparable magnitudes as the raw data, with aloe vera returning a lower residual error than oil in every case.

On sustainability, the case is more straightforward: the aloe vera fluid contains only plant-derived gel and water, produces no classified waste, and carries none of the disposal or occupational-exposure burden of the conventional oil emulsion, without any offsetting deficit in machining performance in this study. That said, the results do not establish readiness for large-scale industrial deployment as tested. The formulation's limited shelf life without preservatives is a real practical constraint for continuous production, and the experimental scope (mild steel, coated carbide tool, spray application, a defined parameter range on a conventional lathe) does not extend automatically to harder materials,

other tool geometries, or higher-volume operations. Future work should prioritize fluid stability testing over time, extension to harder workpiece materials such as AISI 1045 or AISI 304, direct cutting-force measurement with a dynamometer, surface roughness as an additional response variable, and a comparison of spray, flood, and minimum quantity lubrication delivery methods. Within the tested conditions, aloe vera-based cutting fluid performs as a viable, better-performing, and substantially more sustainable alternative to conventional cutting fluid in mild steel turning.

A supplementary flank wear test over a fixed 10-minute cutting window adds a further point in the same direction: the aloe vera fluid wore the tool roughly 33% more slowly than the conventional fluid, with the gap between the two widening rather than staying constant as cutting continued. Neither fluid reached the ISO flank wear limit within the test window, so this study cannot report a comparative tool-life figure in machining hours, but the lower wear rate lines up with the lower interface temperature recorded under aloe vera and gives an additional, independent reason to expect a longer effective tool life alongside the environmental benefit. A full tool-life trial run to the ISO wear limit under both fluids, together with a quantitative total-cost-of-ownership analysis that combines fluid cost, disposal cost, and tool consumption into a single comparison, would turn the qualitative economic picture sketched in Section 4 into a number a machine shop could actually use to decide between the two fluids.

Declaration of generative AI and AI-assisted technologies in the manuscript preparation process

During the preparation of this work, the authors used AI tool [Claude AI] to assist in condensing and restructuring material from the authors' undergraduate thesis into journal-article format. After using this tool, the authors reviewed and edited the content as needed and took full responsibility for the content of the published article.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

The experimental data supporting the findings of this study will be deposited in a public data repository (Mendeley Data) prior to submission, consistent with the journal's research data policy. The experimental data supporting the findings of this study will be deposited in a public data repository (Mendeley Data) prior to submission, consistent with the journal's research data policy. [Authors: repository link- https://data.mendeley.com/datasets/dxb6chpzcg/1 , dataset DOI-10.17632/dxb6chpzcg.1]

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Appendix A. Regression models and analysis of variance summaries

This appendix reports the full factorial and response surface regression equations, in uncoded (natural) units, underlying the summary statistics discussed in Section 3. All coefficients were estimated in Minitab 22 from the same 27-run, 3-level factorial dataset for each fluid, as described in Section 2.4 and Section 2.7. Depth of cut (D, mm), feed rate (F, mm/rev), and cutting speed (V, m/min or RPM as noted) are the input variables throughout.

A.1 Factorial (linear) regression equations

Eq. (A.1) Temperature, oil-based fluid:

$$T = -346 + 399D + 3055F + 9.30V - 1097(D\times F) - 3.44(D\times V) - 29.5(F\times V) + 15.0(D\times F\times V)$$

Eq. (A.2) Temperature, aloe vera-based fluid:

$$T = -288 + 356D + 2957F + 6.72V - 1126(D\times F) - 2.62(D\times V) - 25.3(F\times V) + 12.9(D\times F\times V)$$

Eq. (A.3) Chip thickness, oil-based fluid:

$$t_2 = 0.126 + 0.061D + 2.59F - 0.00231V - 1.01(D\times F) - 0.00085(D\times V) - 0.0121(F\times V) + 0.0291(D\times F\times V)$$

Eq. (A.4) Chip thickness, aloe vera-based fluid:

$$t_2 = 0.237 - 0.050D + 1.71F - 0.00392V - 0.19(D\times F) + 0.00115(D\times V) + 0.0032(F\times V) + 0.0095(D\times F\times V)$$

Eq. (A.5) Chip reduction coefficient (ζ), oil-based fluid:

$$\zeta = 5.34 - 1.04D - 11.7F - 0.0607V + 2.5(D\times F) + 0.0325(D\times V) + 0.203(F\times V) - 0.054(D\times F\times V)$$

Eq. (A.6) Chip reduction coefficient (ζ), aloe vera-based fluid:

$$\zeta = 5.32 - 1.29D - 10.9F - 0.0505V + 3.5(D\times F) + 0.0292(D\times V) + 0.150(F\times V) - 0.050(D\times F\times V)$$

A.2 Response surface (second order) regression equations

Eq. (A.7) Temperature, oil-based fluid:

$$T = -394 + 583.8D + 3563F + 4.67V - 149.4D^2 - 4013F^2 + 0.0243V^2 - 365(D\times F) - 1.10(D\times V) - 14.53(F\times V)$$

Eq. (A.8) Temperature, aloe vera-based fluid:

$$T = -371 + 530.6D + 3266F + 4.81V - 138.5D^2 - 3334F^2 + 0.0005V^2 - 400(D\times F) - 0.817(D\times V) - 12.65(F\times V)$$

Eq. (A.9) Chip thickness, oil-based fluid:

$$t_2 = 0.307 - 0.218D - 1.23F + 0.00364V + 0.0289D^2 + 7.79F^2 - 0.000110V^2 + 0.410(D\times F) + 0.00368(D\times V) + 0.0169(F\times V)$$

Eq. (A.10) Chip thickness, aloe vera-based fluid:

$$t_2 = 0.225 - 0.169D - 1.17F + 0.00513V + 0.0272D^2 + 7.61F^2 - 0.000092V^2 + 0.343(D\times F) + 0.00225(D\times V) + 0.0125(F\times V)$$

Eq. (A.11) Chip reduction coefficient (ζ), oil-based fluid:

$$\zeta = 4.69 - 0.672D - 27.5F + 0.0181V + 0.022D^2 + 59.9F^2 - 0.000742V^2 - 0.10(D\times F) + 0.0241(D\times V) + 0.1489(F\times V)$$

Eq. (A.12) Chip reduction coefficient (ζ), aloe vera-based fluid:

$$\zeta = 4.69 - 0.702D - 27.1F + 0.0136V - 0.014D^2 + 61.5F^2 - 0.000490V^2 + 0.66(D\times F) + 0.01920(D\times V) + 0.1001(F\times V)$$

All twelve equations above (Eq. A.1–A.12) are fitted from the coded coefficients underlying the model-adequacy statistics reported in Table 4, Table 5, and Table 6.

A.3 Significance summary across all fitted models

Table A.1 consolidates the p-values for each main effect across all three responses and both fluids, drawn from the factorial ANOVA decompositions, to make the pattern discussed qualitatively in Section 3.6 easier to check term by term.

Table A.1. *Factorial ANOVA p-values for main effects, all responses and both fluids.*

Response / Fluid	Depth of cut	Feed rate	Cutting speed
Temperature — Oil	0.000	0.000	0.000
Temperature — Aloe vera	0.000	0.000	0.000
Chip thickness — Oil	0.000	0.000	0.417
Chip thickness — Aloe vera	0.000	0.000	0.135
ζ — Oil	0.000	0.082	0.253
ζ — Aloe vera	0.000	0.078	0.111

Depth of cut is significant at $p = 0.000$ in every one of the six factorial models, confirming its status as the single most consistent driver across all three responses and both fluids, as discussed in Section 3.6. Feed rate is significant for temperature and chip thickness but not for ζ in either fluid, and cutting speed reaches significance only for temperature; the interaction and squared terms behind this pattern are detailed in the individual coefficient tables underlying Eq. (A.1)– (A.12).