

INFLUENCE OF ABRASIVE TYPE AND PROCESS PARAMETERS ON MATERIAL REMOVAL CHARACTERISTICS IN ABRASIVE WATER JET DRILLING OF INCONEL 939 ALLOY

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ABSTRACT

Inconel-939 is a high-temperature superalloy comprising nickel and chromium. It has been extensively utilized in diverse applications within aerospace, automotive, and corrosive environments. The reason behind this is owed to its remarkable mechanical strength and thermal stability. Even though it has been the most popular choice for high-strength applications, it can be hard to machine the alloy effectively. Drilling the metal and creating high-quality holes using traditional methods has become extremely challenging due to its significant hardness and strength. Abrasive Water Jet Drilling (AWJD) provides a viable option for the machining of such challenging materials. The objective of the current investigation is to examine the AWJD material removal rate (MRR) with respect to the process parameters like Abrasive jet pressure (P_{aj}), traverse speed (V_t), stand-off distance (G_d), and abrasive mixture (A_m -garnet and silicon carbide). The experimental results depict that as P_{aj} reached its maximum value, the MRR indicated a rise by 32.66%. The ANOVA results further showed that P_{aj} is the most vital factor, accounting for 79.21% of the changes in MRR, while A_m also accounted for 6.43%. The results thus confirm that AWJD offers an efficient and controllable machining procedure for creating holes with minimal duration in Inconel-939 alloy.



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I. INTRODUCTION

Inconel 939 (IN939) is a nickel-based superalloy manufactured for sustained performance at elevated temperatures (up to approximately 850 °C), providing superior resistance to creep, fatigue, corrosion, and oxidation. The γ (gamma) matrix is what makes it strong. The γ' (gamma-prime) precipitates and carbides (MC, M₂₃C₆) make it even stronger [1-3]. Common uses include gas turbine blades and vanes, burner nozzles, and other hot-section parts in power generation and aerospace [4-6]. IN939 is hard to cut and wears down tools quickly, which might lead to a very rough surface finish. Like other the material alloys, IN939 is hard to machine due to it is exceptionally hard when heated, doesn't transmit heat well, and gets harder when you work with it. This makes cutting processes very hot, tools wear out quickly, and surfaces get damaged. These problems are further more important for additively created IN939, which has a thin, directionally cemented microstructure and is more likely to break, making chip-based cutting and welding harder [7-9].

Because of this, abrasive water-jet machining (AWJM) has become a popular non-traditional method for working with Inconel alloys, Shape memory alloys and advanced polymeric composites [10-13]. In AWJM, a high-pressure water jet (usually 200–400 MPa) speeds up abrasive particles that wear down the workpiece, allowing cutting or milling without a thermal-affected zone or contact between the tool and the workpiece. Various researchers proven that the AWJM can make cuts, pockets, and complex profiles efficiently in Inconel 600, 625, 718, and X-750 without causing too much wear on the tools. However, the surface roughness, kerf taper, Material Removal rate depth of cut depend on things like P_{aj} , V_t , G_d , and abrasive flow rate [14-16]. AWJM is typically advised for the processing of nonconductive and conductive hierarchical material structures such as

Inconel alloy, titanium alloy, and metal fiber laminates. Inconel 625 machined using abrasive water jet technology by [17] The influence of process factors P_{aj} , G_d , A_m and V_t , on R_a and KA was analyzed. According to [18] conducted a comparative analysis of three non-traditional machining processes. The electric discharge machining process (EDM), laser beam machining process (LBM), and abrasive water jet machining (AWJM) are employed to process carbides and Inconel superalloys to attain improved material removal rates (MRR) and thickness. The results of this study indicated that AWJM surpasses laser cutting when processing thicker materials because to its capacity for deeper penetration. Furthermore, the AWJM exhibited a superior Material Removal Rate (MRR) compared to EDM, rendering it a more advantageous method for situations necessitating expedited material removal. These results underscore the benefits of AWJM in situations requiring high efficiency and the capacity to sever thick, resilient materials.

According to [19] investigated the performance attributes of Inconel X-750 Superalloy subjected to abrasive water jet (AWJ) machining, focusing on the variables. The combination of minimum G_d , minimum V_t , and P_{aj} has enhanced the machined surface quality (R_a). In [20] examined the influence of abrasive water jet parameters, including traverse rate, abrasive particle size, and number of passes, on the waviness of the titanium alloy Ti-6Al-4V. It was observed that at elevated traverse rates, surface roughness diminishes, whereas waviness escalates due to the reduced abrasive contact in the specified region. Balaji Vasudevan et al. examined the influence of abrasive water jet (AWJ) drilling parameters on the surface properties of Inconel 718 superalloy coated by Yttrium Stabilized Zirconia (YSZ). The variance of jet impact angle (0° – 45°), abrasive flow rate (250–400 g/min), P_{aj} (175–325 MPa), on surface integrity was analyzed. Pressure was identified as the most significant factor. On Inconel 625, by [21] examined changes in water pressure, gap distance, and the abrasives (Sic and Garnet) in relation to surface roughness, kerf angle, and MRR. They observed pressure is predominate factor effect the responses.

II. MATERIALS AND METHODS

The studies were conducted using an abrasive waterjet machine of the MAXIEM 1515 type. The drilling operation is performed as depicted in Figure 1. Single pass techniques were used entire operation. The INX-939, having a thickness of 8 mm, is utilized for AWJD. Because this alloy is widely used in numerous industrial applications, it was chosen as the workpiece. Tables 1 and 2 describe the properties and composition of INX-939.

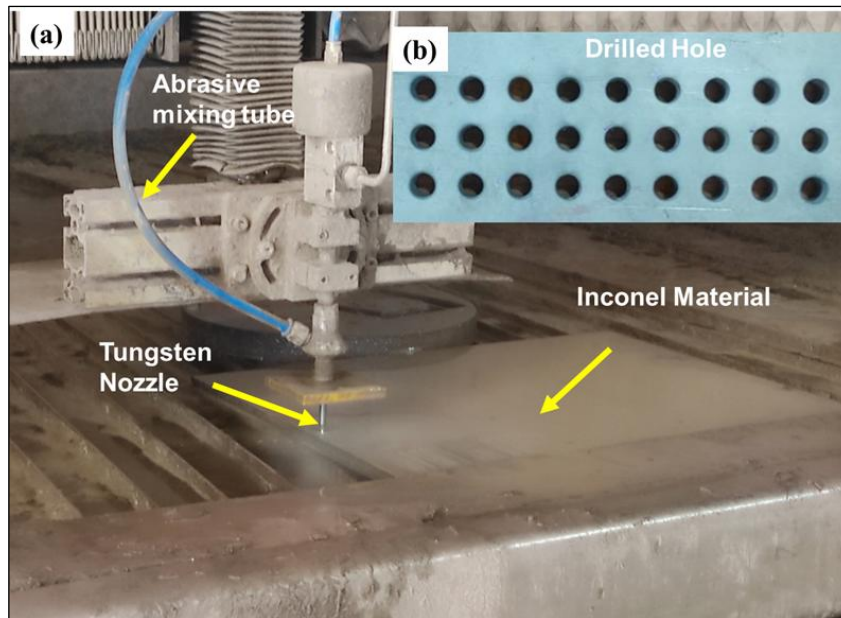


Figure 1: (a) Abrasive water jet setup, (b) Machined Material.

Source: Authors, (2026).

Table 1: INX-939 Chemical Configuration (wt%).

Fe	Al	Zr	C	Cr	Co	Si	Nb	S	Mn	W	B	Ti	Ta	Ni
0.5	2	0.15	0.1	20–23	18–20	0.5	1.2	0.002	0.5	3	0.015	4	2	Bal.

Source: Authors, (2026).

Table 2: Mechanical properties of INX-939.

Structure	Elastic Modulus (GPa)	Ultimate Tensile Strength (MPa)	Hardness (HRC)	Yield Strength (MPa)
Plate	210	1200 – 1400 MPa	38–42	850 – 950

Source: Authors, (2026).

During the experiment, four various levels of parameters were modified, including P_{aj} , V_t , A_m , and G_d shown in Table 3 [14]. The RSM was used to perform rails. The trials were run at random [17] in order to decrease the influence of confounding variables, and two replications were obtained for each experiment. For MRR, W_1 is the beginning workpiece sample before machining, W_2 is after machining, the density of work $\rho = 8.19 \text{ g/cm}^3$ is the cutting time (t) in minutes. as mentioned, equation (1)

$$MRR(\text{mm}^3/\text{sec}) \leftrightarrow \frac{W_1 - W_2}{\rho \times t} \times 1000 \quad (1)$$

Table 3: Characteristics of the drilling process.

Level/Range	-2	-1	0	1	2
P_{aj} , MPa	120	180	240	300	360
G_d , mm	1.5	2,5	2.5	3	3.5
A_m (wt%)	1 (100%Gt)	2 (75%Gt + 25%SiC)	50%Gt + 50%SiC	25%Gt + 75%SiC	100%SiC
V_t , mm/min	65	73	81	89	97

Source: Authors, (2026).

III. RESULTS AND DISCUSSIONS

III.1 ANOVA ANALYSIS

The investigation employed a central composite Linear design including a total of L_{27} trials. Figure 2 (a-c) indicated correlation between actual, predicted, & residual values. It is observed all values in acceptable limits. Table 4 outlines the process parameters and their corresponding levels inside the L_{27} (Center point =3) orthogonal array, together with the response values for INX-939. The conclusive regression models for the analyzed variables, namely Material Removal Rate. Design Expert software (V13), was employed to analyze the impact of process variables on machining outcomes in the context of AWJD. The equations delineating the linear models of the input process parameters are shown in Equations (2). The model had a highly significant fit, evidenced by its substantial F-statistic ($F=788.02$), with a p-value below 0.0001, signifying its efficacy in predicting drilled MRR. The most significant individual influence of the different process parameters on material removal rate (MRR) was attributed to pressure (P_{aj}), which exhibited the highest sum of squares (SS) at 5379.5 and the greatest F-statistic ($F=2514.32$). Furthermore, the standoff gap (G_d), traverse speed (V_t), and abrasive mixture exhibited a statistically significant impact on material removal rate (MRR), evidenced by their respective F-statistics of 335.93, 55.15, and 204.28, all significant at $p<0.0001$. Moreover, the residual error was negligible ($SS=47.07$), indicating that pressure was the principal factor affecting MRR, whereas the complete array of process factors examined collectively influenced MRR.

$$(MRR) = +54.85613 + 0.15 * P_{aj} + 6.6 * G_d + 0.16 * V_t + 2.57 * A_m \quad (2)$$

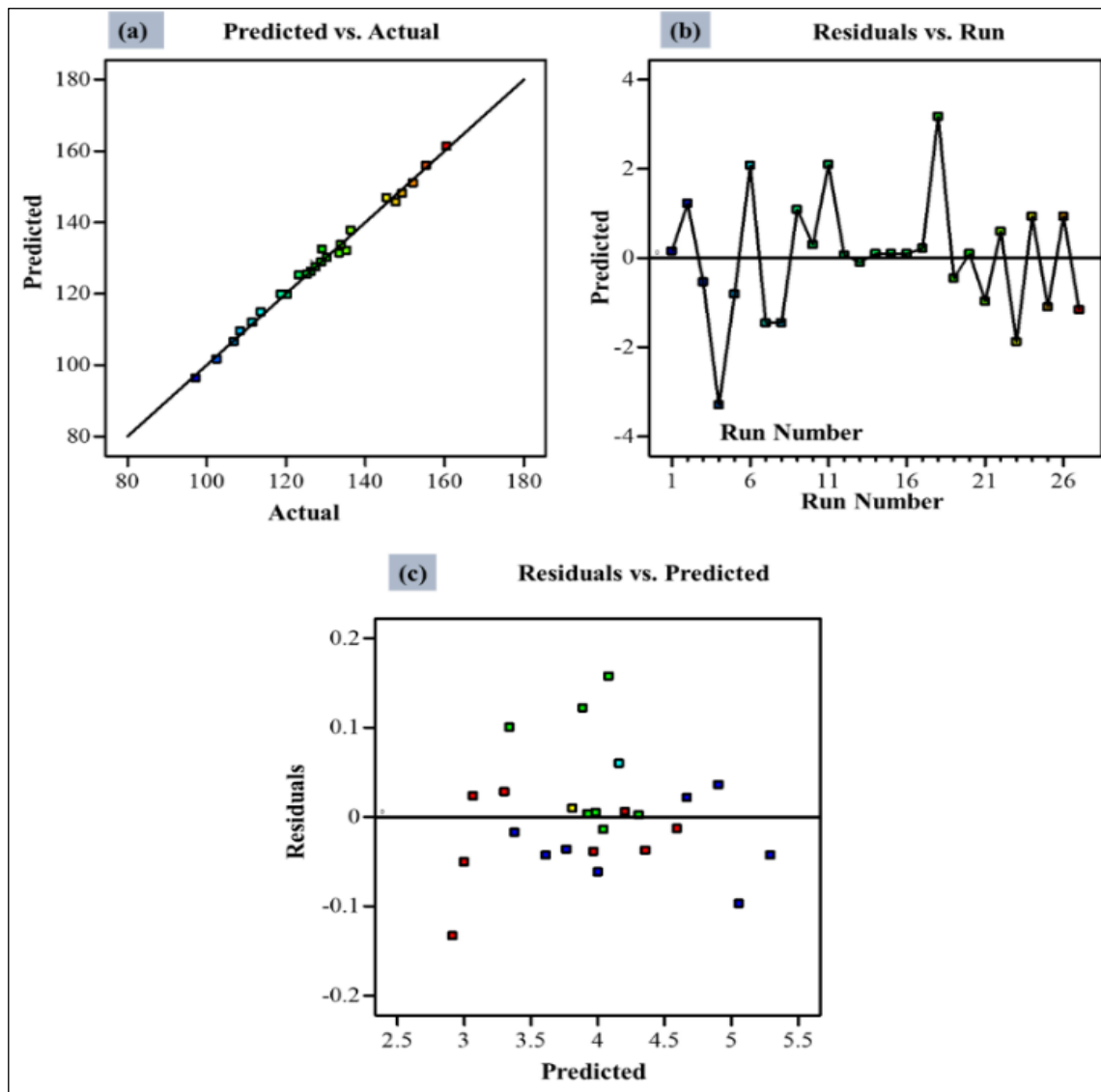


Figure 2: (a) Pred vs Actual plot (b) Residuals vs Run (c) Residuals Vs Predicted.

Source: Authors, (2026).

Table 4: Experimental design matrix and results for INX-939.

S.No	P _{aj}	V _t	G _d	G _d	MRR
1	240	81	2	3	125.39
2	360	81	2.5	3	145.42
3	240	81	2.5	3	128.89
4	300	65	1.5	5	133.86
5	360	97	1.5	5	149.32
6	360	65	3.5	5	155.41
7	360	65	1.5	1	129.15
8	360	97	3.5	5	160.49
9	360	65	3.5	1	147.73
10	360	97	1.5	1	136.34
11	360	97	3.5	1	152.09
12	120	65	1.5	5	106.88
13	240	81	2.5	4	133.46
14	240	73	2.5	3	127.52
15	240	81	2.5	3	128.89
16	120	65	1.5	1	97.22
17	120	65	3.5	1	108.39
18	240	81	2.5	3	128.89
19	240	89	2.5	3	130.35
20	240	81	3	3	135.27
21	120	97	1.5	5	111.48
22	240	81	2.5	2	126.32
23	120	97	3.5	1	113.68
24	120	65	3.5	5	118.82
25	180	81	2.5	3	120.35
26	120	97	3.5	5	123.26
27	120	97	1.5	1	102.57

Source: Authors, (2026).

Table 5: ANOVA analysis and effects of process parameter on MRR.

Source	Sum of Squares	df	Mean Square	F-value	p-value	
Model	6743.99	4	1686	788.02	< 0.0001	significant
P _{aj}	5379.5	1	5379.5	2514.32	< 0.0001	
G _d	718.73	1	718.73	335.93	< 0.0001	
V _t	118	1	118	55.15	< 0.0001	
A _m	437.07	1	437.07	204.28	< 0.0001	
Residual	47.07	22	2.14			Not Significant
Cor Total	6791.06	26	R ² =0.9931	Adj R ² =0.9918	Std.Dev =1.46	

Source: Authors, (2026).

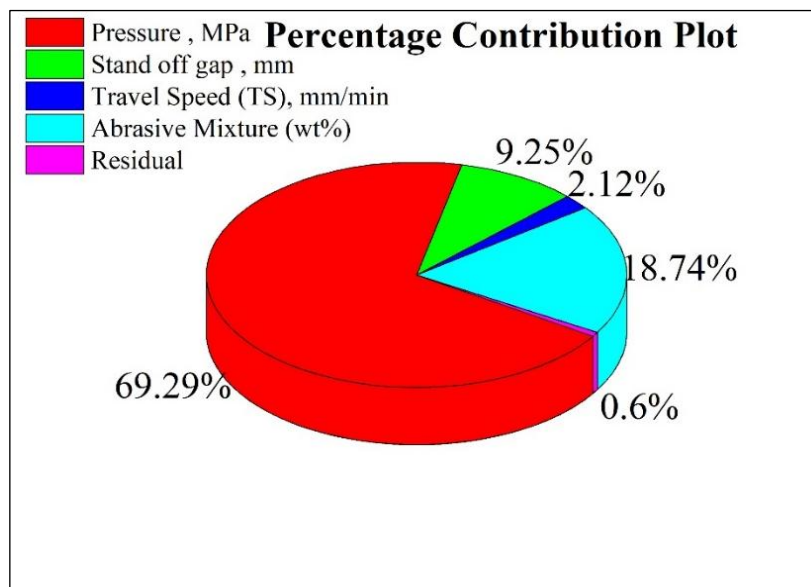


Figure 3: Percentage contribution plot.

Source: Authors, (2026).

Individual parameter percentage contribution indicated in Figure 3. It is observed P_{aj} 69.29% predominant factor affect the MRR.

III.2 RSM ANALYSIS OF MRR

As shown in figure 4(a), it is clear how the pressure affects the MRR. When P_{aj} increased from 120 Mpa to 360 Mpa it observed 32.66% increased in MRR & Figure 4 (b) shows the Effect of G_d on MRR. When G_d reaches its higher value the MRR increased by 11.24% Furthur more combined effect of P_{aj} and G_d on MRR described in Fig figure 5(a), the distance from the workpiece surface affects the material removal rate (MRR) since it can be seen in this surface plot that an increase in pressure from 120 MPa up to 360 MPa has a very significant impact on MRR; especially when the distance from the workpiece surface is high (i.e., 1.5-2.0 mm). The obtained MRR almost reaches its highest point of approximately 153.57 mm³/sec. Figure 4(c), shows how the V_t affects the MRR. When V_t increased from 65 mm/min to 97 mm/min it observed 4.24% increase in MRR and Figure 5 (c) shows the trend of V_t and P_{aj} on MRR. Higher levels these parameters enhanced the MRR. Figure 4 (d) shows the effect of mixed abrasives on MRR described. It is observed Level 5 (100%SiC) higher MRR than the other mixture garnets (100%Gt, 75%Gt + 25%SiC, 50%Gt + 50%SiC and 25%Gt + 75%SiC). Combined efferets of Mixed abrasves and P_{aj} shows on Figure 5 (c). It is observed 100%SiC coupled with 100%SiC obtained high MRR.

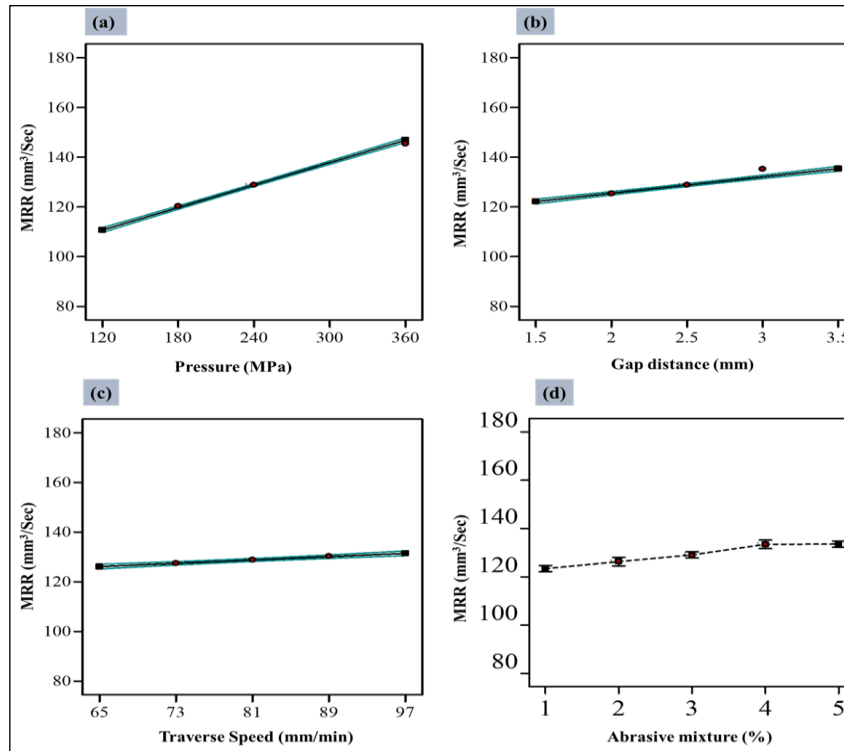


Figure 4: (a,b&c) 3D plots for MRR.

Source: Authors, (2026).

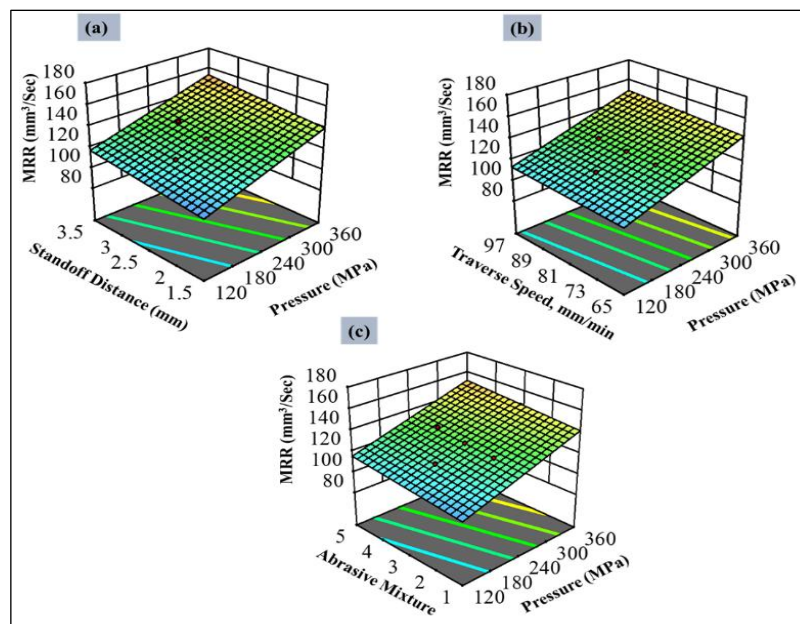


Figure 5: (a,b&c) 3D lplots for MRR.

Source: Authors, (2026).

IV. CONCLUSIONS

The study demonstrated the effectiveness of process parameter optimization for AWJD machining process for INX -939 through systematic evaluation of the key process parameters like pressure, Abrasive mixture, traverse speed and standoff gap. The Abrasive water jet drilling (AWJD) experimental investigation employed to enhance the material removal (MRR). This study showed that the MRR greatly enhanced by modifying the input parameters. During the investigation, the following particular observations were made:

- The ANOVA results show that the removal rate (MRR) is significantly influenced by the factors included in the model, and that the models are very reliable given the very high F-values and p-values less than 0.0001 for all parameters evaluated. P_{aj} was found to be the most influential parameter affecting the material removal rate. However, A_m , G_d , and V_t also have a significant impact on response variables.
- The ANOVA analysis described the variables influence on machining performance like $P_{aj} > G_d > A_m > V_t$. Increasing Abrasive waterjet parameters linearly increases the MRR.

V. AUTHOR'S CONTRIBUTION

Conceptualization: Praveen Jayapalan, Rajesh Munusamy.

Methodology: Rajesh Munusamy and Sandhya Jayakumar.

Investigation: Praveen Jayapalan, Rajesh Munusamy and Sandhya Jayakumar.

Discussion of results: Praveen Jayapalan, Rajesh Munusamy and Sandhya Jayakumar.

Writing – Original Draft: Praveen Jayapalan, Rajesh Munusamy and Sandhya Jayakumar.

Writing – Review and Editing: Rajesh Munusamy and Sandhya Jayakumar.

Resources: Praveen Jayapalan, Rajesh Munusamy and Sandhya Jayakumar.

Supervision: Rajesh Munusamy and Sandhya Jayakumar.

Approval of the final text: Praveen Jayapalan, Rajesh Munusamy and Sandhya Jayakumar.

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