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Experimental Investigations of Drilling Process Parameters for Hemp Polyester Composites

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Abstract

The development of polymer composites with natural fibers offers a cost-effective alternative for applications in the aviation and automotive industries. The synthetic fibers possess impressive mechanical properties; they are more expensive than natural fibers. This has led to increased interest in hybrid composite materials combining both types. Researchers are focused on creating new fiber-reinforced composites to expand their applications. However, machining these composites can be challenging due to their heterogeneity and issues like delamination, influenced by both the fiber type and cutting parameters. In the current research, the hemp-polyester composites were developed using hemp fibre and as reinforcement and isophthalic polyester resin as a matrix material employing the hand layup technique. This study aims to analyze how speed, feed and tool geometry affect delamination and Thrust Force (TF). Drilling tests were conducted using a full factorial Design of Experiments (DoE) approach, considering various feed rates (0.09, 0.19, 0.29 mm/rev), spindle speeds (700, 2700, 4700 rpm), and tool geometries (plexi point, twist, parabolic). Analysis of Variance (ANOVA) was employed to evaluate their interactions and percentage contribution of machining parameters on thrust force and delamination. The results showed that spindle speed has little effect on delamination and that tool geometry and feed rate are the main determinants.

Major Findings: *The investigations conclude that drill geometry and feed rate effectively influence the hole drilling in hemp polyester composites. The plexi point and parabolic tool reduced thrust force and delamination compared to standard twist drill. The feed rate directly increased thrust force and delamination factor, spindle speed had no prominent effect on thrust force.*

Keywords: *Delamination, Drilling, Hemp-polyester, Thrust Force, Tool Geometry*

1.0 Introduction

Composites have evolved over the last few decades from a laboratory invention to a useful material; they are highly appealing for a wide range of uses. The ability of composite materials to create goods that are long-lasting, high-quality, and reasonably priced has been acknowledged by the industry. Two or more materials- the reinforcement and the matrix- that have different macroscopic structures or arrangements make form a composite. This arrangement results in a material that improves certain performance properties[1,2]. Both the reinforcement and the matrix maintain their physical and chemical properties; however, their combination results in a set of characteristics that cannot be achieved when each constituent acts independently. Composite materials are extensively utilized across various engineering fields due to their potential to be both very strong and rigid while remaining lightweight, resulting in strength-to-weight and stiffness-to-weight ratios that

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are significantly higher than those of steel or aluminum[3]. Depending on the matrix material, composite materials can be divided into 3 primary categories: Metal Matrix Composites (MMCs), Polymer Matrix Composites (PMCs), and Ceramic Matrix Composites (CMCs). Each type offers distinct combinations of strength, weight, and thermal properties for specific engineering usage. In every type of composites there are 2 main components, Fiber (Reinforcement) and Base (Matrix or Binder).

Natural fibers are increasingly being considered as a desirable substitute for reinforcing materials in a variety of polymer composite applications. A greater focus on sustainability and the benefits of natural fibers over synthetic ones are the main forces behind this change. In general, natural fibers are less expensive to manufacture and have higher specific strength, stiffness, and a lower density. They also cause less damage to tools during processing, emit fewer toxic fumes when heated or incinerated at the end of their life, and are available from renewable resources. Therefore, it is evident that further investigation is needed to expand their engineering applications[1-3].

Numerous studies on drilling in composites have shown that the hole quality is influenced by drilling factors such as speed, feed, drill tool material, drill tool geometry, and type of the composite material. In order to drill different composite materials, speed and feed optimization are also being studied. To make holes in composites, extremely inadequate tool geometries are devised and abstracted[4-6].

Drilling in composite materials, especially Fiber-Reinforced Polymers (FRPs) is a complicated operation affected by a range of parameters such as feed rate, spindle speed, drill geometry, and thickness of the composites. These factors directly affect critical outcomes such as thrust force, delamination, tool wear, and surface finish[7-9]. Low spindle speeds and high feed rates typically result in higher thrust forces, which in turn exacerbate delamination at both hole entry (peel-up) and exit (push-out)[10]. Drill geometry, particularly the point angle, plays a pivotal role- studies have shown that point angles near 120° reduce delamination compared to other geometries[11].

Despite their high strength-to-weight ratios, composites are inherently challenging to manufacture because of its anisotropic and abrasive nature. Common drilling-related issues include rapid tool wear, fiber pull-out, matrix cracking, and inconsistent hole quality. Additionally, the poor thermal conductivity of composites results in localized heat buildup, which can degrade the polymer matrix and adversely impact dimensional accuracy[12]. When compared to metals, composites demand more refined control of drilling parameters and specialized tools to avoid damage, as metals typically exhibit uniform structure and better thermal dissipation properties[13].

Optimizing drilling conditions is therefore essential for achieving high-quality holes in composites. Research indicates that using higher spindle speeds along with reduced feed rates can minimize thrust force and delamination while improving surface finish[14]. Furthermore, appropriate tool selection, including coated or diamond tools, can reduce wear and extend tool life in composite machining applications[15]. A comprehensive understanding of these factors enables manufacturers to enhance productivity while maintaining structural integrity in composite-based components. There are few works has been done on examining the effect of drilling parameters on the hemp polyester composites. The current work examines the influence of parameters like tool geometry, feed rate and speed on the drilling operations on hemp polyesters composites.

2.0 Materials and Methods

2.1 Development of Composite Specimen

The current effort aims to investigate drilling of hemp polyester composites experimentally. Composites need both matrix material and reinforcement. Resin and reinforcement can be made from a variety of materials. The selection of materials is mostly determined by the requirements for strength performance and weight limitations. Isophthalic polyester, often referred to as improved polyester resin, was utilized as the matrix and woven hemp fiber yarn fibers as reinforcement in the creation of hemp polystyrene composites. The requisite 300 mm × 300 mm dimensions for the woven hemp fiber laminates were prepared, which is displayed Figure 1. A single distinct configuration of pure hemp

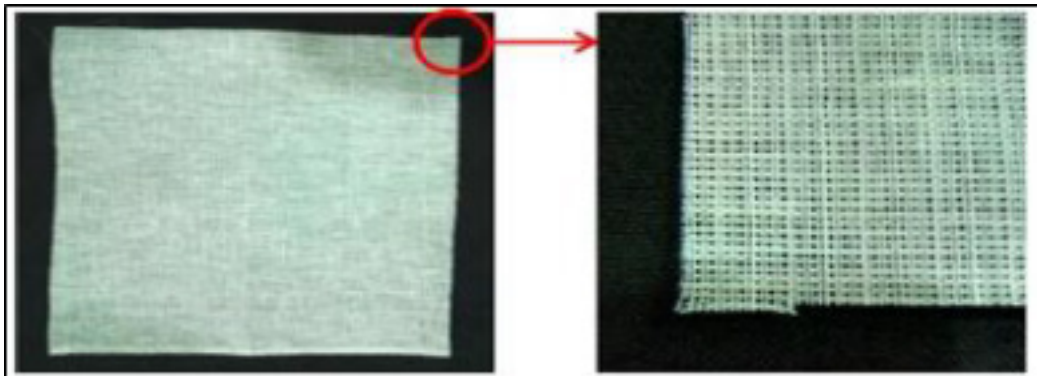


Figure 1. Woven hemp mats.



Figure 2. Prepared hemp polyester composite.

polyester was fabricated using the hand lay-up method. The prepared composite specimen is displayed in Figure 2.

2.2 Experimental Design for Drilling

A well-structured experimental design is essential for understanding how drilling parameters influence composite materials. The impacts of drill geometry, speed and feed were assessed in this work using a conventional complete factorial Design of Experiments (DoE) approach. These factors were chosen because they have a big impact on the quality and performance of drilling in composites. The factorial design allows for comprehensive interaction analysis among variables, ensuring reliable and interpretable results. A total of 27 experimental runs were conducted using a Vertical Milling Center (VMC, Jyoti PX10), with different HSS drills. Thrust Force (TF) during drilling was recorded using a piezoelectric dynamometer (KISTLER 9272). The detailed setup is illustrated in Figure 3.

2.3 Determination of Delamination Factor

Using machine vision techniques and a Mitutoyo QS-L 2010 ZB laboratory 3D microscope, the delamination in the hemp polyester composite plates was detected, as illustrated in Figure 4. The delamination factor can be computed by comparing the damaged area (A_{damage}) to the hole area (A_{hole}) or by measuring the ratio of the maximum diameter of the damaged region (D_{max}) to the diameter of the hole (D_{hole}). The D_{max} to D_{hole} ratio has been utilized by numerous investigations to assess the degree of delamination[16-19]. In order to clearly separate the delamination, the image of the drilled hole was taken using a 3D microscope at the same magnification and with enhanced contrast. MATLAB software was used for image processing in order to measure the damaged area in the drilled hole. In this study, the MATLAB program was used to evaluate the delamination factor by image analysis. A Delamination Factor (DF) is depicted in Figure 5. The following formula has been used to determine the Delamination Factor (DF) value[19].

Table 1. Drilling process parameters selected for DoE

Parameter/ Factor	Symbol/Unit	Levels
Tool geometry	TG	Plexi point, twist, parabolic
Spindle speed	S (rpm)	700, 2700, 4700
Feed	F (mm/rev)	0.09, 0.19, 0.29



Figure 3. Experimental setup for drilling.

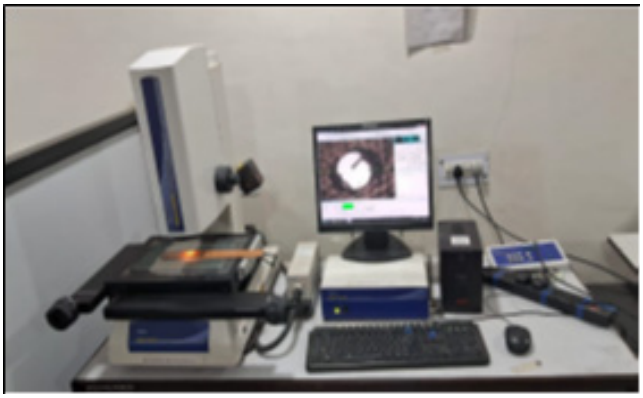


Figure 4. 3D microscope.

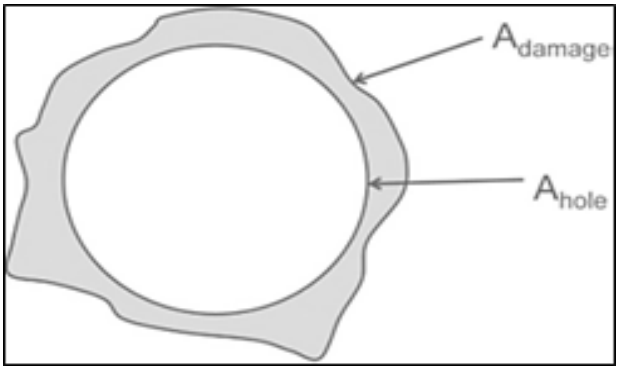


Figure 5. Illustration of delamination factor.

$$DF = \frac{A_{damage}}{A_{hole}}$$

Where A_{hole} is the actual hole area as shown in Figure 5 and A_{damage} is the maximum region of the damage surrounding the hole periphery (including hole area).

3.0 Results and Discussion

The current study used a full factorial design and conducted a total of 27 experimental trials. ANOVA for main effect and interaction graphs was used to analyze the response values.

3.1 Effect of Input Parameters on Thrust Force

The main effect plot for Thrust Force (TF) for Tool Geometry (TG), Speed (S) and Feed rate (F) is as shown in Figure 6. After examining the graph, it is obvious that the highest TF occurs with a Twist (Standard) drill bit due to its larger contact angle, while the Parabolic drill bit yields lesser thrust due to efficient chip evacuation. The Plexi point drill, with a lower point angle, reduces contact area, resulting in smoother drilling and minimal thrust force. It was also observed that speed of the spindle has negligible effect on the TF, as values cluster near the mean line. In contrast, feed rate considerably influences TF, as observed in Figure 6 at lower feed rates, particularly 0.09 mm/rev, correspond to reduced thrust, emphasizing feed rate as a critical parameter in drilling performance. The similar observation was reported in the many studies that tool penetrating the work surface at higher feed rate produces elevated TF[6,16,18,20].

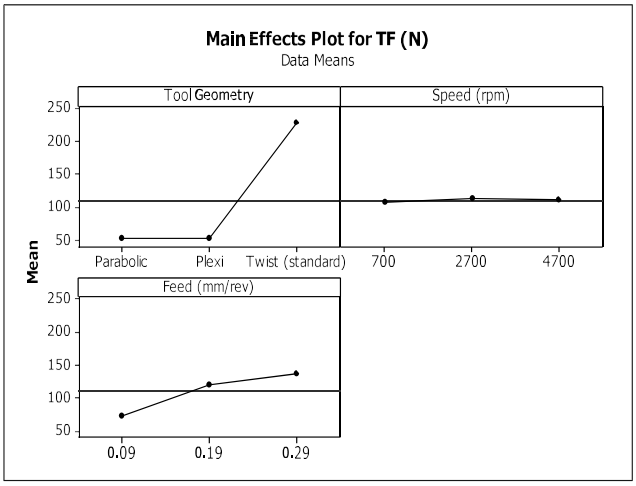


Figure 6. Main effect plots for TF and TG, S and F.

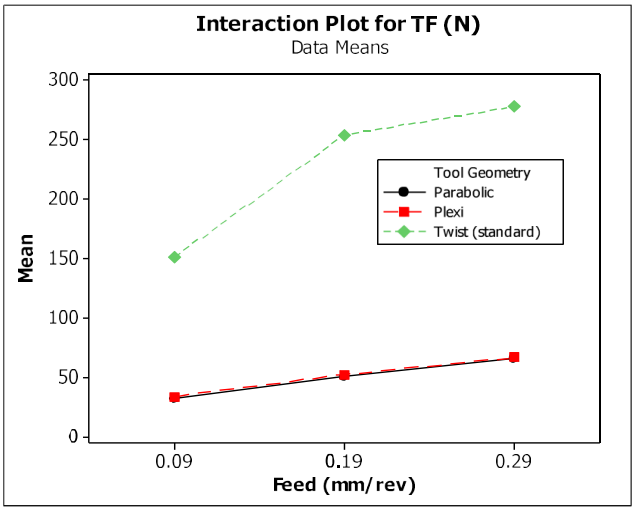


Figure 7. Interaction plot between TG and F for TF.

The Analysis of Variance (ANOVA) findings for TF and specific parameters are displayed in the Table 2. Feed and TG have a substantial impact on the TF, according to the p-value derived from the ANOVA table. Also, the percentage contribution shows that tool geometry is the most influential parameter affecting TF with 87%, followed by feed with 9% in drilling process. The speed has no discernible effect on the TF. An adequate model fit is indicated by the corrected R-Sq value for trust force (97.48%). Additionally, there are important relationships between feed and speed, feed and TG and speed and feed. But when compared to individual factors, the impact of these interactions is negligible.

The Thrust Force (TF) interaction plot between Tool Geometry (TG) and feed rate shows that the Parabolic and Plexi Point drill bits produce nearly identical TF values, as illustrated in Figure 7. In contrast, the Twist (Standard) geometry generates the highest thrust force among the three. Additionally, the graph indicates a clear trend, showing TF increases with an increase in feed rate.

3.3 Effect of Process Parameters on Delamination Factor at Entry

The major effect plot for Delamination Factor at (DF_{entry}) for Feed rate (mm/rev), Speed (rpm), and Tool Geometry (TG) is displayed in Figure 8. It is found that the Plexi point tool geometry yields the lowest DF_{entry}, followed by the Parabolic, while Twist (Standard) yields the greatest value. The Plexi point tool has a sharper point angle, resulting in a smaller contact area sandwiched between the tool and the composite, reducing the axial thrust force eventually reducing DF_{entry}. The twist drill has higher

Table 2. ANOVA table for TF in drilling

Source	DF	SeqSS	AdjSS	AdjMS	F	P	% Contribution
Tool geometry	2	188236	188236	94118	64.89	0	87.73362417
Speed (rpm)	2	171	171	86	1.4	0.3	0.080166298
Feed (mm/rev)	2	19947	19947	9974	27.59	0	9.297426289
Tool geometry* Speed (rpm)	4	669	669	167	1.49	0.292	0.155671766
Tool geometry* Feed (mm/rev)	4	10607	10607	2652	0.97	0.476	2.472104925
Speed (rpm)* Feed (mm/rev)	4	1121	1121	280	2.12	0.169	0.261006553
Error	8	1723	1723	215			
Total	26	222473		107277			
S=14.6765R-Sq=99.23%R-Sq(adj)=97.48%							

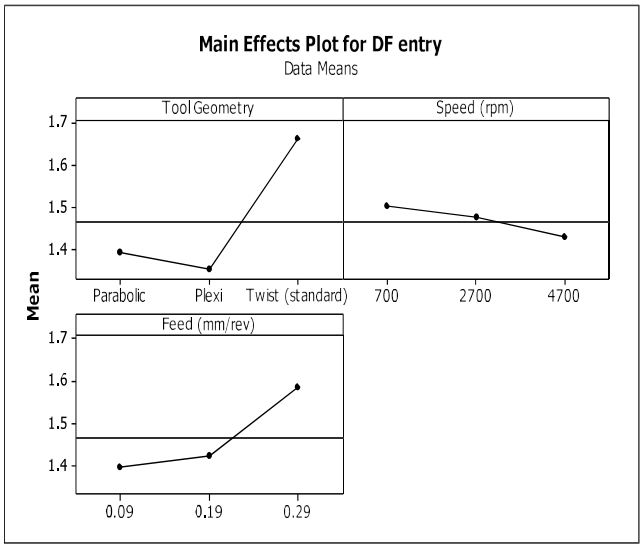


Figure 8. Main effect plots for DFentry and TG, S and F.

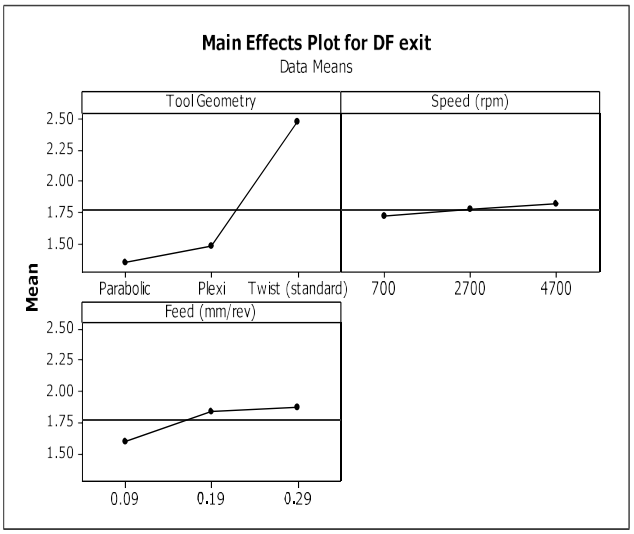


Figure 9. Main effect plots for DFexit and TG, S and F.

Table 3. ANOVA table for DF_{entry} in drilling

Source	DF	SeqSS	AdjSS	AdjMS	F	P	% Contribution
Tool geometry	2	0.64479	0.64479	0.3224	64.89	0	65.90486
Speed (rpm)	2	0.01394	0.01394	0.00697	1.4	0.3	1.424804
Feed (mm/rev)	2	0.27414	0.27414	0.13707	27.59	0	28.01979
Tool geometry*speed (rpm)	4	0.02959	0.02959	0.0074	1.49	0.292	1.512705
Tool geometry*feed (mm/rev)	4	0.01921	0.01921	0.0048	0.97	0.476	0.981214
Speed(rpm)*feed (mm/rev)	4	0.04221	0.04221	0.01055	2.12	0.169	2.156626
Error	8	0.03975	0.03975	0.00497			
Total	26	1.06365		0.48919			
S=0.0704886R-Sq=96.26%R-Sq(adj)=87.85%							

point angle resulting in higher thrust force causing severe delamination and hence highest DF_{entry}. It was also evident from the graph for speed that the DF_{entry} decreases as we increase the speed and shows a decline trend indicating use of higher speed value for achieving lower DF_{entry}. The graph again indicates an increasing trend of DF_{entry} value with feed rate. As the feed rate is higher, high thrust forces are generated, which exceeds the interfacial strength fiber and matrix causing maximum delamination. It was clearly observed in the graph that feed rate of 0.09 mm/rev has the lowest DF_{entry} and 0.29 mm/rev has the highest DF_{entry}.

The ANOVA table for DF_{entry} and chosen parameters is displayed in Table 3. While speed has negligible effects on DF_{entry}, TG and feed rate have substantial effects, according to the p-value derived from the ANOVA results. The percentage contribution shows that tool geometry is most effective parameter having 65%, while feed is having

Table 4. ANOVA table for DF exit for drilling

Source	DF	SeqSS	AdjSS	AdjMS	F	P	% Contribution
Tool geometry	2	6.9621	6.9621	3.4811	222	0	88.86705
Speed (rpm)	2	0.0383	0.0383	0.0192	1.22	0.34	0.490146
Feed (mm/rev)	2	0.4146	0.4146	0.2073	13.2	0	5.292045
Tool geometry*speed (rpm)	4	0.0574	0.0574	0.0144	0.92	0.5	0.36761
Tool geometry*feed (mm/rev)	4	0.7506	0.7506	0.1877	12	0	4.791688
Speed (rpm)*feed (mm/rev)	4	0.0299	0.0299	0.0075	0.48	0.75	0.191463
Error	8	0.1253	0.1253	0.0157			
Total	26	8.3782		3.9172			
S=0.125138R-Sq=98.50%R-Sq(adj)=95.14%							

28% effect on DF_{entry} in drilling. There is no discernible relationship between TG and speed, TG and feed, or speed and feed. The R-Sq (adj) value (87.85%) suggests an acceptable fitting of the model.

3.3 Effect of Process Parameters on Delamination Factor at Exit

The main effect plot for delamination factor at Entry (DF_{exit}) for Tool Geometry (TG), Speed (rpm) and Feed rate (mm/rev) is as shown in Figure 9. DF_{exit} *vs* TG indicates that the highest value of DF_{exit} is observed in Twist (standard) while the lowest value of DF_{exit} is achieved in parabolic tool geometry. The twist drill, with a higher point angle cause more exit delamination due to greater thrust and poor chip evacuation, while parabolic drill, with a more open flute design, reduce damage by allowing better chip evacuation and smoother cutting. On the contrary, plexi drill having a smaller point angle, perform better than twist but not as well as parabolic. The graph again indicates that there is no significant effect of speed on DF_{exit} as all the points lie near to the mean value. We also observe that for 0.09 mm/rev of feed rate we get lowest value of DF_{exit} and the trend line becomes stable as higher value of feed rate causes more delamination and hence higher value of thrust force at exit is reported.

Table 4 displays the ANOVA table for the chosen parameters and DF_{exit}. Speed has negligible influence on DF_{exit}, whereas feed rate and TG have substantial effects, according to the p-value from the ANOVA results. Similar to results obtained in TF and DF_{entry}, the percentage contribution revel as that TG is most influential parameter with 88 %, followed by feed having 5% on DF_{exit} during drilling. TG and feed have a large relationship, but speed and feed and tool geometry have negligible interactions. The R-Sq(adj) value of 95.14% indicates that the model fits the data well.

4.0 Conclusion

The purpose of this study is to support the use of hemp polyester composites in the manufacturing of final components by examining their drilling behaviour. The effects of speed, feed and tool geometry and on Delamination Factors (DF) and the Thrust Force (TF) for hemp polyester composite were studied using Analysis of Variance (ANOVA) followed by regression analysis. The following are the main findings from the

investigation and testing of drilling hemp polyester composites:

For the created composite specimens, speed has no effect on thrust force, but it does increase with an increase in feed rate.

The thrust force is significantly affected by the drill geometry. Compared to the Twist (standard) drill, the Plexi point and Parabolic drills produce less thrust force.

The lowest value of DF_{entry} is achieved for the Plexi point tool geometry followed by Parabolic and the highest value is achieved for Twist (standard).

The highest value of DF_{exit} is observed in Twist (standard) while the lowest value of DF_{exit} is achieved in Parabolic tool geometry.

The increase in feed rate increases the DF_{entry} and DF_{exit}.

The ANOVA results yields that percentage contribution of tool geometry is highest followed by feed in analysis of TF, DF_{entry} and DF_{exit}.

5.0 Author Contribution

Conceptualization, V.P.C and M.O.; Methodology, V.P.C. and M.O.; Investigation, V.P.C and M.O.; Writing-review and editing, M.O.; Supervision, V.P.C. All authors have read and agreed to the published version of the manuscript.

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