Abstract: The withdrawal and lateral holding properties of three types of plywood with one stapled as well as one-row multi-stapled joints were studied and compared. The results show that variations in plywood density have a significant effect on withdrawal strength and a relatively small effect on lateral holding strength. At four staples, the withdrawal strength of the eucalyptus plywood with a density of 0.59 g/cm$^3$ is 1821 N, which is 21% higher than that of poplar plywood with a density of 0.51 g/cm$^3$ at 1498 N and 32% higher than that of eucalyptus/poplar composite plywood with a density of 0.53 g/cm$^3$ at 1275 N. In terms of lateral holding strength, eucalyptus plywood has a lateral holding strength of 1603 N, 12% lower than the 1807 N of eucalyptus/poplar composite plywood and 10% lower than the 1761 N of poplar plywood. As the number of staples increased from 1 to 4 in increments of 1, the withdrawal strength of eucalyptus plywood continued to increase, while the nodal strengths of the poplar plywood as well as eucalyptus/poplar composite plywood did not differ significantly between 3 and 4 staples, and there is a significant increase in the lateral holding strength for all three plywood nodes. Equations for predicting the withdrawal and lateral holding strengths of one-row multi-stapled joints were derived separately.

Keywords: poplar; eucalyptus; staple; plywood; material density; wood joint

1. Introduction

The various appearances of the sofa depend to a large extent on the structure of the frame and the structural design of the frame, as the stability of the nodes not only affects the overall mechanical properties of the sofa but is also an important factor in determining the service life and function of the sofa [1–3]. At present, the structural frame of sofas is mainly made of wood composite material and solid wood connected by staples.

As a common connection in sofa frames, staples are fast and easy to use. Since most failures of the frame are concentrated in the connecting nodes, the structural strength is an important step to research in the design of the whole frame structure [4–6]. According to a study of forces on staples in sofa frames [7], staple joints are usually subjected to transverse lateral holding strength or direct withdrawal force, so the study of these two forces at the peg joint can provide a reference for the strength design of the frame structure [8]. In addition, the material is also an important factor affecting the mechanical strength of furniture nodes. Poplar as well as eucalyptus have been used for a long time as man-made panel materials in the furniture field [9], and the application of poplar and eucalyptus composites has long been proven to be feasible [10]; however, their use under conditions of varying mechanical strengths in furniture nodes has been studied less [11,12].

As for the research on staples, early studies mostly focused on different tree species to study the influence of the number of staples, the spacing and length of staples on the pullout resistance and the lateral shear force of the staple joints [13–17]. The follow-up study aimed to investigate the effect of different materials on the mechanical strength of
the nodes. Kamperidou and Vasileiou (2012) introduced the edgewise bending moment capacity of four commonly used woods in upholstered furniture nodes [18]. Demirel et al. (2012) studied and compared the transverse shear performance of three kinds of OSB face-to-face joints, one stapled and the other one-row multi-stapled [19]. Demirel et al. (2013, 2014) studied the increasing effect of three OSB materials with different numbers of staples and gluing on the lateral resistance load of joints [20,21]. Demirel et al. (2020) studied the lateral shear performance of one staple and one-row of multi-stapled joints of pine, alder and beech [22].

Through field visits to several domestic sofa enterprises, we found that poplar plywood and pine are the most used materials in sofa frame nodes, whilst the most used staple length is 40 mm. Due to the lack of relevant research, there are less applications of eucalyptus plywood and eucalyptus/poplar composite plywood, and thus the study of these three materials may not only be conducive to the promotion of new materials, but also serve as a frame of reference for enterprises with regard to the choice of plywood.

The objectives of this study were to examine the effect of the density of the plywood on the withdrawal and lateral holding strength of the one-row multi-stapled joints; to study the effect of the number of staples and the density of the plywood on the withdrawal and lateral holding strength of the one-row multi-stapled joints; and derive some equations to predict the withdrawal and lateral holding strength of the one-row multi-stapled joints. By studying these three materials, it is not only beneficial to the promotion of new materials, but also has implications for companies in terms of their choice of plywood.

2. Material and Methods

Materials

The staple wood joint specimens used in this study are shown in Figure 1. They are both composed of plywood and pine wood, which are only connected by staples. Three views of the test specimen for withdrawal strength are shown in Figure 1a. Three views of the test specimen for lateral holding strength are shown in Figure 1b. The arrangement of staples in the withdrawal strength specimen is shown in Figure 2a, and the arrangement of staples in the lateral holding strength specimen is shown in Figure 2b.

![Figure 1. Withdrawal and lateral holding strength test specimen dimensions: a multi-layer board, b pine chord-cut board, c staple.](image-url)
In this study, 20 mm thick pine was used, all the planks were chord-cutboard, and their air-dry density was 0.476/cm$^3$. All three types of plywood were 7-ply and 12 mm thick, purchased from Global Sanborn, using Mildred E0 grade eco-friendly glue. The plywood was constructed either one of two different wood species, namely poplar and eucalyptus, and a mixture of poplar and eucalyptus; Meite 440 K staples were used, the staple crown was 5.8 mm, the leg width was 1.05 mm, the staple thickness was 1.26 mm, the material was Shougang Q235, the staple gun was a 440 KB pneumatic code staple gun from Meite, the air pressure regulating valve was RHE and the pressure regulating valve, which can adjust the air pressure of 0–10 KPa, and the mechanical test adopted the Japan Shimadzu AG-X universal Material testing machine and related auxiliary fixtures. The experiments were carried out in an indoor environment with an ambient temperature of 20 °C and a relative humidity of 48%.

In this experiment, the withdrawal strength of the different plywood and pine woods connected by staples was measured by withdrawal test. The test method is shown in Figure 3a. During the measurement, the test piece was fixed on the bracket, and the pine wood was connected by metal joints. The wooden square was pulled up slowly, and the loading speed was 2.5 mm/min. A total of 9 groups of experiments with 2 factors and 3 levels were carried out, and each group of experiments was repeated 5 times. These factors were the wood types (poplar plywood, eucalyptus plywood, poplar–eucalyptus plywood) and the number of staples (1, 2, 3, 4), with a total of 60 specimens.

In order to analyze the main force of the joint, it is also necessary to test the lateral holding strength. The size of the specimen is shown in Figure 1, and the measurement
method is shown in Figure 3b. During the measurement, the specimen is fixed on the base. The block and two bolts are fixed, the iron block is placed on the top of the test piece, the test piece is located between the two bolts, and the bolts on both sides are passed through the holes drilled into the iron block and screwed into the test machine base. In the corresponding hole, the plywood is fixed onto the left side of the specimen with a metal joint and then pulled up at a loading rate of 2.5 mm/min. A full experiment with 2 factors and 3 levels was carried out, and each experiment was repeated 5 times. These factors were wood species (poplar plywood, eucalyptus plywood, eucalyptus/poplar composite plywood) and the number of staples (1, 2, 3, 4), with a total of 60 test pieces.

The moisture content (MC) and density of wood materials were determined according to the ASTM D 4442 (2010) and ASTM D 2395 (2010) standards, respectively.

All materials were placed into a closed room at a temperature of 20 ± 5 °C and a humidity of 48 ± 5% for 2 weeks prior to testing. After that, the staples were driven into the test piece with a staple gun at an air pressure of 483 KPa. All specimen samples were tested on an AGS-X universal testing machine at a speed of 2.5 mm/min. The maximum withdrawal or lateral holding load and failure mode of the specimen were recorded.

3. Results and Discussions

3.1. Material Density

The material densities used in this experiment are shown in Table 1. From the average density of these three materials, the eucalyptus plywood has the highest density, followed by the eucalyptus/poplar composite plywood, and the poplar plywood has the lowest density.

<table>
<thead>
<tr>
<th>Plywood Specie</th>
<th>Poplar</th>
<th>Eucalyptus</th>
<th>Eucalyptus/Poplar</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density (g/cm³)</td>
<td>0.51(3)</td>
<td>0.59(1)</td>
<td>0.53(6)</td>
</tr>
</tbody>
</table>

The numbers in parentheses in the table are the coefficients of variation (COV).

3.2. Edge and Face Withdrawal Strength

Outliers were detected in the experimental results according to the Grubbs test method, then the average value of the maximum value was taken, and the integer bits were reserved. The maximum withdrawal forces and coefficients of variation for three different plywood specimens at four different numbers of staples are shown in Table 2. Each value is the average of the test results of 5 specimens out of a total of 60 specimens.

<table>
<thead>
<tr>
<th>Number of Staples</th>
<th>Poplar</th>
<th>Eucalyptus</th>
<th>Eucalyptus/Poplar</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>854(9)</td>
<td>814(10)</td>
<td>725(18)</td>
</tr>
<tr>
<td>2</td>
<td>1263(7)</td>
<td>1415(3)</td>
<td>1380(20)</td>
</tr>
<tr>
<td>3</td>
<td>1476(8)</td>
<td>1585(12)</td>
<td>1256(22)</td>
</tr>
<tr>
<td>4</td>
<td>1498(5)</td>
<td>1821(8)</td>
<td>1275(13)</td>
</tr>
</tbody>
</table>

Numbers in parentheses indicate coefficients of variation (COV).

The form of failure of the withdrawal specimen varies with the number of staples and with the plywood material. In the case of one staple, the failure mode of the specimen was when the staple was directly pulled out, as shown in Figure 4a; in the case of two staples, the failure mode of the poplar plywood and eucalyptus plywood was mostly when the staples were mostly directly pulled out, as shown in Figure 4b; and the failure form of the
eucalyptus/poplar composite plywood was not only the staples being pulled out, but also the phenomenon of cracking in the middle of the plywood, as shown in Figure 4c. At three and four staples, the failure modes of the three types of plywood were mostly plywood breakage, as shown in Figure 4d, while the eucalyptus/poplar composite plywood had a cracking phenomenon, as shown in Figure 4c, which may also be the cause of the test results of the eucalyptus/poplar composite plywood not being as good as those of the other two plywood.

![Figure 4. Wood joint failure mode: (a) staple legs are pulled out; (b) staple legs are pulled out; (c) cracks in the middle of the plywood; and (d) broken plywood.](image)

The withdrawal strength test has a total of three failure modes: (1) The staples are pulled out directly, in which case the maximum grip of such staples is equivalent to that of pine; (2) The plywood breaks in the middle, it can be concluded that with this number of staples the maximum tensile strength of the node is achieved; and (3) The plywood cracks in the middle, which occurs less frequently and only in eucalyptus/poplar composite plywood, and is therefore presumed to be due to technical problems with the plywood, with fractures in the glue layer.

Figure 5a shows the typical load–displacement curves of the three plywood with one staple. It can be clearly seen that the load–displacement curves of the poplar plywood and eucalyptus plywood are similar, and the maximum failure load is similar, while the maximum limit value of the poplar–eucalyptus plywood is relatively low and the load rising speed is approximately a straight line; the maximum limits of poplar plywood, eucalyptus plywood and eucalyptus/poplar composite plywood are approximately 2 mm, 1.5 mm and 0.9 mm, respectively.

![Figure 5. Load-displacement curves for the withdrawal strength of three kinds of plywood: (a) one staple; and (b) four staples.](image)
Figure 5b shows the load–displacement curves of the three types of plywood when there are four staples of 2–3 mm to reach the maximum limit value. The changes in the three curves can be roughly divided into two stages: in the first stage, the withdrawal strength rapidly increases with the increase in displacement, which is a linear change process; in the second stage, the growth rate of the withdrawal strength of the specimen begins to slow down. Then, it reaches a maximum value and rapidly decreases.

In order to more intuitively display the test data, a histogram is drawn, as shown in Figure 6, which is a comparison chart of withdrawal strength. It can be clearly seen from the figure that for the staple nodes of different materials, the withdrawal strength of the eucalyptus plywood increases with the increase in the number of staples and reaches the maximum when there are four staples. The withdrawal strength of poplar plywood is also at its maximum at four staples, but it is not very different from the withdrawal strength at three staples, taking into account the experimental error, which is reached at three staples. In the case of eucalyptus/poplar composite plywood, the withdrawal strength reaches its maximum at two staples and decreases when the number of subsequent staples increases. As can also be seen from the above chart, the eucalyptus plywood has the highest withdrawal strength with a maximum withdrawal strength that is 21% higher than that of poplar plywood, at approximately 323 N and 32% higher than that of eucalyptus/poplar composite plywood, at approximately 441 N.

![Withdrawal load histogram.](image)

Figure 6. Withdrawal load histogram.

Based on the above experimental data, referring to the research on the lateral and withdrawal resistances of furniture grade pine plywood joints by Jilei Zhang [15], the regression analysis was carried out with the following equations:

\[ P = K_1 \times N^a \]  \hspace{1cm} (1)

where:
- \( P \)—donates the average maximum withdrawal static load of one-row multi-stapled joints (N);
- \( N \)—denotes the numbers of staple;
- \( a \)—denote regression constants.

Based on the data obtained from the regression analysis of the three types of plywood in Table 3, the prediction equation for this experiment was derived. Since the regression constant obtained in Equation (1) is very similar to the withdrawal load of one staple, it can be replaced by Equation (2):

\[ P = F_1 \times N^{0.45} \left( r^2 = 0.89 \right) \]  \hspace{1cm} (2)
Table 3. Constants \( K_1, r^2 \) and \( p \) values in the prediction equation for the average maximum withdrawal loads of one-row multi-stapled joints composed of three different plywood types.

<table>
<thead>
<tr>
<th>Wood Species</th>
<th>( K_1 )</th>
<th>( a )</th>
<th>( r^2 )</th>
<th>( p )-Value</th>
<th>( F_1 )</th>
<th>( F_{K_1/F_1} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Poplar</td>
<td>855</td>
<td>0.57</td>
<td>0.96</td>
<td>&lt;0.0001</td>
<td>854</td>
<td>1</td>
</tr>
<tr>
<td>Eucalyptus</td>
<td>887</td>
<td>0.42</td>
<td>0.95</td>
<td>&lt;0.0001</td>
<td>814</td>
<td>1.01</td>
</tr>
<tr>
<td>Eucalyptus/poplar</td>
<td>817</td>
<td>0.41</td>
<td>0.67</td>
<td>&lt;0.0001</td>
<td>725</td>
<td>1.1</td>
</tr>
</tbody>
</table>

\( F_1 \) donates the average maximum withdrawal load of one stapled joint made of three different plywood types (N).

3.3. Lateral Edge Holding Strength

Outliers in the experimental results were detected according to the Grubbs test, and then the average value of the maximum value was taken, and the integer bits were reserved. The maximum lateral holding strengths and coefficients of variation for three different plywood specimens with four different numbers of staples are shown in Table 4. Each value is the average of the test results of five specimens for a total of 60 specimens.

Table 4. Average comparisons of maximum lateral holding loads of one-row multi-stapled joints for plywood species with different numbers of staples.

<table>
<thead>
<tr>
<th>Number of Staples</th>
<th>Poplar</th>
<th>Eucalyptus</th>
<th>Eucalyptus/Poplar</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>485(7)</td>
<td>487(7)</td>
<td>442(8)</td>
</tr>
<tr>
<td>2</td>
<td>954(2)</td>
<td>920(3)</td>
<td>945(6)</td>
</tr>
<tr>
<td>3</td>
<td>1357(8)</td>
<td>1328(7)</td>
<td>1285(4)</td>
</tr>
<tr>
<td>4</td>
<td>1761(3)</td>
<td>1603(5)</td>
<td>1807(3)</td>
</tr>
</tbody>
</table>

Numbers in parentheses indicate coefficients of variation (COV).

The failure mode of the specimen varies with the number of staples and the plywood material. As shown in Figure 7, when there are one or two staples, the failure mode is when the staples are directly pulled out, as shown in Figure 7a,b; when there are three and four staples, the failure modes of the three plywood are mostly the square cracking and square front end cracking of pine, as shown in Figure 7c,d, whilst eucalyptus/poplar composite plywood also has the phenomenon of plate fracture, as shown in Figure 7e. As can be seen, it is speculated that there may be technical limitations and the material properties are not very good.

![Figure 7](image-url)

Figure 7. Wood joint failure mode: (a) staple legs are pulled out; (b) staple legs are pulled out; (c) cracked pine wood; (d) cracked front end of pine wood; and (e) broken plywood.

The lateral holding strength test has a total of three failure modes: (1) Staples that are pulled straight out, in this case, the maximum grip of such staples is equivalent to
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that of pine wood; (2) Pine wood squares cracking indicates that the maximum lateral holding strength of the node has been reached for this number of staples; and (3) The front end of the plywood splits, which occurs less frequently and only in eucalyptus/poplar composite plywood, and is therefore presumed to be due to plywood technical problems with plywood cracking.

Figure 8a shows the typical lateral holding load–displacement curves for the three woods at a single staple. Poplar plywood has the most stable lateral holding load curve for a single staple; eucalyptus plywood is fastest in reaching the yield load but has a longer time between the yield load and breaking load; while the eucalyptus/poplar composite plywood has the highest yield load but reaches its maximum breaking load quickly after reaching the yield load.

![Figure 8a](image_url)

**Figure 8.** Load-displacement curves for the lateral holding strength of three kinds of plywood: (a) one staple; and (b) four staples.

Figure 8b shows the lateral holding load–displacement curves for the three types of plywood with four staples. It is clear that the lateral holding strength of the eucalyptus plywood is relatively poor, while the eucalyptus/poplar composite plywood is more similar to the poplar plywood and basically reaches the breaking load between 6 and 8 mm. The three curves can be roughly divided into two stages, which are similar to those for individual staples, all rising rapidly in a straight line until the yield load is reached, after which the curve begins to slow down and reaches the second stage, between yield load and breaking load, where the displacement curve for eucalyptus/poplar composite plywood is the best of the three.

As shown in Figure 9, the nodal lateral holding strength of all three plywood compositions increases with the number of staples, and the lateral holding strength of the poplar plywood at a single staple is 442 N which is the lowest. The lateral holding strengths of poplar plywood and eucalyptus plywood are similar at 485 N and 487 N, respectively. However, as the number of staples reaches four, the lateral holding strength of the eucalyptus/poplar composite plywood is instead the highest of the three plywood nodes, with eucalyptus plywood having the lowest lateral holding strength in comparison, being 10% lower than the poplar plywood at approximately 158 N and 12% lower than the poplar–eucalyptus plywood at approximately 204 N.
where:

By studying the withdrawal and lateral holding strengths of one-row multi-stapled joints of poplar plywood, eucalyptus plywood and eucalyptus/poplar composite plywood with a pine timber cube, the following conclusions can be drawn: the variation in plywood density has a significant effect on the withdrawal strength, while the effect on the lateral holding strength is relatively small. With one staple, the withdrawal strength of the poplar plywood joint with a density of 0.51 g/cm$^3$ was 129 N higher than that of the eucalyptus/poplar composite plywood with a density of 0.53 g/cm$^3$ and 40 N higher than that of the eucalyptus plywood with a density of 0.59 g/cm$^3$. At one staple, the lateral holding strength of the three plywood did not differ significantly.

As the number of staples increased from 1 to 4, the withdrawal strength of both types of plywood increased with the number of staples, except for the eucalyptus/poplar composite plywood, which reached its maximum withdrawal strength at two staples. At the same time, the average maximum withdrawal strength of the densest eucalyptus plywood joint was significantly greater than that of the poplar and eucalyptus/poplar composite plywood joints as the number of staples increased. In terms of lateral holding strength, the lateral holding strength of all three types of plywood increased with the number of staples, with no significant difference in the mean maximum lateral holding strength of the three types of

Figure 9. Lateral holding load histogram.

By summarizing the above data, combined with international research, namely on the basis of Samet Demirel’s research on the influence of material density on the lateral holding strength of staple joints [22], it is deduced that three kinds of plate density changes suitable for this experiment have an effect on joints. The formula for the effect of lateral holding strength is as follows:

$$P = K_2 \times D^b \times N^c$$  \hspace{5pt} (3)

where:

- $P$—denotes the average maximum lateral holding static load of one-row multi-stapled joints ($N$);
- $N$—denotes the numbers of staples;
- $K_2, b, c$—denote regression constants;
- $D$—material density (g/cm$^3$).

Based on this formula, regression analysis was carried out to verify the fitting degree of the plywood density change to this equation. The overall fitting degree of the regression equation obtained was good, and the values of the regression constants $K_2, b$ and $c$ were 4.6, 2.12 and 3.7, respectively, while $r^2$ is 0.97, indicating that as long as the material density of the plywood and the number of staples are known, the lateral holding load of one-row multi-stapled joints can be predicted by this equation.

4. Conclusions

By studying the withdrawal and lateral holding strengths of one-row multi-stapled joints of poplar plywood, eucalyptus plywood and eucalyptus/poplar composite plywood with a pine timber cube, the following conclusions can be drawn: the variation in plywood density has a significant effect on the withdrawal strength, while the effect on the lateral holding strength is relatively small. With one staple, the withdrawal strength of the poplar plywood joint with a density of 0.51 g/cm$^3$ was 129 N higher than that of the eucalyptus/poplar composite plywood with a density of 0.53 g/cm$^3$ and 40 N higher than that of the eucalyptus plywood with a density of 0.59 g/cm$^3$. At one staple, the lateral holding strength of the three plywood did not differ significantly.

As the number of staples increased from 1 to 4, the withdrawal strength of both types of plywood increased with the number of staples, except for the eucalyptus/poplar composite plywood, which reached its maximum withdrawal strength at two staples. At the same time, the average maximum withdrawal strength of the densest eucalyptus plywood joint was significantly greater than that of the poplar and eucalyptus/poplar composite plywood joints as the number of staples increased. In terms of lateral holding strength, the lateral holding strength of all three types of plywood increased with the number of staples, with no significant difference in the mean maximum lateral holding strength of the three types of

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where:

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- $N$—denotes the numbers of staples;
- $K_2, b, c$—denote regression constants;
- $D$—material density (g/cm$^3$).

Based on this formula, regression analysis was carried out to verify the fitting degree of the plywood density change to this equation. The overall fitting degree of the regression equation obtained was good, and the values of the regression constants $K_2, b$ and $c$ were 4.6, 2.12 and 3.7, respectively, while $r^2$ is 0.97, indicating that as long as the material density of the plywood and the number of staples are known, the lateral holding load of one-row multi-stapled joints can be predicted by this equation.

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As the number of staples increased from 1 to 4, the withdrawal strength of both types of plywood increased with the number of staples, except for the eucalyptus/poplar composite plywood, which reached its maximum withdrawal strength at two staples. At the same time, the average maximum withdrawal strength of the densest eucalyptus plywood joint was significantly greater than that of the poplar and eucalyptus/poplar composite plywood joints as the number of staples increased. In terms of lateral holding strength, the lateral holding strength of all three types of plywood increased with the number of staples, with no significant difference in the mean maximum lateral holding strength of the three types of
plywood joints at 1–3 staples, but at 4 staples, the mean maximum lateral holding strength of the densest eucalyptus plywood was significantly lower than that of the poplar and eucalyptus/poplar composite joints.

For the test of withdrawal strength, the specimens failed in the form of the cracking of the plywood surface for a small number of eucalyptus/poplar composite plywood at with one and two staples, whilst the rest were pulled out by the staples. With three or four staples, a small number of eucalyptus/poplar composite plywood failed in the form of plywood cracking, while the rest were plywood fractures. For the lateral resistance test, the failure of the specimens was mainly in the form of staples being pulled out when the number of staples was one or two, while the failure was mainly in the form of pine wood square cracking and pine wood front cracking when the number of staples was three or four, and eucalyptus/poplar composite plywood also showed the phenomenon of plate cracking.

The experimental test results are close to the prediction equations derived from the regression analysis and therefore the withdrawal and lateral holding strengths of one-row multi-stapled joints can be predicted using Equation (2) as well as Equation (3), as Equation (2) requires knowledge of the withdrawal load at a single nail and Equation (3) requires knowledge of the material density.

Poplar and eucalyptus plywood are currently the most common plywood used for sofa frames in China, while eucalyptus/poplar composite plywood is the material being investigated for use in sofa frames, so the selection of these three plywood for study will help sofa companies concerned with choosing the right plywood for their frames.

**Author Contributions:** Conceptualization, Y.M. and S.P.; methodology, Y.M.; software, S.P.; validation, Y.M., S.P. and W.X.; formal analysis, Y.M.; resources, Y.M.; data curation, S.P.; writing—original draft preparation, Y.M.; writing—review and editing, Y.M.; visualization, S.P.; supervision, W.X.; project administration, Y.M.; funding acquisition, Y.M. All authors have read and agreed to the published version of the manuscript.

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