

Effects of micro-drilling parameters on the drilling force and pore morphology of *Sapindus mukorossi* seeds

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Research Article

Keywords: *Sapindus mukorossi*, Micro-drilling, Drilling parameters, Drilling force, Pore morphology

Posted Date: February 24th, 2023

DOI: <https://doi.org/10.21203/rs.3.rs-2614404/v1>

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Abstract

Sapindus mukorossi seeds are commonly drilled and processed into strings and other craft products. To improve the machining qualities of micro-drilling of *S. mukorossi* seeds, the effects of these drilling parameters on the drilling force and pore morphology were found. The mechanism behind these changes was further analyzed. The drilling parameters (feed rate, drilling speed, and drill diameter) and machining process for the micro-drilling of *S. mukorossi* seeds were optimized. Results indicated that each drilling parameter influenced the drilling force and hole-machining quality by affecting the amount of cutting, the working conditions of the drill bit, chip formation, and the generation of drilling heat. Moreover, the feed rate and drill diameter are main influence factors that influence the drilling force, and the drilling speed plays a leading role that influences the hole-machining quality. Interestingly, for the drilling of *S. mukorossi* seeds, a feed rate of 0.03 mm/r, a drilling speed of 6 m/min, and a drill-bit diameter of 0.9- or 1.5 mm resulted in a hole with high accuracy, good pore morphology, and minimal wear on the drill bit. This study facilitates the selection of suitable drilling parameters and processing technology for the micro-drilling of *S. mukorossi* seeds to improve the processing accuracies and qualities, and provides a theoretical basis for the improvement of related drilling processing equipment.

Introduction

Seeds have played, and continue to play, an important role in human culture as one of the earliest decorative materials. People have commonly used hard-shelled, richly colored seeds as beads and drilled holes through them to make them into necklaces, bracelets, and other decorative objects (González-Pérez et al. 2013). Bodhi seeds are the collective name for all seeds suitable for making Buddhist prayer beads, which have an important place in Buddhism as a counting device for chanting. A fixed number of bodhi seeds are drilled and strung into strings to make Buddhist prayer beads and strings to be worn on the hands (Li et al. 2014). *S. mukorossi* is the most common type of bodhi seed (Liu et al. 2021). *S. mukorossi* is mainly found in Southeast Asia, and North and South America. It is an important biological resource for forestry (Liu et al. 2022), and is widely used in medicine (Shiu et al. 2020), as an ingredient in cleaning products (Sochacki et al. 2022), in the production of biodiesel (Chakraborty et al. 2013), and as a bead accessory. *S. mukorossi* fruits (Fig. 1a) consist of a translucent yellow coating and black seeds (Fig. 1b). *S. mukorossi* seeds consist of a seed shell (which is a hard, dense kernel coating about 2-mm thick) and a seed kernel (consisting of 42.3% oil, including various higher fatty acids) (Fig. 1c). Because of their hard outer shell, *S. mukorossi* seeds are commonly drilled and processed into strings (Fig. 1d) and other handicrafts.

Owing to its high material removal rate and wide applicability, drilling is the most cost-effective method for producing holes in woody materials, including *S. mukorossi* seeds (Bedeleian et al. 2022). Micro-drilling is a type of micro-fabrication that is gaining importance in a wide range of precision-production industries (Hasan et al. 2017). In response to today's rapidly evolving manufacturing industry, a great deal of research has focused on optimizing drilling processes in metallic materials. For example, wear analysis in micro-drilling of 718 high-temperature alloys has been investigated (Agrawal et al. 2022) and a new model for determining the cutting parameters in metal-drilling processes has been developed (Türkcs et al. 2020). Research has also been conducted on inorganic, non-metallic materials. For example, Huang et al. (2020) investigated the chip-adhesion mechanism in micro-drilling with a high-ceramic-content-particle-filled GFRP (glass fibre-reinforced plastic), and studied the effect of the process parameters on the drilling temperature and chip adhesion. They

then proposed a method to control chip adhesion. The study of micro-drilling of organic materials has also developed, albeit more gradually and systematically. For example, Akhbar et al. (2019) studied the surgical drills used in bone-drilling procedures and obtained the optimal drill design that caused minimal thermal damage through rigorous drilling simulations and statistical analysis. In addition, for composite materials, Shi et al. (2019) reviewed the micro-drilling process for high-frequency, high-speed PCB (printed circuit board) materials. They also reviewed research advances in micro-drill bit design and wear performance, micro-drilling force and temperature analysis, and micro-hole quality.

For woody materials, micro-drilling has mainly been used as an inspection technique. An example of this is the micro-drilling resistance method for wood (which is a micro-damage inspection technique) (Li et al. 2019; Hu et al. 2020; Hu et al. 2022). Research on the process parameters of micro-drilling of woody materials, such as *S. mukorossi* seeds, is lacking. A review of the literature shows that there is little research on the changes in drilling forces and pore morphology in woody materials under different drilling parameters, and that the influence of the drilling forces on the drilling process has not yet been revealed. The correct selection of drilling parameters is of great importance for improving the drilling efficiency, ensuring durability of the drilling tool, reducing costs, and improving quality (Liu et al. 2022). In addition, drilling a round hole in such a tiny and hard structure as a *S. mukorossi* seed is not easy. The layered structure of the *S. mukorossi* seed leads to new problems in the drilling process, such as tool wear and roughness of the hole appearance. Therefore, the design of relevant equipment (e.g. special drilling machines for *S. mukorossi* seeds) lacks experimentally obtained parameters.

To address this knowledge gap, this study focuses on the drilling parameters for the micro-drilling of *S. mukorossi*. Specifically, the effects of feed rate, drilling speed, and drill diameter on the drilling force, hole diameter, and pore morphology are analyzed. The optimal selection of suitable drilling parameters for micro-drilling processing of *S. mukorossi* seeds (and similar wood structures) to improve the processability and accuracy of the drilling process are determined. A theoretical basis is also provided for the improvement of drilling equipment. These findings are also useful for related fields of micro-drilling applications in wood materials (e.g. micro-damage inspection technology).

Material And Methods

Seed materials

High-quality *S. mukorossi* trees in southeastern China were selected as the seed source. The selected seed material was obtained in October 2022 in Fujian Province, China (26°14'36"N;117°35'48"). A sufficient number of *S. mukorossi* fruits of moderate size, regular shape, and uniform quality were obtained from *S. mukorossi* trees that had a high fruiting rate, full fruit, few seed pests, and minimal disease. The *S. mukorossi* fruits were dried naturally in a cool place, peeled off, and stored in a refrigerator at 4°C under low humidity.

Experimental design

Fixed seeds of the same size were drilled with a micro-drill with the feed rate, drilling speed, and drill diameter as the independent variables. To reduce experimental error, 48 homogeneous *S. mukorossi* seeds of approximately 12-mm diameter were selected, 12 of which were used as test pieces and spare parts for the

drilling process. The range of drilling parameters for the drilling experiments was determined by test drilling. With a feed rate of 0.02–0.07 mm/r, a drilling speed of 3–24 m/min, and a drill diameter of 0.9–1.5 mm, 36 sets of experiments were designed for 36 *S. mukorossi* seeds. The drilling parameters for these experiments are shown in Table 1.

Table 1
Drilling parameters of the drills

No.	D [mm]	f_z [mm/r]	v [m/min]	No.	D [mm]	f_z [mm/r]	v [m/min]	No.	D [mm]	f_z [mm/r]	v [m/min]
1	1.0	0.02	24	13	1.0	0.03	12	25	0.9	0.03	6
2	1.0	0.02	21	14	1.0	0.03	9	26	1.3	0.03	6
3	1.0	0.02	18	15	1.0	0.03	6	27	1.5	0.03	6
4	1.0	0.02	15	16	1.0	0.03	3	28	0.9	0.03	12
5	1.0	0.02	12	17	1.0	0.04	12	29	1.3	0.03	12
6	1.0	0.02	9	18	1.0	0.05	12	30	1.5	0.03	12
7	1.0	0.02	6	19	1.0	0.06	12	31	0.9	0.03	18
8	1.0	0.02	3	20	1.0	0.07	12	32	1.3	0.03	18
9	1.0	0.03	24	21	1.0	0.04	6	33	1.5	0.03	18
10	1.0	0.03	21	22	1.0	0.05	6	34	0.9	0.03	24
11	1.0	0.03	18	23	1.0	0.06	6	35	1.3	0.03	24
12	1.0	0.03	15	24	1.0	0.07	6	36	1.5	0.03	24

In the experiments, the drilling positions were divided into seven groups according to the path of the drill and the structure of the *S. mukorossi* seeds (as shown in Fig. 2). The drilling forces for each drilling position within the seeds and the diameters of the import and export holes were collected, and the relationship between each drilling parameter and the drilling force and hole diameter was analyzed.

Drilling experiment

Experiments were performed for dry drilling at low speed. The experimental platform (Sauer Ultrasonic 50, DMG, Germany) is shown in Fig. 3. The drills, which were made by UNION TOOL (Union Tool Co., Ltd, Shanghai, China), all belonged to the lengthening blade series and had two blades made from carbide materials. The helix and tip angles were 30° and 130°, respectively. Because of drill wear, the drills were replaced after every two drillings.

Owing to the smooth and hard spheres of *S. mukorossi* seeds, the seed during drilling is difficult to fix. To avoid skewing of the hole axis, enlargement of the hole diameter, and deformation of the round hole shape, a drilling die was used to fix the seeds. This ensured the accuracy and stability of the drilling process.

Measurement and observation

A Kistler dynamometer recorded the drilling force with high accuracy and high repeatability. The Dynoware data acquisition system, which is a general-purpose data acquisition and analysis software supporting the Kistler dynamometer, was adopted to measure the micro-drilling forces. Forces in three directions (F_x , F_y , and F_z) could be obtained, but only the drilling force in the z-direction was used. All test data were taken during a phase of stable cutting.

A FAS-VII fiber measuring instrument (OLYMPUS CX41, Japan) that provides high-definition images was used to observe the morphology of the holes in the seeds. A UV-G particle-size-analysis microscope was used to accurately measure the hole diameter. The magnification was 200× or 300×.

Results And Discussion

Effect of feed rate on drilling force and pore morphology

Figure 4a–d shows the relationship between the feed rate and the drilling force generated at different positions in the hole when the drill diameter and drilling speed were constant. For a drill diameter of 1.0 mm, a drilling speed of 6 m/min, and a feed rate of 0.02–0.07 mm/r, the drilling force at different positions of the *S. mukorossi* seeds varied from 0 to 25 N. When the drilling speed was 12 m/min and the feed rate was in the range of 0.02–0.07 mm/r, the drilling forces at different positions of the seeds varied from 0 to 14 N. For a fixed drill diameter and drilling speed, the drilling force increased with increasing feed rate at all positions on the seeds. This phenomenon can be explained by the following reasons. First, an increase in feed rate leads to an increase in the cutting thickness and cutting area, which increases the drilling force (Latha et al. 2009). Second, *S. mukorossi* seeds have high plasticity. Thus, a greater feed rate will lead to greater plastic deformation, increasing the friction coefficient between the chip and the front tool surface, which increases the drilling force. Furthermore, an increase in feed rate increases the height of the residual drilling area, resulting in a rougher hole wall (Palanikumar 2011) and an increase in friction with the sub-rear tool face of the guiding part of the drill, which also serves to increase the drilling force. In addition, a higher feed rate leads to more material being removed. This increases the torque and drilling power (Kumar et al. 2022), in turn increasing the drilling heat generated per unit time and a rise in drilling temperature. The higher temperature accelerates the wear of the carbide drilling tool and reduces the drilling capacity, thus further increasing the drilling force.

For a drilling speed of 12 m/min and a feed rate of 0.05–0.07 mm/r, the drilling force generated during drilling through the seed kernel and the down-shell gradually decreased with increasing feed rate, as shown in Fig. 4d. The reason for this is that when drilling at higher speeds, a larger feed rate facilitates the removal of the wood fiber from the seed kernel and down-shell, which reduces the deformation resistance of the material during drilling and reduces the drilling force. In addition, at higher drilling speeds, a higher feed rate for drilling *S. mukorossi* seeds is beneficial for the formation of good chips and reduces the frictional resistance between the chips and the front tool face, resulting in a reduction in the drilling force.

Figure 5 shows the relationship between the feed rate and diameters of the inlet and outlet holes when the drill diameter and drilling speed were constant. For a drill diameter of 1.0 mm, drilling speed of 12 m/min, and feed

rate of 0.02–0.07 mm/r, the inlet and outlet diameters of the seed holes varied in the range of 0.8–1.0 mm. When the feed rate was less than 0.05 mm/r, the hole diameter gradually decreased with increasing feed rate. There are two reasons for this. First, an increase in feed rate increases the height of the residual drilling area. Second, an increase in drilling force increases the vibration amplitude of the drill bit, leading to the rupture of the wood-fiber structure of the seed shell and an increase in the burr of the hole wall, which affects the processing accuracy of the hole (Natarajan et al. 2022). When the feed rate was greater than 0.05 mm/r, the hole diameter gradually increased with increasing feed rate. This is because a higher feed rate increases the drilling force, leading to an increase in the degree of bending and deformation of the drill bit, and deflection of the drill bit, which enlarges the hole.

These analysis reveals that to reduce the drilling force and avoid undesirable problems (such as low processing accuracy of the hole and high surface roughness due to drill-lead deflection and workpiece vibration), the feed rate should be as low as possible. However, considering the production efficiency and to prevent drilling heat from affecting the durability of the drill and the quality of the hole, the feed rate should be increased appropriately to shorten the drilling time and promote the dissipation of the drilling heat. The recommended feed rate is 0.03 mm/r.

Effect of drilling speed on the drilling force and pore morphology

Figure 6a, b shows the relationship between the drilling speed and the drilling force generated at different positions in the hole when the drill diameter and feed rate were constant. For a drill diameter of 1.0 mm, feed rate of 0.03 mm/r, and drilling speed of 3–24 m/min, the drilling force ranged from 0 to 15 N. The drilling force decreased with increasing drilling speed, which we explain as follows. First, a higher drilling speed facilitates the drilling and removal of the wood-fiber structure from the seeds. This forms good chips and reduces the coefficient of friction between the chips and the front tool face, resulting in a reduction in the drilling force. Second, good chips formation is beneficial to reduce the roughness of the hole wall, a lower surface roughness of the hole wall reduces the frictional force on the guiding part of the drill bit, which serves to reduce the drilling force (Ni et al. 2022). Furthermore, the reduction in friction on the hole wall helps to reduce the generation of drilling heat, and the formation of good chips helps to dissipate the drilling heat. These effects reduce the drilling temperature and the wear of the drill bit, thus reducing the drilling force (Susmitha et al. 2016). However, when drilling at high speeds, the drilling temperature will increase, accelerating tool wear and increasing the drilling force. In Fig. 6, the decreasing trend of drilling force becomes slower as the drilling speed increases.

When the drill diameter, feed rate and drilling speed were constant, the drilling force varied among the different positions on the *S. mukorossi* seeds because of their complex internal structure. As can be seen from Fig. 6, the drilling force at the down-shell was greater than the drilling force at the up-shell, which was greater than that at the kernel. Moreover, the force decreases when drilling into the up-shell and increased when drilling out of the down-shell. The reason for this is that the *S. mukorossi* seeds consist of a hard seed shell and a loosely structured seed kernel, which is softer than the seed shell, such that the drilling force is minimal when drilling the seed kernel. When drilling the seed shell, as the drilling depth increases, the friction between the hole wall and the guide part of the drill increases owing to the vibration and wear of the drill bit, and the drilling force increases. Therefore, the drilling force required to drill the down-shell is larger. In addition, the outer side of the

seed shell is a hard outer seed coat and cuticle, and the inner side is a loose and porous inner seed coat. Therefore, the outer side of the seed shell is harder than the inner side and the drilling force on the outer side is greater than that on the inner side. Thus, the drilling force decreases when drilling into the up-shell and increases when drilling out of the down-shell.

Figure 7 shows the relationship between the drilling speed and the diameters of the import and export holes for different drill diameters for a given drill diameter and feed rate. When the feed rate was 0.03 mm/r and the drilling speed was 6–24 m/min, the diameters of the import and export holes varied from 0.8 to 1.4 mm for different drill diameters. This figure also shows that when the drill diameter and feed rate are constant, the diameters of the import and export holes increase with increasing drilling speed. This is because a low drilling speed is accompanied by a larger drilling force and vibration amplitude of the drill bit, which results in the rupture of the wood-fiber structure of the seed shell, more burrs in the drilling process, and a lower hole-processing accuracy (Li et al. 2019). These factors reduce the diameter of the holes. As the drilling speed increases, the drilling force gradually decreases and the drill bit is less likely to vibrate. This improves the accuracy of hole processing, results in the hole diameter being closer to its ideal value, and increases the diameters of the import and export holes. However, drills with smaller diameters bend and deform when drilling because of their low stiffness and the hard structure of the *S. mukorossi* seeds. This deformation increases with drilling speed (Bediz et al. 2019), causing the diameter of the drilled hole to increase and deviate from its ideal value. This situation is shown in Fig. 7 for a 0.9-mm drill bit.

This analysis demonstrates that to achieve good drilling results, improve the quality and accuracy of the drilling process, and make the hole diameter close to the ideal value, the drilling speed should be as high as possible. However, an increase in drilling speed will accelerate the wear and tear of the drilling tools and reduce their durability. Moreover, small-diameter drills are prone to excessive bending and deformation at high drilling speeds. Therefore, a smaller drilling speed should be selected to improve drill bit durability under the condition of ensuring the quality of processing, and the recommended drilling speed is 6 m/min.

Effect of drill diameter on the drilling force

Figure 8a, b shows the relationship between the drill diameter and the drilling forces generated at different drilling positions in the hole for a given feed rate and drilling speed. The drilling force varied from 0 to 15 N among the different positions under the experimental conditions of a feed rate of 0.03 mm/r, a drilling speed of 6 m/min, and drill diameters of 0.9, 1.0, 1.3, and 1.5 mm. The drilling forces at each position were relatively low when the recommended feed rate (0.03 mm/r) and drilling speed (6 m/min) were selected, using drills of 0.9- and 1.5-mm diameter. There are several reasons for this. First, when the drill diameter is smaller (i.e. the depth of the cut is smaller), the cutting width and cutting area are smaller, which lowers the drilling forces. In addition, a smaller drill diameter is conducive to drilling the wood-fiber structure of the seeds, improving the accuracy of the drilling process (Biermann et al. 2014), and reducing the friction between the hole wall and the guiding part of the drill, which all serve to reduce the force. Furthermore, a smaller drill diameter reduces the amount of removed material, the drilling power and the generation of drilling heat, helping to slow the wear of the drill bit, thus improving drilling efficiency and reducing the drilling force. Therefore, when using a drill bit of 0.9-mm diameter, the drilling force is relatively small. However, because of the lower stiffness of drills of smaller diameters, problems such as drill vibration and bending deformation can arise, resulting in increased drilling forces and reduced hole-processing accuracy. Thus, increasing the diameter of the drill, to a certain extent,

makes stable drilling easy and reduces the drilling forces. Therefore, when using the drill bit of 1.5-mm diameter, the drilling is more stable and the drilling force is relatively small.

On the basis of these analysis, to meet production processing requirements, and to improve drilling stability and drilling accuracy, it is recommend that the use a drill of 0.9-mm diameter when the ideal diameter of the hole to be processed is small, and a 1.5-mm diameter when the ideal diameter of the hole to be processed is large.

Effect of drilling on pore morphology

The inlet and exit morphologies of the hole drilled with a 0.9-mm diameter drill, at a feed rate of 0.03 mm/r and a drilling speed of 6 m/min, are shown in Fig. 9 for *S. mukorossi* seeds. The hole-inlet morphology is relatively complete, but there are a few burrs on the edges. This is because the vibration during the rotation of the drill bit causes the sub-rear face of the guide section to scratch the hole wall, creating a small number of burrs at the hole inlet. However, the integrity of the hole-exit morphology is poor, with visible burrs and a substantial loss of roundness in the hole. This is because the outer part of the seed shell is harder, and the drilling force at the outlet is larger when drilling the seed. The drill bit is impacted at the moment of drilling out the seed, resulting in part of the shell structure breaking and adhering to the edge of the hole, and there are obvious burrs at the outlet of the hole. In addition, as the drilling depth increases, the drilling force increases, making it easy to bend and deform the drill bit (Horiuchi et al. 2013) and deviate from the original axis, resulting in a more serious loss of roundness at the hole exit.

To address the problem of burrs on the hole wall when drilling *S. mukorossi* seeds and to thus improve the accuracy, the drilling depth can be increased after drilling through the seeds and the burrs can be scraped off by the auxiliary cutting edge of the guide part of the drill. To minimize the loss of roundness of the hole exit, a stiffer bit can be used to reduce the bending deformation of the drill bit, thereby avoiding skewing of the hole axis. In addition, the use of a more suitable drilling die is conducive to the clamping and positioning of the workpiece (*S. mukorossi* seeds), reducing the vibration of the workpiece during drilling and improving the accuracy of the hole. In addition, for *S. mukorossi* seeds, a combination of drilling and reaming can be used to improve the accuracy of the position and shape of the holes.

Conclusion

This study methodically reports the effects of drilling parameters (feed rate, drilling speed, and drill diameter) on the drilling force and pore morphology of micro-drilled *S. mukorossi* seeds. A smaller feed rate was found to be conducive to reducing the drilling force and avoiding problems such as low hole accuracy and high surface roughness due to drill lead-off and workpiece vibration. An appropriate increase in the feed rate and a shortening of the drilling time are conducive to promoting the dissipation of drilling heat, increasing the durability of the drill, and improving productivity and hole quality. Considering these factors, a feed rate of 0.03 mm/r is recommended. A higher drilling speed leads to a higher quality and accuracy of the drilling process, resulting in the hole diameter being closer to its ideal value. By contrast, a lower drilling speed helps reduce the wear of the drilling tool and prevent excessive bending and deformation of the small diameter drill bit, thus improving productivity and ensuring the quality of the process. Considering these factors, a drilling speed of 6 m/min is recommended. A smaller drill diameter reduces the drilling force and drilling power, whereas a larger

diameter helps avoid bending and deformation of the drill bit and ensuring drilling stability. When the ideal diameter of the hole to be machined is small, a drill bit with a diameter of 0.9 mm is recommended, and when the ideal diameter of the hole to be machined is large, a drill bit with a diameter of 1.5 mm is recommended.

Declarations

Author contributions Suxiao Zhao was involved in the investigation, data curation, formal analysis, writing the original draft, and reviewing and editing the manuscript; Xiaopeng Bai was involved in validation, supervision, and funding acquisition; Daochun Xu was involved in conceptualization and methodology; Wan Cao was involved in material preparation and visualization.

Funding The authors gratefully acknowledge financial support from the Fundamental Research Funds for the Central Universities (BLX202127), National Natural Science Foundation of China (52206229), National Key Research and Development Program (2019YFD1002401), and Excellent Graduate Tutor Team of Beijing Forestry University (YJSY-DSTD202200).

Competing interests The authors declare no competing interests.

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Figures



Figure 1

S. mukorossi: a) fruit, b) seed, c) seed structure, and d) Buddhist prayer beads.

Drilling forces at different places: 1- F_{iu} (in up-shell)
 2- F_{du} (during up-shell) 3- F_{ou} (out up-shell)
 4- F_{dn} (during kernel) 5- F_{id} (in down-shell)
 6- F_{dd} (during down-shell) 7- F_{od} (out down-shell)

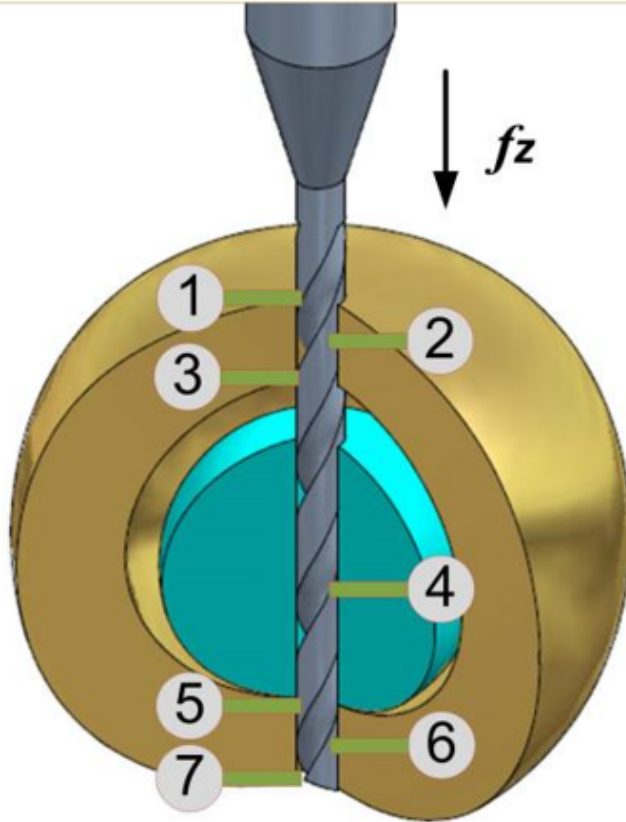


Figure 2

Stages of the drilling process

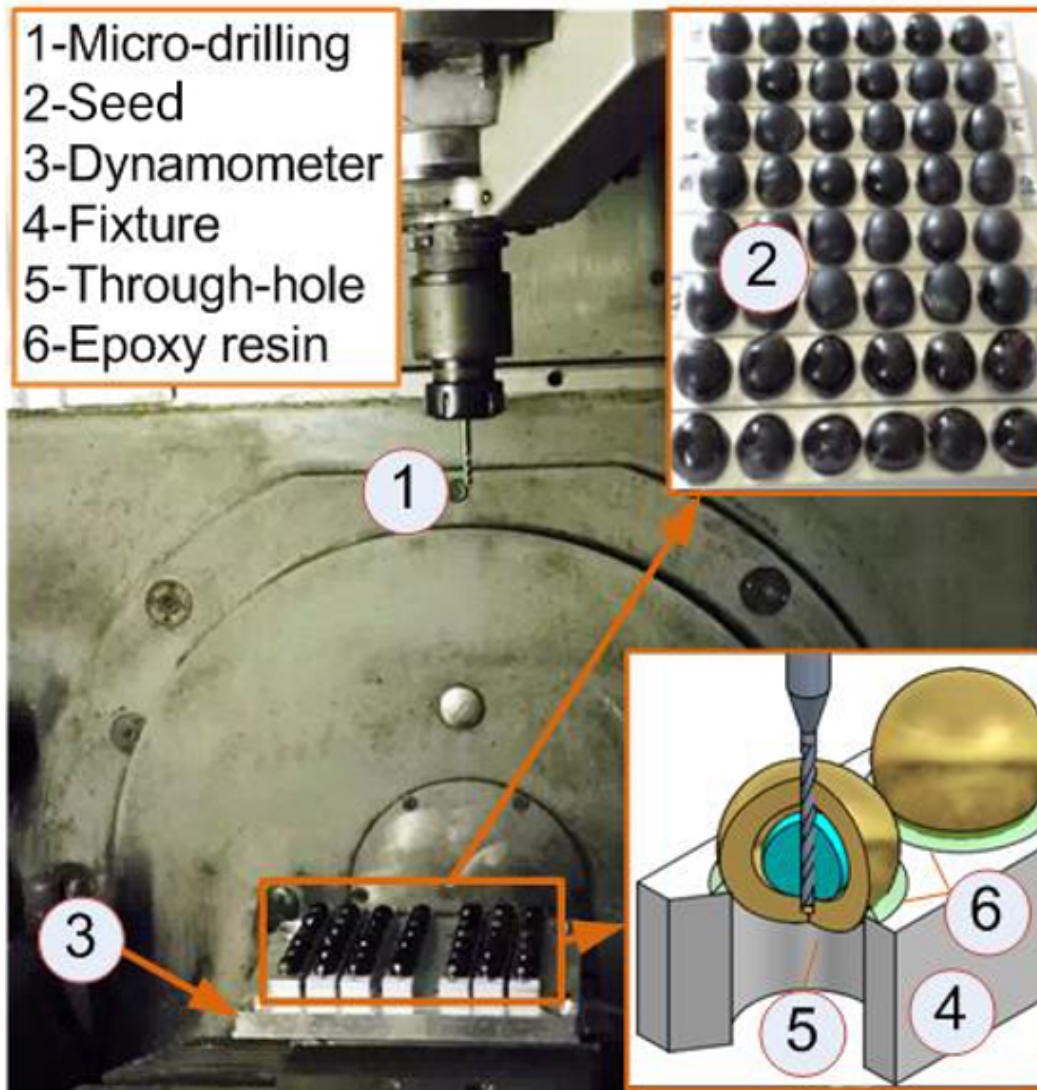


Figure 3

Experimental platform of drillings

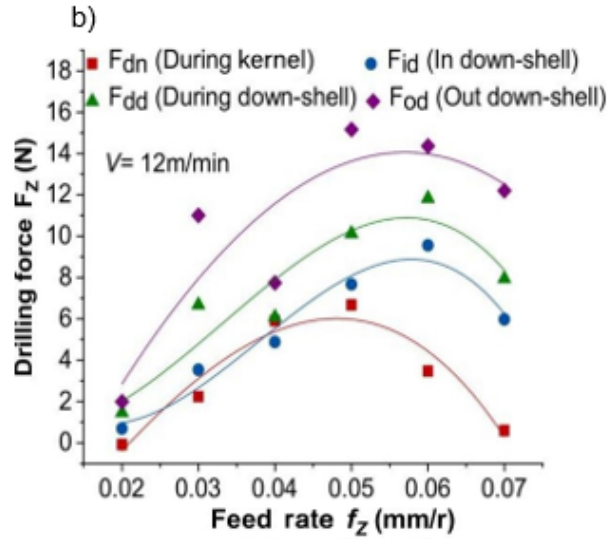
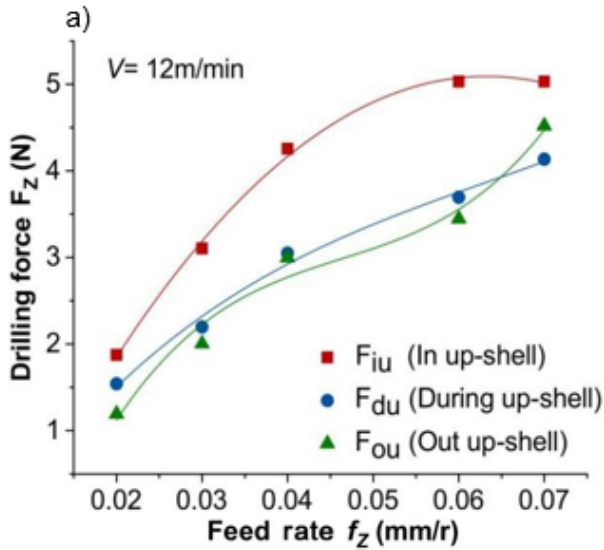
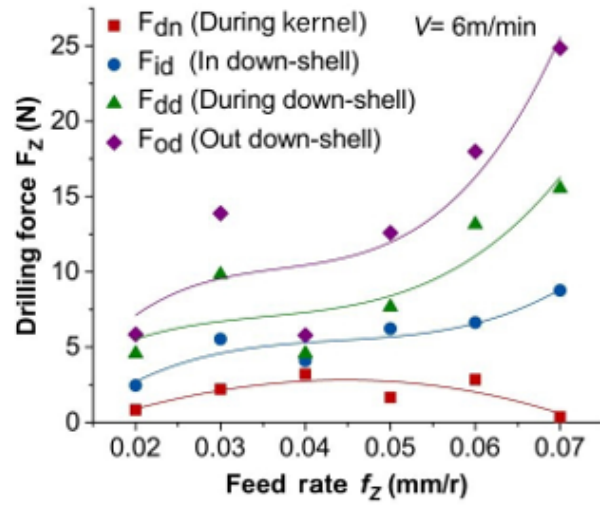
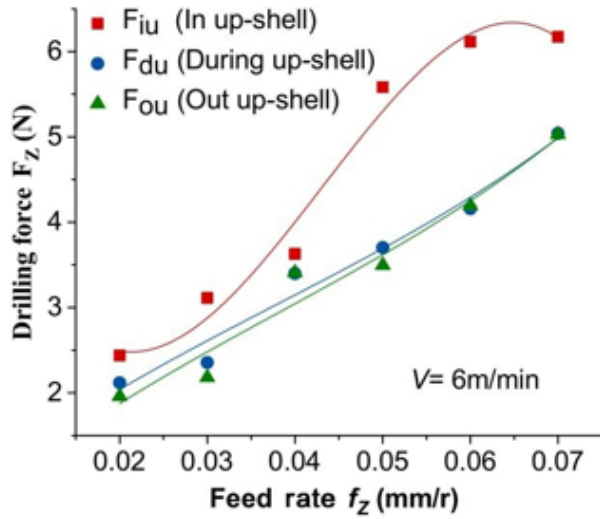


Figure 4

Drilling forces as a function of feed speed.

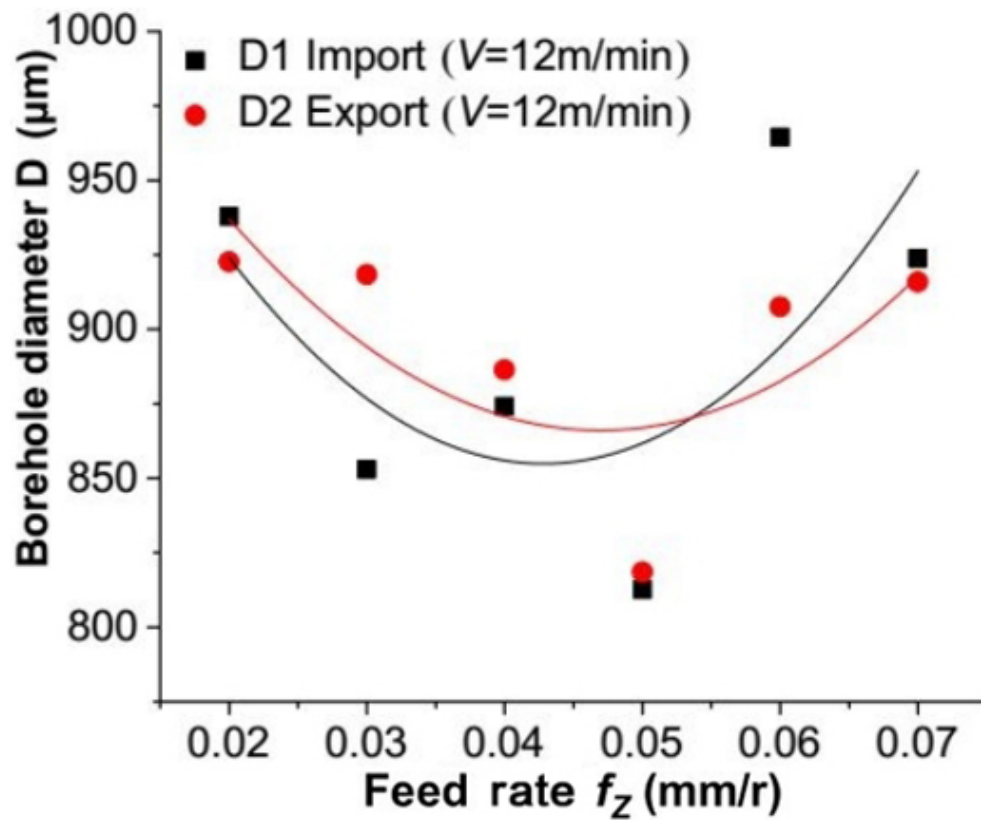
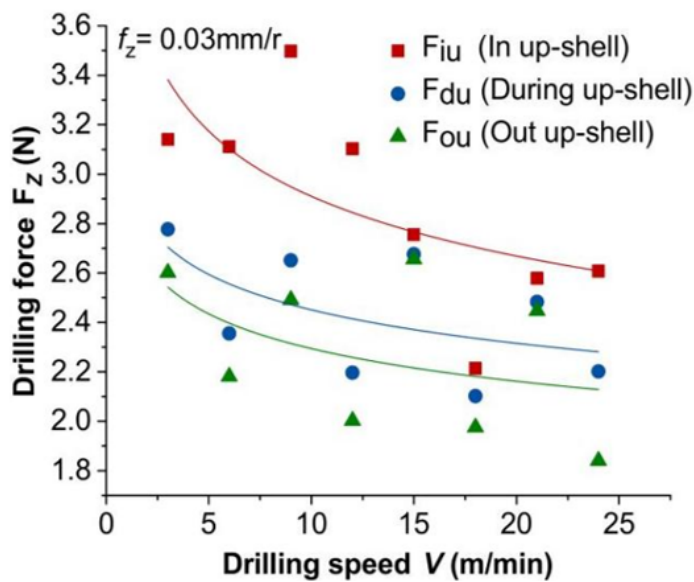
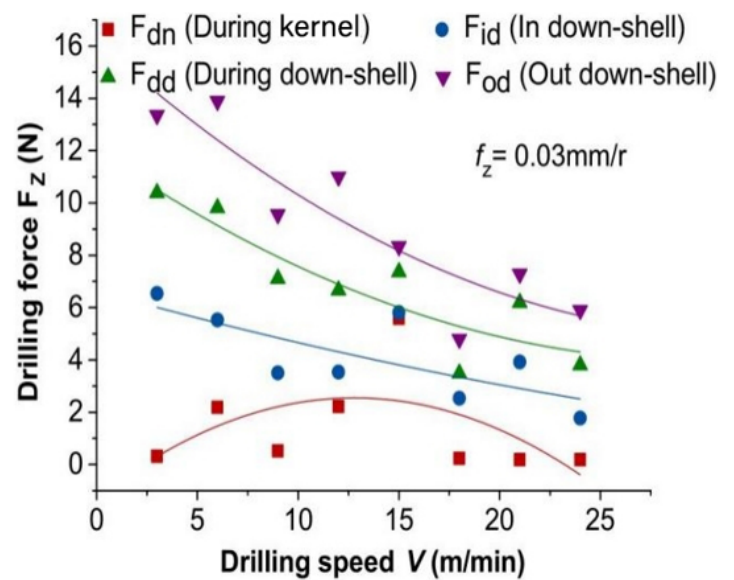


Figure 5

Borehole diameter against feed speed



a)



b)

Figure 6

Drilling force as a function of drilling speed.

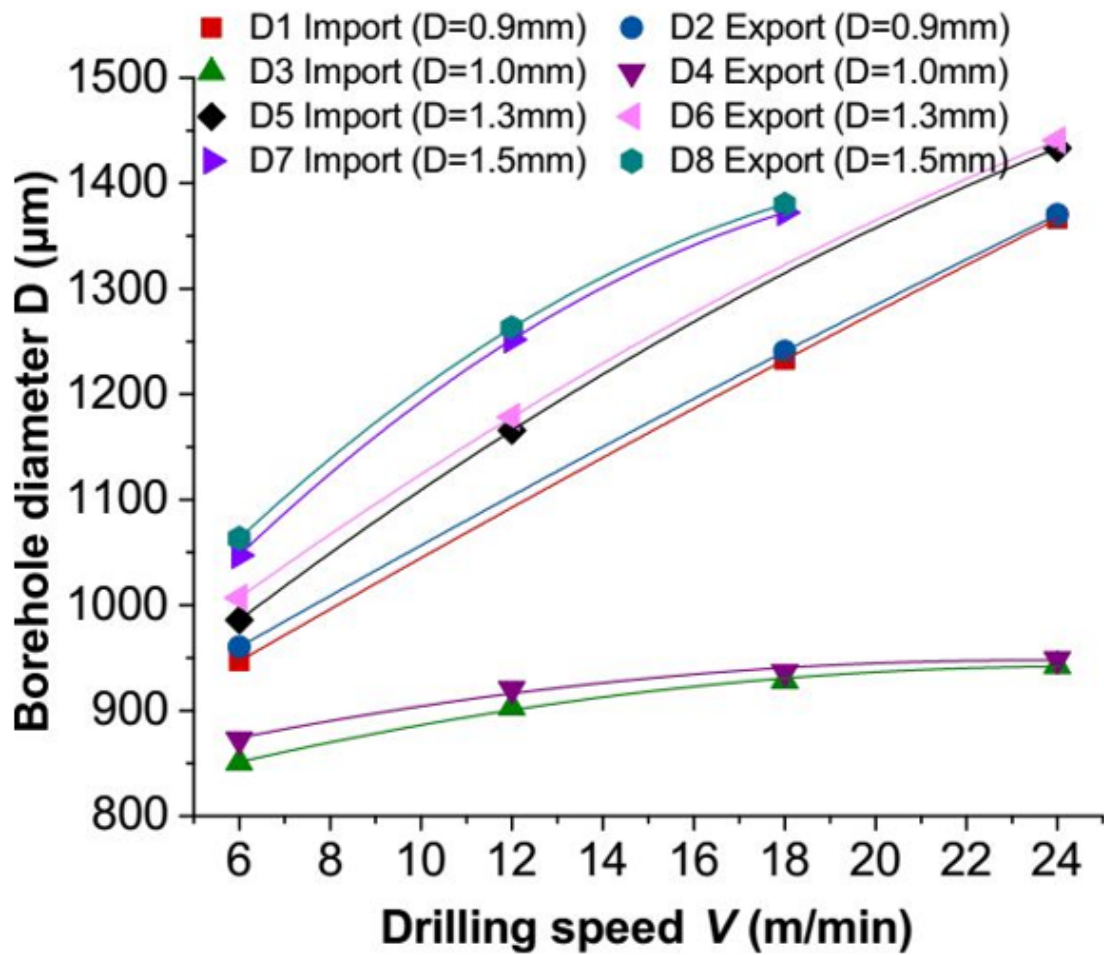


Figure 7

Borehole diameter as a function of drilling speed.

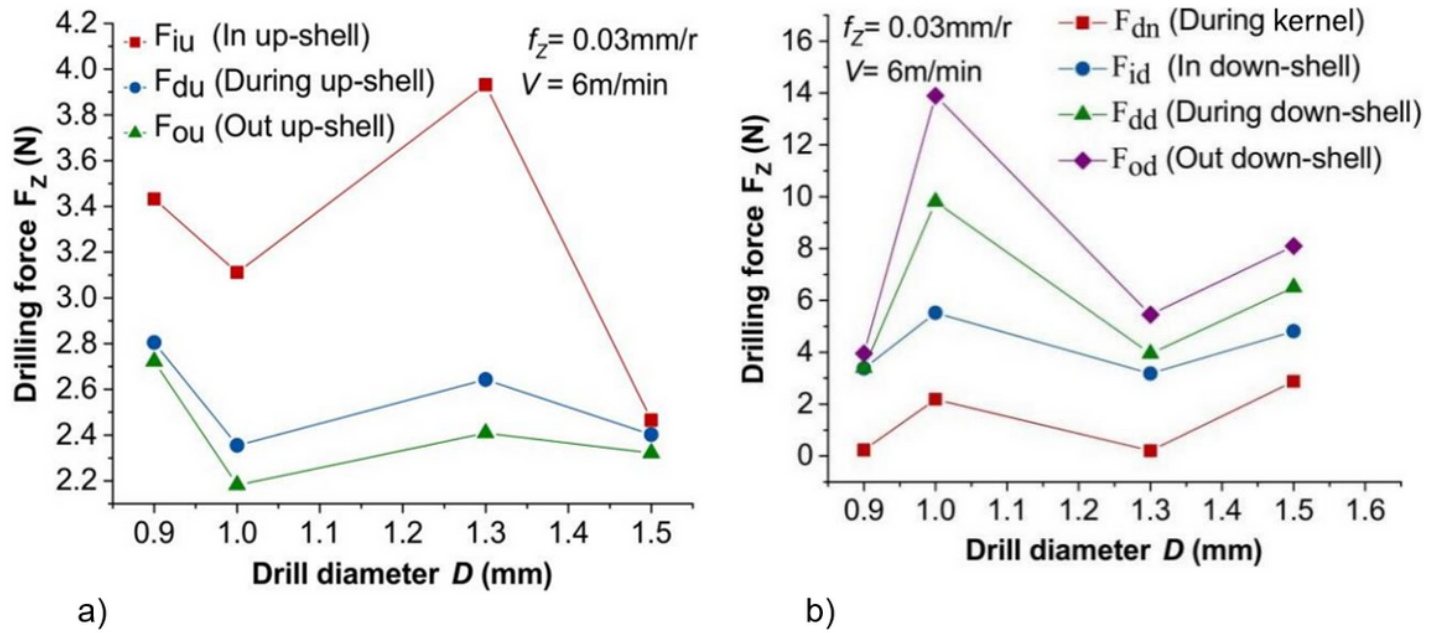
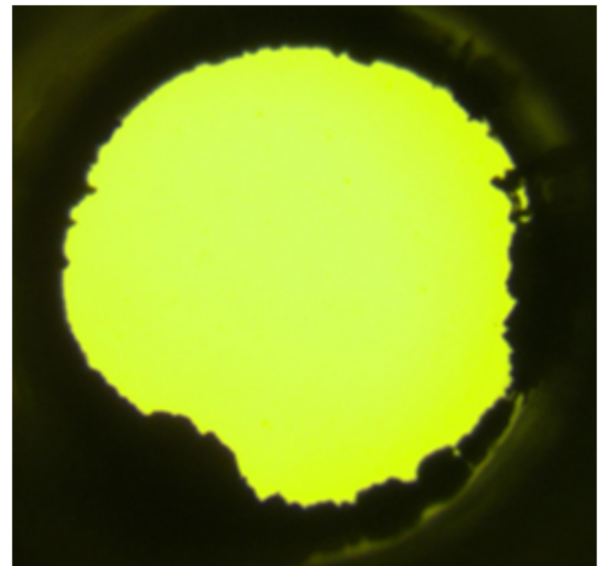


Figure 8

Drilling force as a function of drill diameter.



a) Inlet morphology



b) Outlet morphology

Figure 9

Pore morphology of inlet and outlet for *S. mukorossi* seeds