Original Research Article

Evaluation and Optimisation of Disc Grating Machine for Sago Starch Production (*Metroxylon spp.*)

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Abstract: The production of sago starch involves multiple processes, and grating is among the important processes since it indirectly affects sago starch recovery. In order to produce a finer size of grated sago and high starch recovery, a new design of sago disc grating machine has been developed. An optimization was performed to determine the optimum operation conditions on the basis of the feeding rate and grating speed input of the sago disc grating machine with the starch recovery as the output. The grated sago was dried and sieved at different sizes to determine the size distribution. A mathematical model was developed to predict the starch recovery using Minitab 9.1.0. software. The optimum feeding rate was 0.1 m/min with 1,500 rpm of grating speed to produce 23.57% of sago starch. This study showed that the feeding rate and grating speed affects significantly the size of the grated sago (P < 0.01) and indirectly affects starch recovery. Overall, the optimization process is very important to ensure that the output is at the maximum level.

1. Introduction

In 2016, Malaysia has been the third largest producer of sago starch (*Metroxylon spp.*) in the world (Naim *et al.*, 2016). The annual production of sago starch increased to 212,447 metric tons in 2017 (DOA, 2017), and estimated to be equivalent to RM 189.47 million. Accordingly, this indicates that the increase of sago starch production was due to the increase of current demand, which is in line with the increasing use of starch in the manufacturing industry. However, the sago production industry is still not efficient. It was reported that

65.7% of the grated residue after the extraction process contained starch (Abd Aziz, 2002). Linggang *et al.* (2012) also reported that there was still starch in the residue of about 58%. One of the factors that influence the extraction efficiency is the proportion of the sago trunk structure that ruptured during grating process which produces various sizes of grated sago (Tay *et al.*, 2013). In order to overcome the losses of sago starch, it is important to produce fine grated sago to get higher starch recovery (Wan Mohd Fariz *et al.*, 2020a).

Once the machine is fully developed, it needs to be parameter optimized to ensure the output at the maximum level. The optimization process is a process of component alignment and it does not involve changing the design or adding components. The input method remains the same but with different setting and the changes affect the output. In order to find the best settings that are able to fulfil the goal and lead to better system output, a search process for various values for each input is implemented. Specific problems were studied for the suitable parameter setting used in previous research, in which these settings do not guarantee good performance for other problems, but it is very useful as a start and guide. The trial-and-error method, in which the process of finding for the best parameter values is rather boring and time consuming, depending on the experience of researchers, is another simpler approach (Michalewicz *et al.*, 2010).

Montgomery (2005) claimed that factorial design is more accurate than a one-factor-at-a-time experiment because the interaction between factors can be portrayed by factorial design, which does not mislead the conclusions. In addition, experiments in factorial design make it possible to estimate the effects of a factor at many levels of other variables, generating reasonable results across a variety of experimental conditions. Analysis of variance (ANOVA) is one of the preferred methods for interpreting the experimental effects.

Usually for engineering applications, the parameter optimisation is conducted before a sensitivity analysis since it is always easier to adjust the device settings than to change the input variability. It is possible to obtain the Design of Experiments (DOE) to create a randomization of the experiment repetition. Experimental methods of design have been introduced in the chemical industry since 1950; they were later widely used in the fields of computer aided design (CAD), modelling and applications in the mechanical industry in the 1980s (Hedges, 2008). The DOE is a repeatedly performed activity for each sample type to define the relationships between process parameters and performance measurements through ANOVA tests, and then a multiple response optimization model is constructed to search for the optimal process parameter settings that optimise the overall performance of output. The process parameters used in this study were based on prior research, in which the inputs were the feeding rate and grating speed (El-Hossainy, 2010; Darma, 2017). In detail, the quantity of fine grated sago produced was significantly affected by the cutting area (Wan Mohd Fariz *et al.*, 2020a). The increase in depth cut led to an increase in the cutting area (El-Hossainy, 2010), and it depends on material feeding rate. Other factors that influenced the size of the grated sago were the grating speed as reported by Darma (2017). In this study, the starch

recovery extracted from the grated sago acts as the output. As reported, the grated size affected the starch recovery the most (Wan Mohd Fariz *et al.*, 2020b).

The sago grating machine has several sub-functions that are related and have different parameter function. In this case, the critical sub-function was the grating teeth which it rotates while operating (grating speed) and affects the final product size. Moreover, the grating teeth are also related to the feeding sub-function which is related to the feeding rate. The purpose of this study was to evaluate and determine the optimum operation of the sago disc grating machine on the basis of the input feeding rate and grating speed, towards the starch recovery.

2. Materials and Methods

2.1 Material Preparation and Grating Process

The harvesting process of the sago palms was carried out in Labu, Negeri Sembilan. A quarter of sago trunk with a length of 50 cm was prepared using a handheld chainsaw (OG6816, Ogawa, Japan). The initial moisture content of sago trunk was recorded using laboratory equipment (HE53 230V, Mettler Toledo, USA). A disc grating machine (Figure 1(a)) performance test was conducted to evaluate the grated sago size distribution and the resulting starch recovery after extraction process. A roller grating machine (Figure 1(b)) was prepared and used as a comparison. The machines were set at the lowest of grating speed (1,000 rpm) and feeding speed (0.1 m/s) as a precaution for the basic of primarily studies. According to the study by Wan Mohd Fariz *et al.* (2018), grating in the parallel direction to the vertical axis of sago trunk lignin orientation provided finer grated trunk and greater recovery of starch as compared to the perpendicular direction. Therefore, the sago trunk was fed at a position where the lignin orientation of the sago trunk pointed to the direction of the grater blade for both machines. Grated sago size distribution (*Section 2.2*) and starch recovery (*Section 2.3*) were determined.
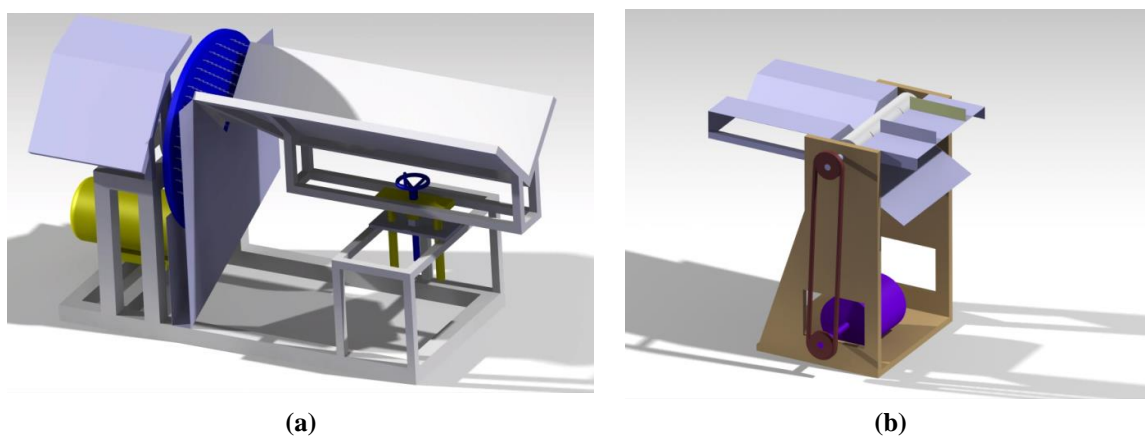

(**a**)   (**b**)

Figure 1. The sago grating machine: (**a**) Disc grating machine.; (**b**) Roller grating machine.

2.2 Grated Sago Size Distribution Assessment

To determine the distribution of sago particle size, the sieving method was used. Firstly, the initial moisture content of grated sago fibre was recorded before the sieving process using a moisture analyser (HE53 230V, Mettler Toledo, USA). The grated sago was dried at a temperature of 68^0C using a drying oven (FAC-100, Protech, Malaysia) (Okazaki, 2018). The moisture contents of dried samples were taken every 30 minutes until 3 samples showed constant value, and the weight was recorded. The selected sieved grade sizes were 2.80 mm, 2.00 mm, 1.00 mm, 0.85 mm, 0.45 mm, and 0.30 mm (Wan Mohd Fariz *et al.*, 2018). A sieve shaker (EFL1, Endecott, United Kingdom) was used to sieve 100 g of sample, and the weight of the material sieved was taken every 10 minutes (ASTM, 2001; Standards: C136-01). The sieving process was stopped after 3 readings showed constant values. The final weight of the sieved product was recorded for each grade sizes. The procedures were repeated 6 times for an average value. Equation 1 was used to measure the percentage ratios of weight for sieve product (Wan Mohd Fariz *et al.*, 2018).

$$\text{Weight percentage ratio (\%)} = \frac{\text{Weight of the sieved products}}{\text{Total weight of grated sago sample}} \times 100\% \qquad (1)$$

2.3 Extraction Process and Starch Recovery

In order to separate the starch from the grated sago, the extraction process was performed using water as a solvent. The recovery of the starch refers to the percentage of the extracted starch weight from the initial total weight (fresh grated sago). One kilogram of grated sago was mixed with 3 kg of clean water to generate slurry (Wan Mohd Fariz *et al.*, 2018). The slurry was left for 5 minutes to allow the water to seep into the grated sago fibre. Then, using a muslin cloth, the slurry was squeezed manually until all the droplets of sago liquid were collected into a container and left for the sedimentation process for 2 hours. Thereafter, the excess water on the top surface of starch liquid was removed and the remaining starch inside the container was weighed. Starch slurry moisture content was recorded and then dried using a drying oven (FAC-100, Protech, Malaysia) at 68°C (Okazaki, 2018).

The moisture content of the sample was taken every half an hour during the drying process and the drying process was halted after 3 sample readings showed no difference upon which the final weight and moisture content of the sample were registered. The starch recovery was determined using Equation 2 (Kamal *et al.*, 2007):

$$\text{Starch recovery (\%)} = \frac{\text{Weight of dry starch}}{\text{Total weight of fresh grated sago}} \times 100\% \qquad (2)$$

2.4 Determination of Optimal Process Conditions

The determination of optimal process condition's goal was to maximize the output while ensuring others are within their constraints. In order to produce the smallest product size, an experiment was conducted to determine the grating speed and the feeding speed. Minitab 9.1.0 software was used to establish the DOE to create a randomization of the experiment repetition. Two factorial types (grating speed and feeding rate) were set for the DOE, with 3 speed differences for each type and each experiment was conducted with 6 replications. The grating speed was set at 1,000 rpm, 1,500 rpm, and 2,000 rpm (A1, A2, and A3) (Darma *et al.*, 2017), and each speed was tested with feeding rates of 0.1 m/min, 0.3 m/min, and 0.5 m/min (B1, B2, and B3) during the grating process. In this case, the starch recovery was set as the respond and full run type of DOE was selected. As a result, the final products of grated sago were sieved to determine the size distribution and then extracted to measure the sago starch recovery. Statistical analysis was conducted to determine the relationship between grating speed, feeding speed, and starch recovery.

2.5 Statistical Analysis

Using IBM SPSS Statistics 25.0 software, the statistical data and ANOVA was analysed to test the key effects of independent and interaction parameters. The program was used to measure the mean value (μ), the standard deviation ($\pm$), the *P*-value and the one-way variance study. The substantial difference was calculated at a 99 percent confidence level ($P<0.01$). Regression analysis was performed to obtain the R^2 value using SigmaPlot 12.0. DOE and determination of the optimum process of the machine was implemented with Minitab 9.1.0.

3. Results and Discussions

3.1 Sago Grater Performance Test

The prototype performance test was conducted to compare between the generated technology with a selected technology (roller grater). In comparison, the performance evaluation was based on the ability of the technologies to produce a fine grated sago size and percentage of starch recovery. The particle size distribution assessment was conducted at

3.53±1.76% average moisture content of grated sago after the drying process from the initial average moisture content of 60.97±0.52%. Figure 2 shows the weight percentage ratio (WPR%) of grated sago at different grated sago size distribution according to the type of grater. At a grated size of *X*<0.30 mm, the WPR (%) of disc grater (7.41±0.08%) was higher than the roller grater (2.52±0.72%) with a significant difference of P<0.01. A same distribution pattern was identified for grated sago size of 0.30≤*X*<0.45 mm, 0.45≤*X*<0.85 mm, and 0.85≤*X*<1.00 mm whereby the WPR (%) was (5.80±1.16%; 3.52±0.67%), (20.90±1.55%; 11.15±1.88%), and (5.52±0.18%; 4.04±1.14%), respectively for the disc grater and the roller grater. Further, it shows an opposite value of WPR (%) for next grated size. At grated size of 1.00≤*X*<2.00 mm, the WPR% of roller grater (34.59±1.27%) was higher than the disc grater (27.03±0.65%) and continued showing a same pattern for the grated size of 2.00≤*X*<2.80 mm and *X*≥2.80 mm whereby the WPR (%) was (19.86±13.49%; 13.49±1.52%) and (24.33±2.32%; 19.85±0.74%), for the roller grater and the disc grater, respectively.
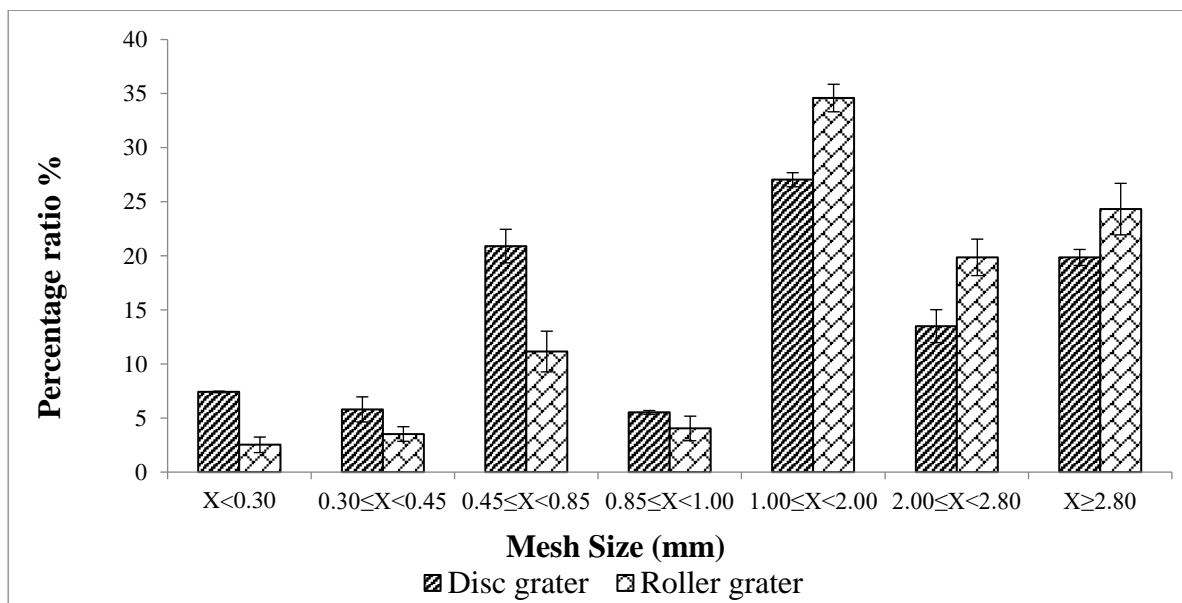

Figure 2. Effect of grater type (Disc grater and Roller grater) towards different grated size distribution on WPR (%) of grated sago. Error bars were expressed as mean ± SD; *n* = 6

Overall, the result showed that the particle size distribution of grated sago between disc grater and roller grater has significant differences from each other (*P*<0.01). At the extraction efficiency of 45% (*X*<1.00 mm), the result showed that the WPR (%) of disc grater was higher than the roller grater with a percentage difference of 46.42±0.59% (*P*<0.01). The WPR (%) of disc grater was lower than the roller grater at the grated size of X≥1.00 mm with a percentage difference of 30.47±1.35% (*P*<0.01). In this case, it shows that the disc grater produces finer grated sago as compared to the roller grater. According to Darma (2014), the

occurrence of this difference was due to the grater teeth speed, grater teeth density and grater teeth arrangement. In addition, it was reported by Wan Mohd Fariz *et al.* (2018) that the effect of grating direction also influenced the grated size distribution. Theoretically, the disc grater was expected to produce a higher starch recovery as mentioned by Tay (2013) which stated that reduction of the size of extracted material showed a significant increase of starch yield due to the larger surface area that allowed more material extraction into the steeping solution. As the pulp has a complex structure, an increase in pulp particle size has contributed to a decrease in the efficiency of starch extraction (Saengchana *et al.*, 2015).

Figure 3 showed that the starch recovery produced by disc grater (21.37±0.58%) was 55.54% which was higher than roller grater (9.50±0.17%) with a significant difference of $P<0.01$. The result of starch recovery produced by disc grater was close to a prior study by Siti Mazlina *et al.* (2007) where the wet grating method was used prior to the extraction process which has reported starch recovery of 25.76%. The wet grating process produced the highest sago starch recovery as compared to the dry grating method since the starch granules that was present in the pith were dissolved in water and released during the grinding process. Therefore, the technology of disc grater shows a great potential to be used as a sago trunk grater which is almost as good as using the wet grating method.
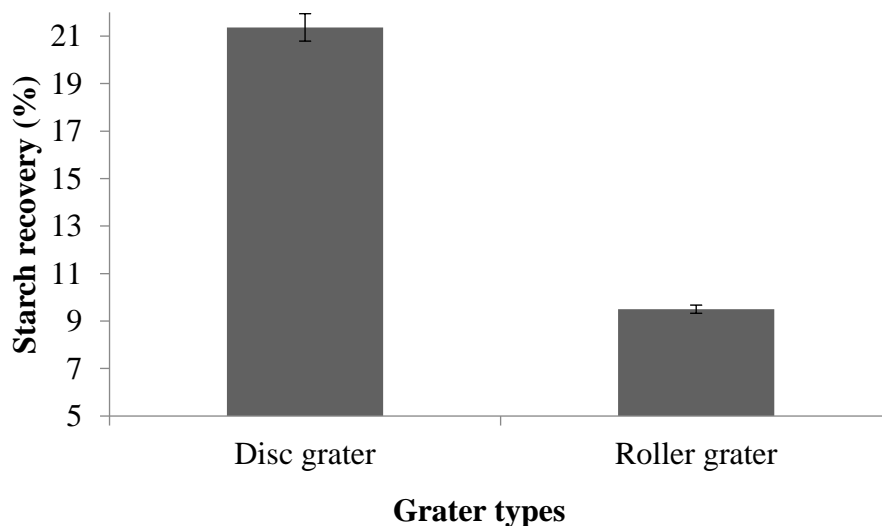

Figure 3. Effect of grater type on the starch percentage recovery (%). Error bars were expressed as mean ± SD; *n* = 6

3.2 Optimisation Process

The determination of the optimal process condition's goal was to maximise the output (starch recovery) while maintaining inputs within their constraints (grating speed and feeding

speed). Figure 4 shows the percentage of grated sago distribution weight at mesh size of $X<1.00$ and $X\geq1.00$ mm for different combinations of parameters. The WPR (%) of grated sago distribution for mesh size $X<1.00$ mm was lower than $X\geq1.00$ mm at a combination of parameters for A1B1, A1B2, A2B3, A3B3, A2B2, A1B3 and A2B3 with significant difference of P<0.01. However, opposite results were obtained by which finer grated sago was produced for A3B1 (51.83±2.20%; 48.17±1.65%) and A2B1 (55.01±2.29%; 44.99±1.92%) for mesh size $X<1.00$ mm and $X\geq1.00$ mm with a significant difference of $P<0.01$. This behaviour was explained by El-Hossainy *et al.* (2010), where a different combination of parameters (feeding speed and grating speed) will create a difference in cutting area at the grater teeth during the grating process which leads to the production of different grated sago size distribution.
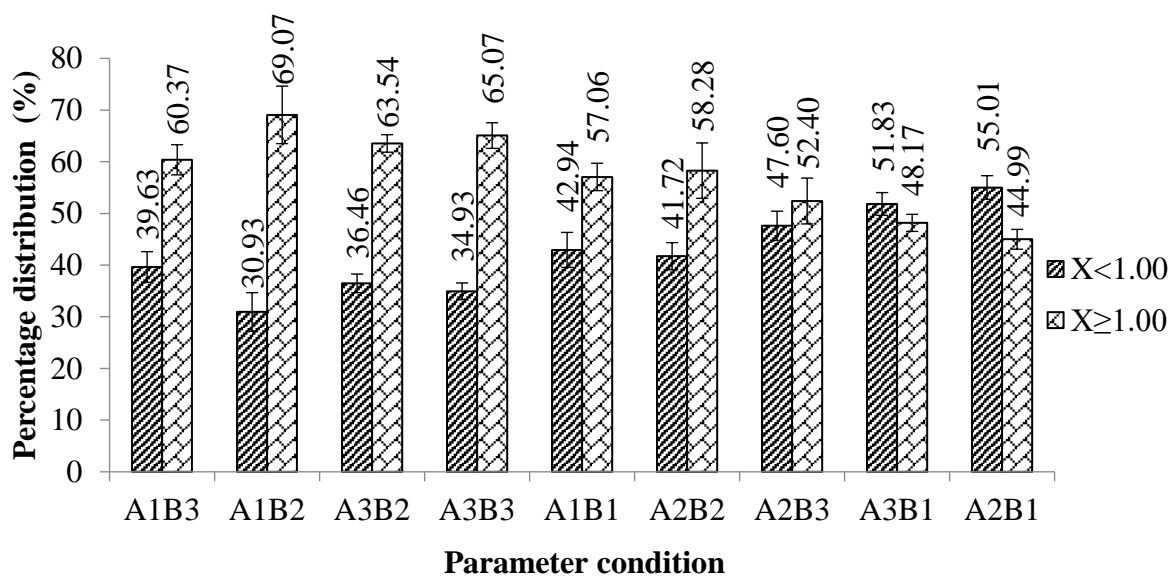

Figure 4. Percentage of grated sago weight distribution at mesh size $X<1.00$ and $X\geq1.00$ for the difference combination parameter. Error bars were expressed as mean ± SD; $n = 6$.
*   Grating speed: A1= 1,000 rpm, A2= 1,500 rpm, A3= 2,000 rpm
          Feeding speed: B1= 0.10 m/min, B2= 0.30 m/min, B3= 0.50 m/min

Furthermore, the statistical analysis highlighted that the combination of parameter significantly affected the extracted starch recovery results ($P<0.01$). Figure 5 shows the starch recovery at different grating speed (A) and different feeding speed (B). A high starch recovery distribution occurred at the medium grating speed (1,500 rpm), followed by 1,000 rpm and 2,000 rpm. A high starch recovery distribution occurred at the lowest feeding speed (0.1 m/min) and gradually decreased after the increment of feeding speed at 0.3 m/min and a slight increase at 0.5 m/min. In detail, Figure 6 shows that both graphs have a concave line shape (parabola) for the average of starch recovery percentage at different parameters. The grating speed concaves with **n** shape (A) which means that the maximum value occurred at

the medium position. Meanwhile, the feeding speed concaves with **u** shape (B) which means that the maximum value occurred at the initial and final positions. A multiple regression was conducted to determine the percentage of starch recovery. A mathematical model was developed as in Equation 3. The percentage of variation developed model was $R^2 = 86.93\%$ (Figure 7). Based on prediction and optimization result, the highest sago starch recovery occurred at 1,515.15 rpm of grating speed and 0.1 m/min of feeding speed with 95% predicting interval in the range of 22.01% to 25.14% of starch recovery. Since the prototype uses a standard sized pulley system, the grating speed and feeding speed depend on the standard pulley ratio available in the market. Table 1 shows the alternative solution to predict the most five highest starch recovery that can be produced based on the standard pulley ratio. The suitable grating and feeding speed were 1,500 rpm and 0.1 m/min respectively, with the highest starch recovery (23.57%) at 55.57% of extraction efficiency.
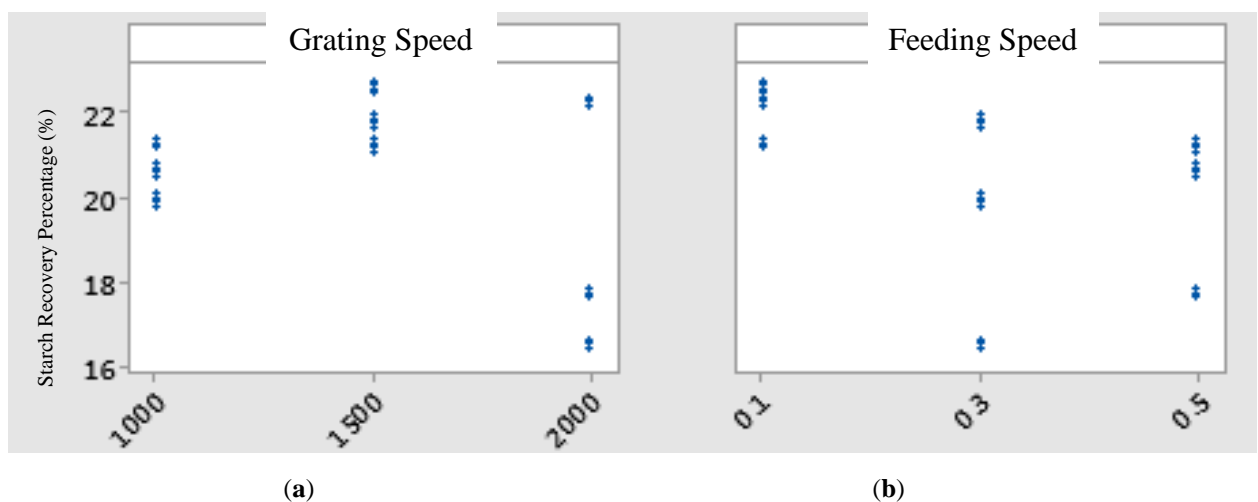

(a)   (b)

Figure 5. Starch recovery percentage distribution at difference of parameters: (a) Grating speed, (a) Feeding speed.
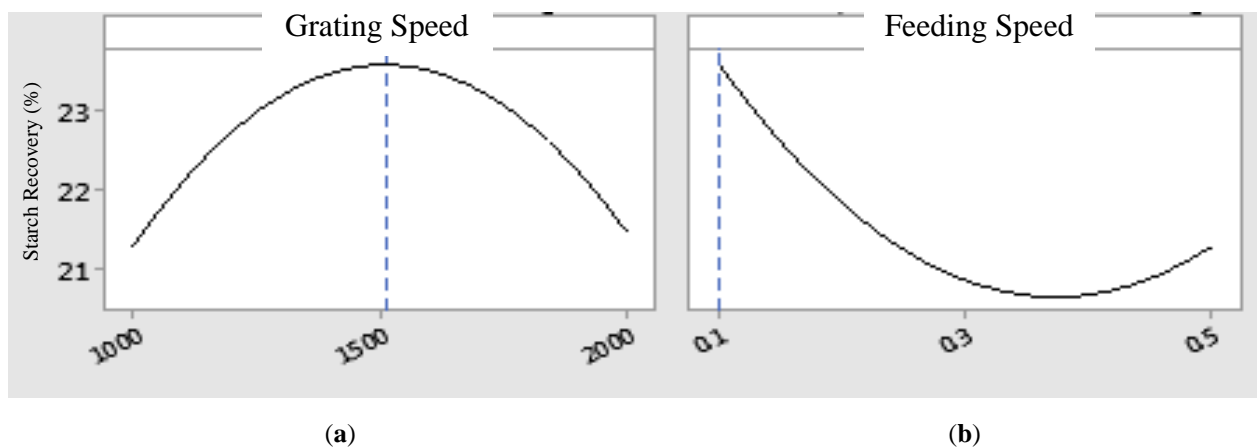

(a)   (b)

Figure 6. The average of starch recovery percentage curve line at difference of parameters: (a) Grating speed, (b) Feeding speed.

Starch recovery (%)

$$=4.60+0.02746(X_1)-14.19(X_2)-0.00000(X_1^2)+38.99(X_2^2)-0.00986(X_1)(X_2) \qquad (3)$$
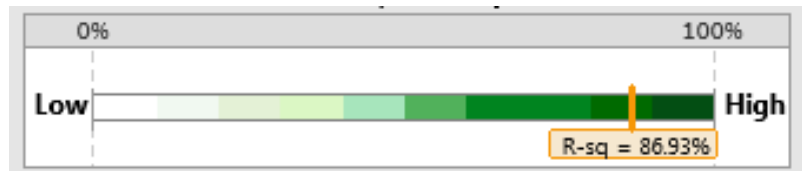
Where value of X_1 = grating speed, X_2 = feeding speed

Figure 7. Percentage of variation developed modal (R2)

Table 1. Alternative solution to predict the starch recovery based on the parameter.

Grating speed (rpm)	Feeding speed (m/min)	Starch recovery (%)
1,500	0.10	23.57
2,000	0.10	21.47
1,500	0.50	21.34
1,000	0.10	21.29
1,000	0.50	21.03

4. Conclusions

The optimum parameter for sago disc grating machine was at the feeding rate of 0.1 m/min and grating speed of 1,515.15 rpm with 95% predicting interval in the range of 22.01% to 25.14% of starch recovery. However, the disc grating machine speed was not flexible to adjust. Therefore, the optimum feeding rate was suggested at 0.1 m/min with 1,500 rpm of grating speed with 23.57% of sago starch recovery. This study also proved that the feeding rate and grating speed affect the size of the grated sago produced (P<0.01) and indirectly affect starch recovery. For further improvement, the study can be expanded by studying the effect of variable shape or grater teeth size as factorial factors on the grated sago size produced. However, the addition of factors will lead to the need of having a large number of experiment repetitions to be performed and due to financial constraints; it is not feasible at present.

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