Evaluation of Handling and Storage Characteristics of an Intermediate Granulated Food Ingredient Using a Fabricated Screw Extruder

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Evaluation of Handling and Storage Characteristics of an Intermediate Granulated Food Ingredient Using a Fabricated Screw Extruder

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Abstract: *Developing a laboratory scale screw extrusion agglomeration equipment was done to assess its effectiveness in granulation of pre-formulated food powders in which bitter gourd "ampalaya" powder as the main ingredient. Two screw speeds (80 rpm and 120 rpm) were used to determine the handling and storage properties of the agglomerated product. The effectiveness of the equipment was based on the handling and product properties namely Carr's Index, Hausner Ratio, Friability and Disintegration Time. The Carr's index of the agglomerates ranged from 0.0333 to 0.07333 while the Hausner ratio ranged from 1.0346 to 1.0792. The lowest friability measured was 0.096 indicative of a stable and strong agglomerate. The maximum mass output efficiency and throughput of the agglomeration equipment was 96.15% and 0.3163 kg/kW. Finally, the partial economic analysis showed that the equipment is economically feasible with an Internal Rate of Return of 50.99% for a period of 1.84 years.*

Keywords: Single Screw Extrusion; Agglomeration; Powder Technology, Solids handling, Food Science

1. INTRODUCTION

Extrusion has gained attention because of its simple and fast processing technology. Most industries require ingredients that have a consistent smooth surface with a narrow size distribution to ensure accurate free flowing granules for specific downstream operations. Any nutritional products that utilize pellets as a delivery system can be effectively produced by the extrusion process. The main objective of extrusion is to produce pellets or spheroids of uniform size with high active material loading capacity [1].

Extrusion processes can operate wet or dry to produce a narrowly sized and fairly dense product. All extrusion equipment operates on the principle of forcing the powder in a plastic state through a die, perforated plate or screen. The material undergoes considerable shear in the equipment and product attributes are strongly influenced by the frictional interaction between the feed material and the wall. For wet extrusion, the rheology of the paste is significant [2]. The definition of the process describes not only the sole function of extrusion, which is to impart to the product a certain shape or form while affecting the properties of the material, but it may also be defined as a thermomechanical process in which heat transfer, mass transfer, pressure changes and shear are combined to produce effects like viscous dissipation, material denaturation, mixing and mass transport. The extruder machine can be considered as a pump, a heat exchanger and a continuous high pressure-high temperature reactor, all combined in one piece of equipment [3].

In this study, the extrusion process was selected as an agglomeration technique and the extrusion agglomeration equipment will be designed, fabricated and tested. A single-screw extrusion equipment will be used in the agglomeration of a well-known nutritious ingredient which is the ampalaya (Momordica charantia) powder.

2. MATERIALS AND METHODS

2.1 Materials

The main reagents used in the study were the bitter gourd or ampalaya (Momordica charantia) powder, which was the main ingredient in the granule matrix, cassava flour, as the filler for the granule and distilled water as the liquid binder. The ampalaya powder was obtained from Greenspark Organic from Cavite. According to Greenspark Organic, the supplier of the main ingredient used, was prepared by air drying then oven drying at 200°C before pulverizing into fine powder.

The materials that were used in fabrication of the equipment were steel round bar and steel flat plate for the screw; angle bar, pillow block with various dimensions which were intended for hopper, barrel, stand and die application, electric motor and magnetic switch, belt and pulley for transmission, metal sheet for cutting mechanism, bolts and nuts, and set screws. All these materials were outsourced from independent suppliers.

Other materials used in the experiment were graduated cylinder for density measurement, beaker and stainless-steel strainer basket for disintegration time measurement, aluminum foil containers used for oven drying, round and rectangular plastic containers for ambient temperature tempering and air drying. The equipment used were: the fabricated extrusion agglomerator, an improvised friability tester which was a latte machine mounted with a plastic drum container; electronic weighing scale, oven and automatic standard sieve machine.

2.2 Methodology

The general procedure comprised of series of stages which include: preparation of the materials, fabrication of extrusion equipment, testing and evaluation of the equipment under different feed and process variables, measurement of product variable properties and responses, data gathering and data interpretation and analysis.

For the fabrication stage, the whole equipment was machined and assembled at the College of Engineering and Agro-Industrial Technology machine shop.

Prior to testing and evaluation, all dry ingredients were combined and kneaded manually. First, the ampalaya powder was blended with the four (20% to 30% of the total mass of feed) and water was gradually added (20% to 30% of total mass of feed) to form the wet mass [4]. The agglomeration process was done using the fabricated laboratory screw extrusion equipment.

After stabilization and running in of the equipment, the agglomerates were dried subjected to automatic sieve analysis. The sieve analysis was done using standard series of 6 sieves are put together and shook on a Ro-Tap automatic sieve shaker device for 5-20 minutes. The data of the performance criteria of the fabricated agglomeration equipment based on the efficiency, throughput and outcome of the particle size analysis were recorded and analyzed.

For the feed variables, the feed was pre-blended with different percentage of compositions generated by the Design Expert software for a D-optimal Mixture Design. For the bulk density measurement, a graduated cylinder was filled with the test sample, followed by slight tapping. The filled volume of the sample was noted, and its mass was determined by weighing. The bulk density was obtained by dividing the mass of the sample by its volume while for the tapped density, a graduated cylinder was filled with the test sample and tapped until the volume of the sample in the cylinder did not change. The mass of the sample was determined by weighing. Tap density was obtained by dividing the mass of the sample by its final tapped volume. For the Hausner Ratio and Carr Index, the tapped density (t) and bulk density (b) of the test sample are determined by the methods described previously. The granule friability was determined using a rotating drum, by subjecting 10 g of agglomerates at a speed of 25 rpm for 10 min. The granules were removed and the weight of granules retained determined.

A combined design of experiment was used to generate a model for the effect of selected screw speeds and feed composition on the properties of the agglomerates produced. The calculated Carr's Index, Hausner ratio as well as the measured friability and disintegration time were used as the response values in the generated models.

3. RESULTS AND DISCUSSION

3.1 Design Calculations for the Agglomeration Equipment

The basic assumptions for the design calculations to obtain the operating L/D ratio of the screw of the single screw agglomeration equipment are summarized in Table 1. The screw diameter selected was 38.10 mm with a target mass throughput capacity of 100 kg/h.

Table 1. Basic Assumptions for the Design Calculations

Screw Diameter (D)	38.10 mm
Channel Depth at the Entrance (H)	9.525 mm
Channel Depth at the Exit (W)	9.525 mm
Screw Diameter (D)	38.10 mm
Screw Speed (N)	200 rpm (maximum assumption)
Fluid Density (ρ)	506.2 kg/m3
Throughput Capacity (Q)	100 kg/h
Consistency Coefficient (K)	16,700 Pa-sn (Faridi and Faubion, 1990)
Flow behavior index (n)	0.50 (Faridi and Faubion, 1990)

Solving for the volumetric capacity (V) using Eq. 1:

$V = Q = 100$ kg/hr (1 hr/3600 s) (1 m^3/506.2 kg) = 5.4875×10^{-5} m^3/s (1)

Solving for the Screw Rotational Reynolds Number (N_{Res}) using Eq. 2:

$$N_{Res} = \frac{[\rho(DN)^{2-n}H^n]}{K\pi^{2+n}} \quad (2)$$

$$N_{Res} = \frac{\left[506.2\ kg/m^3 \left[\left(\frac{38.1}{1000}\right)\left(\frac{200}{60}\right)\right]^{2-0.5}\left(\frac{9.525}{1000}\right)^{0.5}\right]}{(16{,}700\ Pa - s^n)\pi^{2+0.5}}$$

$N_{Res} = 7.6537 \times 10^{-5}$

Screw Power Number (Np) [Levine, 1982] is obtained using Eq. 3:

$N_p = 1.307 \times 10^5$ (3)

Solving for the required length (L):

Solving the total power (P_t) and power of shaft (P_s) using Eq. 4 and Eq. 5 with 250 V and 2 A actual measurements.

$P_t = 500$ W

where

$P_t = P_s + V_d\Delta P$ (4)

$P_s = N_p\rho N^3D^4L$ (5)

$P_s = 1.307 \times 10^5$ (506.2 kg/m^3)20060338.110004L

P_s = 5161.66 L

On the other hand pressure drop can be calculated using Eq. 6,

$$\Delta P = \left[V - \frac{(4+n)}{10}\ WHu_{wall}\right]\left[\frac{L\ (1+2n)4K}{WH^3}\right]\left[\frac{H}{u_{wall}}\right]^{1-n} \quad (6)$$

Assume $u_{wall} = 0.5$ m/s:

$$\Delta P = \left[5.4875\ x\ 10^{-5} - \frac{(4+0.5)}{10}\ (0.09525)(0.09525)(0.5)\right]\left[\frac{L\ (1+1)4(16700)}{(0.09525)(0.09525)^3}\right]\left[\frac{0.09525}{0.5}\right]^{1-0.5}$$

$\Delta P = 1.41 \times 10^6$ L

Solving for the length, L using Eq. 4:

$500 = 5161.66\,L + (5.4875 \times 10^{-5})\,(1.46 \times 10^6)\,L$

L = 0.0954 m = 3.75”

Allot another 3.75” for the feeding section:

Total length, L = 7.5”

For this length, we will check the pressure drop:

$\Delta P = (1.41 \times 10^6$ Pa/m) L

$\Delta P = (1.41 \times 10^6$ Pa/m) (0.1905m)

ΔP = 268,605 Pa

3.2 Fabrication of the Equipment

The fabricated screw of the extrusion equipment (Figure 1) conformed to the desired design specifications. The diameter of the screw is 38.1 mm or 1.5 in. while its length is 190.5 mm or 7.5 in., thus the actual L/D ratio is achieved. It has single parallel flights with equidistant pitch of 38.1 mm or 1.5 in. and maintained a diameter-to-channel height.

Fig. 1. The Helical Screw

The fabricated die is cylindrical in geometry wherein a cone is engraved along the cross-section of the solid cylinder. The die has a single exit point located at the center whose diameter is approximately 3 mm while, the die cavity length is 10 mm.

The fabricated barrel is cylindrical in shape in order to conform to the geometry of the die. It cannot be considered as a smooth barrel because it has no special coating inside its surface thus, it can add to friction during the movement of the mass inside. The diameter of the barrel is 38.15 mm or 1.502 in. to maintain the screw clearance of 0.00254 mm or 0.0001 in. inside the barrel. The hopper is directly welded to the barrel perpendicular to the beginning flight of the screw.

The parts were manually assembled and mounted in the stand connected with the motor. The equipment was powered by a single-phase motor (Wizz, China). It is a type of capacitor start motor with an actual power of 0.6032 hp. The assembly was relatively small but heavy because of the motor. The assembly was carefully mounted to ensure that the barrel was aligned with the shafting of the motor.

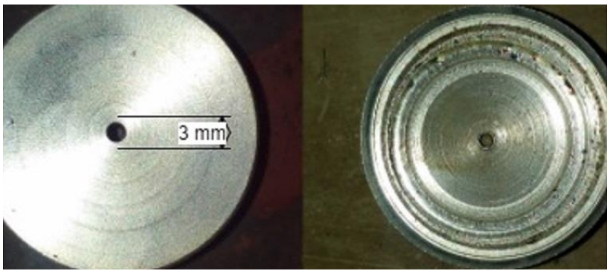

Fig. 2. The die

Fig. 3. The Single Screw Extrusion Agglomerator

Overall, the appearance of the single screw extrusion equipment and the design specifications of each element conformed to the drawing prior to fabrication. The equipment showed smooth and fast start-up.

3.3 Product Size Properties

The produced agglomerates are shown in Figure 4. The particle size distribution plots are shown in Figures 5 and 6 while the summary of grain characteristics is shown in Table 2, respectively.

Fig. 4. Agglomerated Bitter Gourd Powder

The sectional expansion index (SEI) of the agglomerates before and after drying are 1.05 ± 0.05 and 0.45 ± 0.03 respectively.

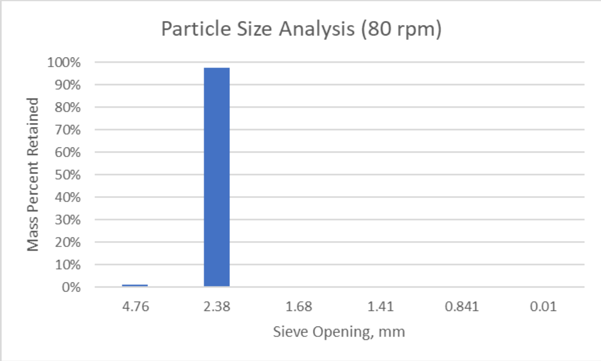

Fig. 5. Particle Size Distribution of the Agglomerates at 80 rpm Screw Speed.

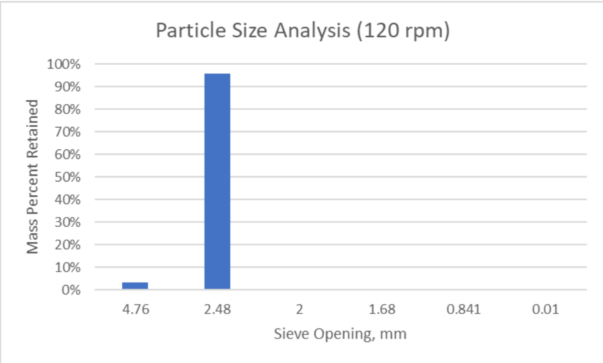

Fig. 6. Particle Size Distribution of the Agglomerates at 120 rpm Screw Speed.

It can be observed in the particle size distribution plots that the particle size of the agglomerates was mainly mesh -4/+8, in which, most of the granules retained on the 2.48-mm sieve opening after passing through 4.76-mm opening.

On the other hand, the calculated values for the SEI indicate that the diameter of the agglomerates before drying was close to the diameter of the die before drying. Thus, there is sufficient forming across the die cavity while there is no observed radial expansion of the products. The significant decrease in the value of SEI after drying is mainly because of the extracted moisture after drying.

Table 2. Summary of Granule Characteristics

Screw Speed	Fineness Modulus	Average Diameter (mm)	Surface Area (cm^2)	Granules per charge
80	3.97 ± 0.0251	1.63 ± 0.0285	2564.6 ± 27.0	13935 ± 1893
120	4.00 ± 0.0462	1.67 ± 0.0539	2595.9 ± 40.2	13399 ± 2066

The size and shape of the individual granules are dependent on the physical characteristics of the material to be agglomerated and the method of agglomeration. It can be observed that the size and shape of the individual granules obtained depend on the extrusion operating condition but more importantly the geometry of the die. The granule characteristics of the agglomerates produced at 80 rpm screw speed is not significantly different compared to the agglomerates produced at 120 rpm screw speed.

The sieve analysis provides sizing and grading of the agglomerates. There is no significant difference between the fineness modulus of the two agglomerates. Thus, the dried granules produced mostly retained in mesh 8 sieve irrespective of the screw speed. The average diameter of the agglomerates produced at low and high speed are 1.632 ± 0.0285 mm and 1.6695 ± 0.0539 mm respectively. There is no significant difference between two average diameters. When the screw speed is higher, high-pressure drop is expected. This is due to the increase of pressure flow that counteracts the increasing drag flow caused by the screw speed.

3.4 Carr's Index and Hausner Ratio

The only factor that contributes to the magnitude of the Carr's index is the screw speed. The generated model shown in Eq. 7 correlating the effect of mixture and process variable in the Carr's Index is shown in Equation 8. The diagram for Carr's index is shown in Figure **7.**

$$Carr's\ Index = 0.053 + 3.881 \times 10^{-3} D \qquad (7)$$

Where,
D = Screw Speed in revolutions per minute (rpm)

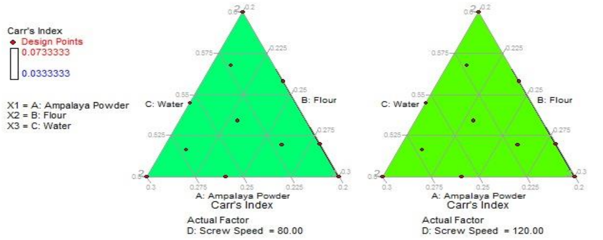

Fig. 7. Effect of Feed Composition and Process Variable in Carr's Index

Based from the generated model, the magnitude of the Carr's Index increases as the screw speed increases. Although the ternary diagrams are in the same hue of green, it can be observed that the diagram for 120 rpm screw speed is darker than at 80 rpm screw speed. Thus, the higher magnitude of the Carr's Index is observed form the granules at 120 rpm. Since the magnitude of the response is independent of the mixture components, the degree of compaction brought about by the screw speed solely affect the Carr's index. Overall, the Carr's index of the agglomerates produced have an excellent flow performance. The lowest CI value, which corresponds to the agglomerates with most excellent flow performance, is observed in mixture 3, 12 and 13 at 80 rpm screw speed while the highest value is observed in mixture 7 at 120 rpm.

Similar to Carr's index, the diagram for 120 rpm screw speed is darker than at 80 rpm screw speed. Thus, the higher magnitude of the Hausner ratio, based on the generated model shown in Eq. 8, is observed form the granules produced at 120 rpm.

$$Hausner\ Ratio = 1.06 + 4.297 \times 10^{-3} D \qquad (8)$$

Where,
D = Screw Speed in revolutions per minute (rpm)

Overall, the Hausner ratio of the agglomerates produced have an excellent flow performance. The lowest HR value, which corresponds to the agglomerates with most excellent flow performance, is observed in mixture 12 and 13 at 80 rpm screw speed while the highest value is observed in mixture 7 at 120 rpm.

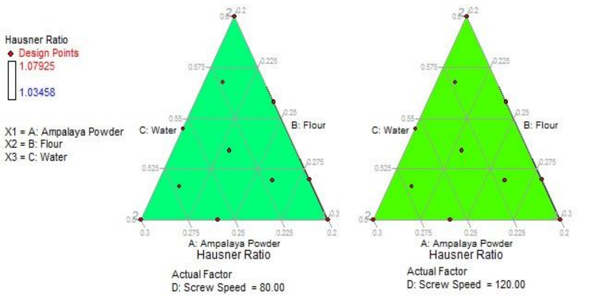

Fig. 8. Effect of Feed Composition and Process Variable in Hausner Ratio

3.5 Friability and Disintegration Time

The generated model equation correlating the effect of mixture and process variable in the % friability is shown in Eq. 9. The diagram for %friability is shown in Figure 9.

$$\%\,Friability = 0.60BC - 0.08BD + 0.83BCD \qquad (9)$$

Where,
BC = binary interaction between filler material (flour) and liquid binder (water)
BD = binary interaction between filler material (flour) and screw speed (rpm)
BCD = ternary interaction of filler, binder and screw speed

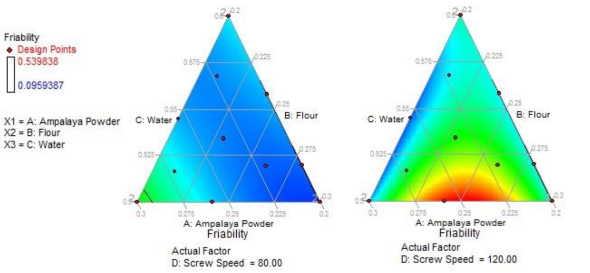

Fig.9. Effect of Feed Composition and Process Variable in % Friability

The magnitude of the %friability is affected by the binary interaction terms BC and BD and the ternary interaction term BCD. The binary interaction of the flour content and screw speed have a minimal decreasing effect on the magnitude of the friability. On the other hand, the increase in the binary interaction BC and ternary interaction BCD can increase the granule friability. In these interaction terms, increasing screw speed cause a less-formed and less-dense agglomerate resulting to a friable granule. It can be noted that the highest increasing effect is brought about by the BCD interaction term. It can be inferred that the flour is acting more of a disintegrant in these interaction term rather than a binder. The increased flour content promotes breaking of the overall granule matrix while high water content can cause void spaces after drying especially when agglomerated at higher speed, thus, if these factors are high, the granule tend to be less-formed with a high chance of have many void spaces left after drying. This condition results to more friable agglomerates.

The disintegration determines whether the agglomerates disintegrate within a prescribed time when placed in a liquid medium under the prescribed experimental conditions. It is dependent on solubility of the ingredients, wetting nature of the granules, and overall composition of the granules. The model generated is insignificant, thus the model equation cannot be used in predicting the magnitude of the disintegration time. The mean of the response is better predictor than the model. The diagram for disintegration time is shown in Figure 10.

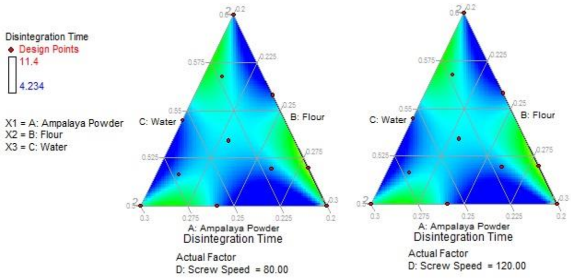

Fig.10. Effect of Feed Composition and Process Variable in Disintegration Time

Overall, the agglomerates achieved a considerable structural integrity and stability based on the selected quantitative parameters that were measured in the study. Therefore, the agglomeration process performed well based on these criteria. Friability and disintegration time are related because they are greatly dependent on the degree of forming those individual granules received as well as their component ratio.

3.6 Performance Evaluation of the Equipment

There is no significant difference between the two output efficiencies thus, the screw speed did not significantly affect the agglomeration of the mass input for a fixed period of operation. Similarly, the throughputs are not significantly different. It can be inferred that the mass simply passed through the equipment such that there was less effective flow resistance that counteract the drag flow caused by the screw speed. The output efficiency was calculated by getting the difference between mass of the feed and mass of the output multiplied by 100 percent. The throughput was calculated by dividing the mass of the output after 15 minutes of operation with the rated power of the motor. The summary of the calculated efficiency and throughput are shown in Table 3.

Table 3. Performance Evaluation of the Agglomerator

Screw Speed	Mass Output Efficiency (%)	Throughput (kg/kW)	Energy Conversion (kWh/kg)
80 rpm	96.15 ± 1.01	0.3163 ± 0.02	0.07910 ± 0.01
120 rpm	95.5 ± 3.17	0.3114 ± 0.01	0.0778 ± 0.00

3.7 Economic Analysis of the Fabricated Equipment

The mass capacity that the fabricated agglomerator can process in an 8-hour per day operation is 20 kg/min. it was based on the actual operation of the equipment. The total cost of the equipment is estimated at PhP 25,000 comprising of the cost of all the hardware materials used, fabrication cost and the motor. A single person can operate the equipment at PhP 200 per 8-hour a day. The agglomeration process power consumption cost includes the power consumption cost of the drying process. On the other hand, the cost of the raw material 627 pesos per kg. Finally, the calculated cost of a 500-mg granule is 0.55 pesos. The repair and maintenance as well as the salvage value is also considered and is estimated as the 10% of the initial cost. The summary of the partial economic analysis is shown in Table 4.

Table 4. Summary of Partial Economic Analysis Results

Item	Value
Payback Period	1.84
Break-even point (BEP, days/yr)	100
Benefit-Cost Ratio (BCR)	1.01
Internal Rate of Return (IRR,%)	50.99%

4. CONCLUSION

The study aimed to develop an agglomeration equipment based on low and medium shear forming extruder; to investigate the effects of the composition of the feed and the screw speed on the performance of the equipment based on the handling and storage properties of the products; to evaluate the performance of the agglomeration equipment based on mass output efficiency and throughput (kg/kW); and to evaluate the economic feasibility of the fabricated agglomeration equipment. The performance of the equipment based on the handling and storage properties of the agglomerates produced was characterized by Carr's index or Compressibility index, Hausner ratio, friability and disintegration time. The Carr's index of the agglomerates ranged from 0.0333 to 0.07333 while the Hausner ratio ranged from 1.0346 to 1.0792. The lowest friability measured was 0.096 indicative of a stable and strong agglomerate. On the other hand, there is no significant difference between the two output efficiencies and throughputs thus, the screw speed did not significantly affect the conversion of the mass input for a fixed period of agglomeration. The maximum mass output efficiency and throughput was 96.15 ± 1.01% and 0.3163 ± 0.02 kg/kW. Finally, the economic projections for the fabricated agglomeration equipment showed a substantial economic feasibility having an internal rate of return of 50.99% for a period of 1.84 years.

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