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# OPTIMIZATION OF PROCESS PARAMETERS IN THE PELLETIZATION OF CROP RESIDUES BY TAGUCHI-GREY RELATIONAL ANALYSIS

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## ABSTRACT

In this study, the effects of material variables on multi-response (performance characteristics) were investigated and, subsequently, parameters were optimized by considering these multi-response outputs using Taguchi-based Grey relational analysis. The analysis revealed the optimal operating level for the control factors such that each response is close to its target value. The response table of means well corroborate with ANOVA results, showing that binder proportion, binder type, and biomass material having important contributions to optimization of pellet quality. The conformational test showed an overall improvement in pellet quality.

**Keywords**: Crop residue, Solid biofuel, Pelletization, Binder, Grey Relational Analysis, Optimization

## INTRODUCTION

Crop residues are promising biomass feedstocks for biofuel or bioenergy due to their abundance, availability, and relatively low cost (U.S DOE, 2011). According to the billion ton report 2005, the sustained yield of straw range between 210 and 320 million dry tons (mdt) annually, however, the total potential of crop residues is over 400 mdt in the United States. Figure 1-1 depicts the harvestable crop residues by county for the contiguous United States.

Bulk density of biomass ranges between 40 kg/m$^3$ to 250 kg/m$^3$ for agricultural straws (Tumuluru et al., 2010; Obernberger, and Thek, 2004; Kaliyan and Morey, 2009; Mani et al., 2003). Bulk density can be increased by a pelletization process to a final density between 500 and800 kg/m$^3$ (Kaliyan and Morey, 2009). Similarly, other quality characteristics of pellets such as energy density, durability, and pellet strength are also increased. Agricultural straws lack adequate natural binders, and the lignin therein is bound to hemicellulose (Lu, Tabil, D. Wang, & G. Wang, 2013). The lignin in herbaceous and cereal straws is less compared that in woody biomass. According to Tumurulu (2009), binders are required to supplement lignin in order to pelletize non-woody feedstock. Wheat gluten, carboxymethylocellulose, gaur gum, agar, alginate, carrageenan are expensive binders, whereas lignin sulfonate, milo (processed), and collagen are inexpensive binding agents in feeds (Li, 1998). The study of binder is still in its infancy and requires more research to understand its effect.

Ali et al. (2010) mixed polymethylolcarbamide (PMC), gura gum, and wheat gluten binders each at three inclusion levels (0.5%, 2.0%, and 3.0%) to the shrimp feed formulations and pelletized them at three different temperatures (70$^{o}$C, 80$^{o}$C, and 90$^{o}$C) in a ring die pellet mill. Chou et al. (2009) used Taguchi method to optimize the conditions for preparing solid fuel briquettes wherein binder types (soybean residue, rice bran, and sawdust), hot pressing temperatures (110$^{o}$C, 130$^{o}$C, and 150$^{o}$C), and particle sizes (10-5, 5-2, and <2) were studied in order to determine optimal conditions. Xia, Sun, Wu, & Jiang (2016) presented multi-objective optimization of a straw ring die briquetting system for rice straws. Grey relational analysis (GRA) combined with the analytic hierarchy process (AHP) was employed to optimize briquetting process parameters, moisture content, raw material particle size, temperature, and gap between the roller and die using average energy consumption, productivity, density, and the rate of qualified biofuels as optimization objects.

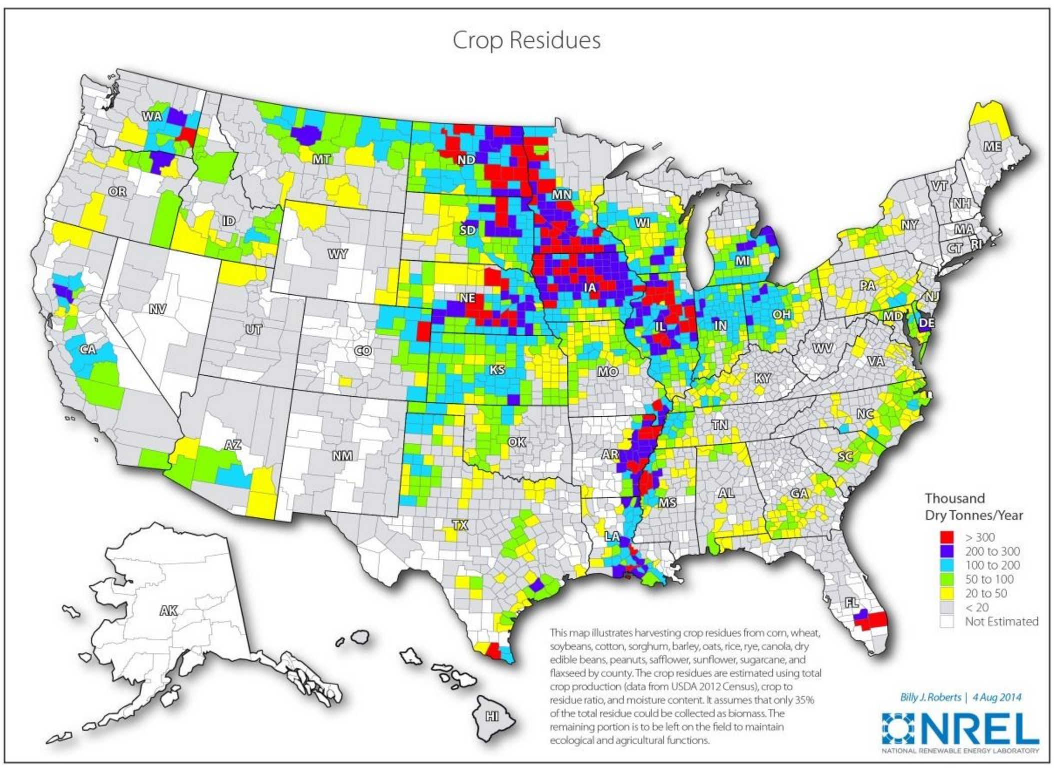


**Figure 1-1: Solid biomass resources by county (crop residues)**
**Source: (NREL, 2014)**

There are rare studies on optimizing material variables for preparing solid biofuel pellets using the Taguchi-Grey relational analysis method. The effect of material variables, namely residue type, particle size, type of binder, and binder proportion, on the multiresponse or performance characteristics such as bulk density, durability, heating value, and compressive strength were investigated. Subsequently, parameters were optimized by considering these multiresponse outputs using Taguchi-based Gray relational analysis. Multiresponse process optimization is gaining popularity in modern manufacturing processes (Sibalija and Majstrorovic, 2016). Thus, this study aims at optimizing material parameters for pelletization of agricultural residues with the objective of maximizing bulk density, durability, compressive strength, and calorific values. Based on own previous experience, we initially hypothesized that the binder would have a prominent effect upon the quality characteristics of pellets and that dry milk binder in 1:15 proportion over 4 mm hammer mill wheat grind i.e. A2B2C3D1 combination, will be the optimum process parameters.

## MATERIALS AND METHODS

Rice straw, wheat straw, and corn stover were used in these pelletization experiments as different materials. These biomass samples were purchased in the form of rectangular bales from local farmers in Mississippi, Craighead, and Greene Counties in Northeast Arkansas. The entire plant residues were first chopped into smaller strands and then ground in hammer mills passing through different screen sizes. Different binders (gelatin, gluten, or dry milk) were added in respective proportions as determined by Taguchi experimental design. Gelatin (Knox® Original Unflavored Gelatin) and Great Value non-fat unflavored instant dry milk powder were purchased from Walmart. Similarly, pure wheat gluten was bought from the Sigma-Aldrich Co. The manufacturer claims that Knox unflavored gelatin contains no added flavor or sugar. The moisture content of the feedstock was kept at 13% ± 0.5% based upon the author's experience and previous studies (Mediavilla, Esteban, & Fernandez, 2012). 2% (w/w%) refined glycerin was added to each mixture to maintain flowability of feedstocks through the die without clogging it. The Future Fuel Chemical Company at Batesville, AR supplied the FutureSol™ refined glycerin. Using these binders, and predetermined moisture conditions, pellets were produced by the extrusion process in a Pellet Pros PP600A flat die pellet mill using die openings of 6 mm and a thickness of 24 mm.

**Table 1-1: Parameters of interest and their corresponding levels**

| Level | Binder Prop$^n$ (A) | Binder (B) | Particle size (mm) (C) | Residue Type (D) |
|---|---|---|---|---|
| 1 | 0.1 | Gelatin | 2 | Wheat |
| 2 | 0.0667 | Dry Milk | 3 | Rice |
| 3 | 0.05 | Gluten | 4 | Corn |

### Experimental Design

The Taguchi-based Grey relational analysis method was employed to optimize multiple output quality characteristics. Taguchi experimental design allows the analysis of many factors with just a minimal number of runs. Each factor is weighted equally in each experiment, thus factors can be analyzed independently of each other. Taguchi design of Experiment (DoE) was performed using Minitab®17.2.1. For this study, a Taguchi L9 Orthogonal Array (OA) was chosen. Several rounds of exhaustive pilot experimentation were conducted before deciding upon the parameter range. The 3^4 (L9) orthogonal array represents four independent variables each having three set values (levels).

**Table 1-2: Taguchi's experimental design L9($3^4$) orthogonal array**

| Binder Prop. | Binder | Particle size(mm) | Residue type | Moisture (%) |
|---|---|---|---|---|
| 0.1 | Gel. | 2 | Wheat | 13 ± 0.5 |
| 0.1 | DM | 3 | Rice | 13 ± 0.5 |
| 0.1 | Glu. | 4 | Corn | 13 ± 0.5 |
| 0.0667 | Gel. | 3 | Corn | 13 ± 0.5 |
| 0.0667 | DM | 4 | Wheat | 13 ± 0.5 |
| 0.0667 | Glu. | 2 | Rice | 13 ± 0.5 |
| 0.05 | Gel. | 4 | Rice | 13 ± 0.5 |
| 0.05 | DM | 2 | Corn | 13 ± 0.5 |
| 0.05 | Glu. | 3 | Wheat | 13 ± 0.5 |

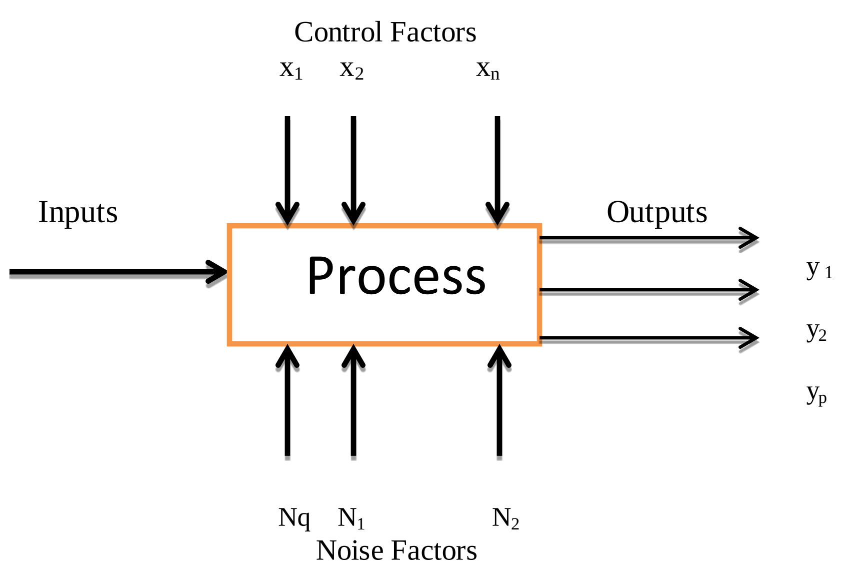


**Figure 1-2: General model of an engineering process (adopted from Sibalija and Majstrorovic, 2016).**

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In the pelletization process, controllable design variables considered for the present study were basically material variables: residue types, particle sizes, moisture range, binder proportion, and binder types. A process variable that can be controlled but wasn't thoroughly investigated is temperature. In the case of the pellet mill 'Pellet Pros PP600A' model, pressure, distance between die and roller, rates of revolutions of die and roller, and other process parameters were difficult to control and measure and were excluded from the study.

**Data Analysis**

The Taguchi Method involves conducting tests as determined by the orthogonal arrays (OA) Design of Experiments, which is L9 or $3^4$ OA. In it, a statistical measure of performance called the (S/N) ratio (logarithmic functions of desired output) is calculated for each of the quality characteristics. Here, "signal" refers to the mean desired effect for the output characteristic while any undesirable effect (that is, signal disturbance effect) is known as noise. The Signal to Noise ratio (S/N) is also termed as the ratio of mean (signals) to the standard deviation (noise) and is taken as an objective function for optimization. For our purpose of study, the quality characteristics fitting "larger the better" was selected for the aforementioned performance characteristics (bulk density, durability, diametric compression strength (hardness), and calorific value). Therefore, S/N for a "larger the better" characteristic is calculated as follows.

S/N ratio (η) = $-10\ log_{10}\left(\frac{1}{n}\right)\sum_{1}^{r}\frac{1}{{y_{ij}}^2}$ …………………… Eq. (1.1)

where,

$Y_{ij}$ – observed response value (i= 1,2,…,n; J= 1,2,…..k)

n = number of replications

Grey by definition is nondescript or indefinite. Thus, a Grey relation is the relation without complete information. Grey relational analysis includes the following steps for computation.

Grey relational generation: It is a method of linear data processing in order to generate a normalized data sequence for the output characteristics.

Deviation coefficient calculation: It is calculated as the difference between the desired performance characteristic (also called referential series) and the compared series (normalized data series).

Calculation of Grey relational coefficient: It is calculated from the minimum, maximum deviation, and difference of desired and actual data. "Ψ" is the distinguishing coefficient;

0 < Ψ <1, and we adopt 0.5 normally.

Determination of Grey relational grades: It is the weighted average of the Grey relational coefficients corresponding to each process response.

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Grey relational analysis: Multiple process responses so converted into single Grey relational grades (step 4) were ranked in descending order. Then, the optimal process parameter label was assigned to the factor-level combination which had the largest grey relational grade (Liu and Lin, 2006).

The following formulas were used for the standardized transformations. When the target value is "larger is better", the original sequence is normalized as

$$x_i*(k) = \frac{x_i(k) - \min x_i(k)}{\max x_i(k) - \min x_i(k)} \quad \text{........................................ Eq. (1.2)}$$

where,

$x_i*(k)$ is the normalized value of the k$^{th}$ performance characteristic in the ith experiment.; and $x_i(k)$ is the original kth performance value in the ith experiment.

The deviation coefficient is determined by using Eq. (1.3)

$$\Delta x_i(k) = \left| x_0(k) - x_i*(k) \right| \quad \text{........................................ Eq. (1.3)}$$

where,

$\Delta x_i(k)$ is a deviation coefficient

$x_0(k)$ is the reference sequence or ideal series, and

$x_i*(k)$ is a comparability sequence.

The Grey relational coefficient is calculated using Eq. (1.4)

$$\xi_i(k) = \frac{\Delta\min + \Psi\Delta\max}{\Delta x_i(k) + \Psi\Delta\max} \quad \text{........................................ Eq. (1.4)}$$

where,

$\xi_i(k)$ is grey relational coefficient and $\Psi$ is a distinguishing coefficient

$\Delta\min$ is the smallest value of $\Delta x_i(k)$ whereas $\Delta\max$ is the largest value of $\Delta x_i(k)$

The Grey relational grade is calculated by,

$$\Upsilon_i = \frac{1}{n}\sum_{k=1}^{n} \xi_i\ (k) \text{...................................................... Eq. (1.5)}$$

where,

n is the number of output response characteristics

Optimal values of GRG can be predicted using equation (1.6)

$\Upsilon_e = \Upsilon_m + \sum_{i=1}^{q}(\overline{\Upsilon_i} - \Upsilon_m)$ ………………………………………………… Eq. (1.6)

Where, $\Upsilon_m$ = The total mean of the GRG

q = no. of input parameters/factors

$\overline{\Upsilon_i}$ = mean GRG value at the optimal level for the $i_{th}$ parameter

Now, the Grey relational grades are considered for optimizing the multi-response parameter design problem.

Unlike in single objective optimization, optimizing multiple objective functions is associated with the loss in some quality characteristics. However, the overall quality of the product is improved which is confirmed by the experimental run at optimal conditions.

The characteristic performance of biomass pellets was measured by the method described below (Table 1-3).

**Table 1-3: Methods used for measuring performance characteristics**

| S. No. | Quality characteristics | Method |
|---|---|---|
| 1 | Bulk density | ASTM E 873 |
| 2 | Higher heating value (HHV) | ASTM E 711 |
| 3 | Durability (PDI) | EN 14961-2 |
| 4 | Pellet strength (Hardness) | ASTM D4179-11 |

Analysis of variance (ANOVA) was used to determine the contribution of each parameter on the responses.

## RESULTS AND DISCUSSIONS

The inherent friction produces frictional heat as the material gush into die openings being crushed between die and roller. A gelatinization process takes place when the moisture and starch or gelatins are heated at temperatures higher than the gelatinization temperature, which is continuously maintained inside the pellet mill due to the frictional heat. If the binder is protein (dry milk, in our case), protein denaturation occurs under heat, plasticizing and enabling to act as a binder. Both processes help to increase durability, and hardness of pellets.

Important performance characteristics of biomass pellets such as Bulk density, durability, compressive strength, and calorific value were measured. Measurements were done in triplicates and the mean of each measurement set are presented in the table below.

**Table 1-4: Taguchi OA ($3^4$) and mean responses for each experimental run**

| Expt. No. | Control Factors | | | | Mean Responses | | | |
|---|---|---|---|---|---|---|---|---|
| | Binder Prop. (wt/wt) | Binder | Particle Size(mm) | Residue Type | BD (Kg/m$^3$) | PDI (%) | Hardness (Kg) | HHV (Mj/Kg) |
| 1 | 0.1000 | Gel. | 2 | Wheat | 602.125 | 96.000 | 20.875 | 17.625 |
| 2 | 0.1000 | DM | 3 | Rice | 684.089 | 87.567 | 18.400 | 16.799 |
| 3 | 0.1000 | Glu. | 4 | Corn | 552.605 | 88.700 | 17.550 | 17.437 |
| 4 | 0.0667 | Gel. | 3 | Corn | 628.902 | 94.667 | 20.300 | 17.359 |
| 5 | 0.0667 | DM | 4 | Wheat | 695.671 | 95.200 | 17.850 | 17.758 |
| 6 | 0.0667 | Glu. | 2 | Rice | 609.408 | 72.767 | 16.200 | 15.706 |
| 7 | 0.0500 | Gel. | 4 | Rice | 620.18 | 83.633 | 17.500 | 16.081 |
| 8 | 0.0500 | DM | 2 | Corn | 558.263 | 67.567 | 14.250 | 17.562 |
| 9 | 0.0500 | Glu. | 3 | Wheat | 523.435 | 76.467 | 12.225 | 17.668 |

Abbreviations: BD - bulk density; PDI - Pellet durability index; HHV - Higher heating value; Gel. - Gelatin; DM - Dry-milk; Glu. – Gluten; Prop. – Proportion; (wt/wt) – Weight over weight

The S/N ratios for the mean responses were calculated according to Eq. (1.1). Further calculations use these S/N values.

**Table 1-5: S/N ratio values of the responses**

| S. No | Binder Prop. | Binder | Particle Size(mm) | Residue Type | S/N ratios | | | |
|---|---|---|---|---|---|---|---|---|
| | | | | | BD | PDI | Sth. | HHV |
| 1 | 0.1000 | Gel. | 2 | Wheat | 55.5937 | **39.6424** | **26.3925** | 24.9226 |
| 2 | 0.1000 | DM | 3 | Rice | 56.7023 | 38.8468 | 25.2964 | 24.5057 |
| 3 | 0.1000 | Glu. | 4 | Corn | 54.8483 | 38.9585 | 24.8855 | 24.8294 |
| 4 | 0.0667 | Gel. | 3 | Corn | 55.9717 | 39.524 | 26.1499 | 24.7905 |
| 5 | 0.0667 | DM | 4 | Wheat | **56.8481** | 39.5727 | 25.0328 | **24.988** |
| 6 | 0.0667 | Glu. | 2 | Rice | 55.6982 | 37.2387 | 24.1903 | **23.9213** |
| 7 | 0.0500 | Gel. | 4 | Rice | 55.8504 | 38.4476 | 24.8608 | 24.1263 |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| 8 | 0.0500 | DM | 2 | Corn | 54.9368 | **36.5947** | 23.0763 | 24.8915 |
| 9 | 0.0500 | Glu. | 3 | Wheat | **54.3773** | 37.6695 | **21.745** | 24.9437 |

Abbreviations: BD - bulk density; PDI - Pellet durability index; HHV - Higher heating value; Gel. - Gelatin; DM - Dry-milk; Glu. – Gluten; Prop. – Proportion

The Signal to noise ratio in Table 1-5 were normalized using Eq. (1.2). The calculation of deviation coefficient, and its further application in Eq. (1.4) resulted, in Grey relational coefficients where Psi (Ψ) distinguishing coefficient is 0.5.

**Table 1-6: Grey relational generation and Grey relational coefficient**

| Expt. No. | Normalized data | | | | Grey Relational Coefficient | | | | GRG |
|---|---|---|---|---|---|---|---|---|---|
| | **BD** | **PDI** | **Sth.** | **HHV** | **BD** | **PDI** | **Sth.** | **HHV** | |
| 1 | 0.4923 | 1.0000 | 1.0000 | 0.9386 | 0.4962 | 1.0000 | 1.0000 | 0.8907 | 0.8467 |
| 2 | 0.9410 | 0.7389 | 0.7641 | 0.5478 | 0.8944 | 0.6570 | 0.6795 | 0.5251 | 0.6890 |
| 3 | 0.1906 | 0.7756 | 0.6757 | 0.8513 | 0.3819 | 0.6902 | 0.6066 | 0.7708 | 0.6124 |
| 4 | 0.6453 | 0.9611 | 0.9478 | 0.8148 | 0.5850 | 0.9279 | 0.9055 | 0.7297 | 0.7870 |
| 5 | 1.0000 | 0.9771 | 0.7074 | 1.0000 | 1.0000 | 0.9562 | 0.6309 | 1.0000 | **0.8968** |
| 6 | 0.5346 | 0.2113 | 0.5262 | 0.0000 | 0.5179 | 0.3880 | 0.5134 | 0.3333 | 0.4382 |
| 7 | 0.5962 | 0.6079 | 0.6704 | 0.1921 | 0.5532 | 0.5605 | 0.6027 | 0.3823 | 0.5247 |
| 8 | 0.2264 | 0.0000 | 0.2865 | 0.9095 | 0.3926 | 0.3333 | 0.4120 | 0.8467 | 0.4962 |
| 9 | 0.0000 | 0.3527 | 0.0000 | 0.9585 | 0.3333 | 0.4358 | 0.3333 | 0.9233 | 0.5064 |

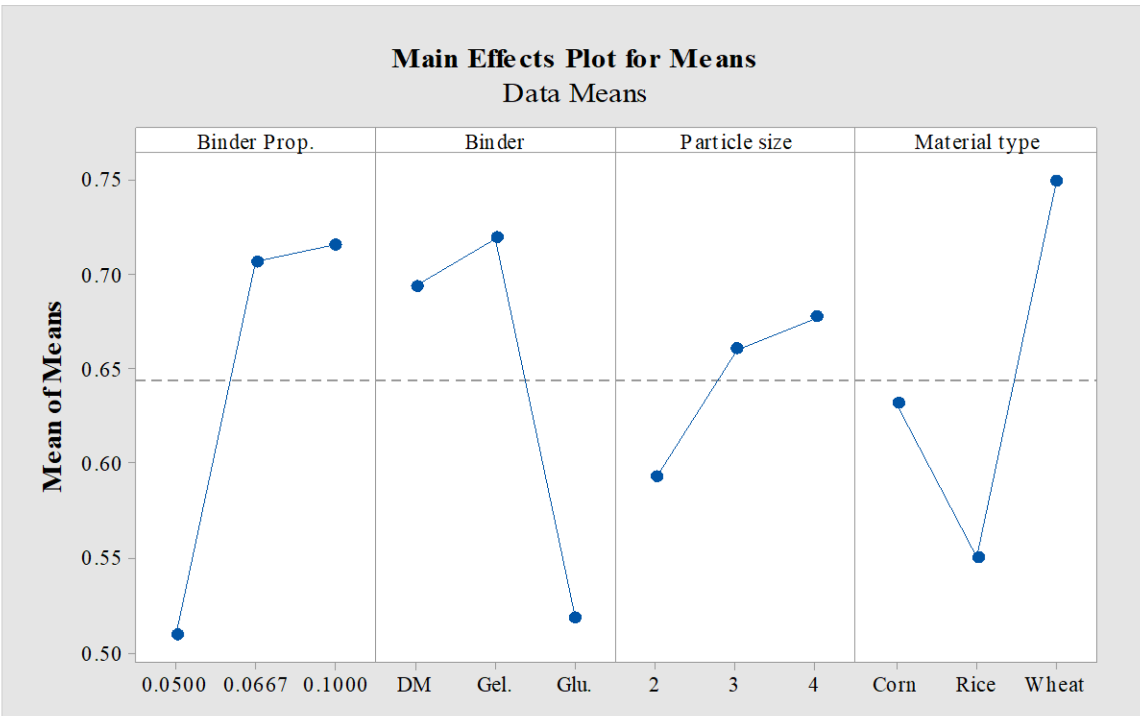
Abbreviations: BD – Bulk density; PDI – Pellet durability index; Sth.- compressive strength; HHV – Higher heating value, GRG – Grey relational grade

Table 1-6 also depicts the computation of grey relational grade, which is the single objective function (That is, multiple response problem condensed or transformed into single responseoptimization problem).

**Table 1-7: Response table for means of Grey relational grade (GRG)**

| Parameters | Grey Relational Grade | | | | |
|---|---|---|---|---|---|
| | Level 1 | Level 2 | Level 3 | Max-min | Rank |
| Binder prop. | **0.7160** | 0.7073 | 0.5091 | 0.2069 | 1 |
| Binder | **0.7195** | 0.6940 | 0.5190 | 0.2005 | 2 |
| Particle size | 0.5937 | 0.6608 | **0.6779** | 0.0843 | 4 |
| Residue | **0.7500** | 0.5506 | 0.6319 | 0.1994 | 3 |

The means of GRG for each level of the controlling factors are summarized in the multi-response performance index table (Table 1.7). Ranks (highest - lowest) on the far-right column shows the relative significance of the parameters. The higher the rank, with 1 being the highest and 4 the lowest rank, the higher will be the effect of that parameter upon the overall performance characteristics. We determined that the binder proportion has the largest effect upon the processor yield. The effect of parameters upon the processor yield is as follows: Binder Prop. > Binder type > Residue Type > Particle size. The result well corroborates with the study conducted Hu et al. (2015). Hu et al. (2015) concluded that the quantity of binder has overall effect in performance characteristics than the types of binders. The main effect plots (Figure 1-3) give the optimal process combinations (parameter levels), based on "higher the better" characteristic which serve to achieve the predicted mean.




Note: Particle sizes are in millimeters; Abbreviations: DM - Dry-milk; Gel. – Gelatin; Glu. – Gluten

**Figure 1-3: Main effect plots for means of Grey relational grade**

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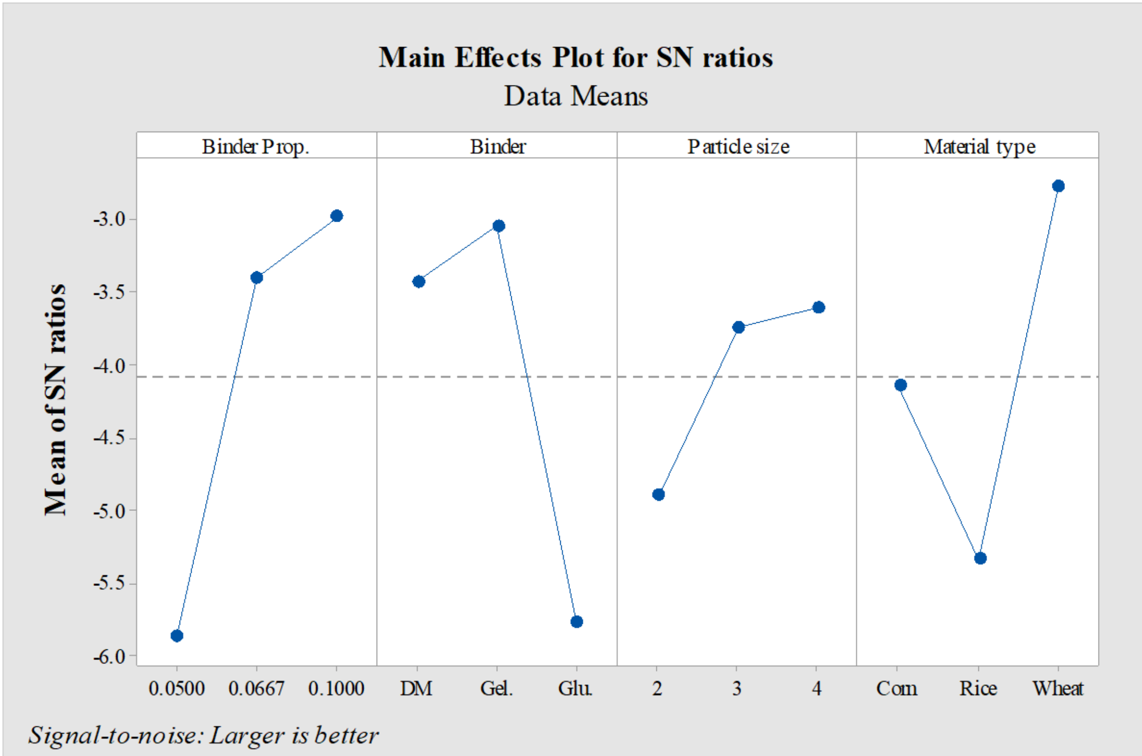


Note: Particle sizes are in millimeters; Abbreviations: DM – Dry-milk; Gel.- Gelatin; Glu.- Gluten

**Figure 1-4: Main effect plots for signal to noise ratio**

**Analysis of Variance for Means**

ANOVA separates the total variability of a response into contributions by each of the parameters which are calculated from the sum of squared deviations upon the grand mean.

**Table 1-8: Calculation of percentage contribution of each parameters**

| **Factors** | **DF** | **SS** | **MS** | **ρ (%)** |
|---|---|---|---|---|
| Binder Prop. | 2 | 0.0822 | 0.0411 | 36.39 |
| Binder | 2 | 0.0715 | 0.0357 | 31.65 |
| Particle Size (mm) | 2 | 0.0119 | 0.006 | 5.27 |
| Residue Type | 2 | 0.0603 | 0.0302 | 26.69 |
| Type | 8 | 0.2259 | | |

Abbreviations: DF - degree of freedom; SS - Sum of Squares; ρ (%) - percentage of contribution

The response table of means well correlate with ANOVA results, showing binder proportion, binder, and material type make an important contribution to optimization of pellet quality. Binder types and binder proportion have significant effects upon pellet characteristics. Others found that increasing binder proportion increased durability (Stahl, Berghel, Frodeson, Granstrom, &Renstrom, 2012) driving off relatively less moisture during pelleting (Tumuluru, Conner, & Hoover, 2016), which is in agreement with our result. Increasing the protein content increases durability (Briggs, Maier, Watkins, &Behnke, 1999) and hardness of pellets which is consistent with our result. Wheat gluten as a binder didn't behave well in achieving the target. The response table for mean GRG shows that the wheat gluten is least preferred over other binders, which is consistent with the findings of the Ali et al. (2010). The significant hygroscopic nature of wheat gluten is the reason behind its poor performance during pelletization.

The result showed that particle size was not an important parameter for feedstock when hammer mill grinds of 2 mm, 3 mm, and 4 mm were used. No difference in pellet quality was noticed by Stevens (1987) as mean particle size of wheat and corn reduced to 365μm and 551 μm respectively. However, Kirsten, Lenz, Schroder, & Repke, (2016) reported high bulk density and durability with 4 mm hammer mill grinds. Our result contradicts the outcome of Kirsten et al. (2016) study, suggesting that particle size has little or no effect upon pellet quality. The difference might be due to the use of binders. Each binder has different characteristics properties so the quantity required and effectiveness (influence) of a particular binder is different, as is evident from the table 1-4. Thus, gelatin stood out among binders as most influential. Dry milk seems effective at 1:15 (w/w basis), but since it couldn't render the same influence among different residue types, it is less preferable to gelatin. Bulk density and durability of pellets made from 4 mm Hammer mill grinds are comparatively larger. A similar pattern was reported by Theerarattananoon et al. (2010). The residue type turns out to be the third most important material variable from the analysis. Wheat straw had the most prominent effect among other residues. This might be because wheat straw polysaccharides have more sugar tied-up in their stems as starch in grains, as suggested by Naik, Goud, Rout, & Dalai (2010).

**Confirmation Test**

Optimal performance characteristics are estimated using optimal levels of design parameters. Thus, the final step in the Taguchi-Grey relational analysis is to run experimental confirmation using optimal levels for the control parameters. The predicted optimal GRG at the selected levels of parameters using Minitab software and also by manual calculation was 0.9309.

$$\mu GRG = GRG + (A1 - GRC) + (B1 - GRG) + (C3 - GRG) + (D1 - GRG) \quad \ldots\ldots Eq.\ (1.7)$$

$$= 0.716 + 0.7195 + 0.6779 + 0.75 - 3\,(0.64415)$$

$$= 0.9309$$

**Table 1-9: Conformation of experimental results**

| Responses | Initial Setting | Grey Relational Analysis | Improvement in S/N ratio |
|---|---|---|---|
| Level | A2B2C3D1 | A1B1C3D1 | A1B1C3D1 |
| BD | 695.671 (56.848) | 693.22 (56.817) | (-0.031) |
| PDI | 95.2 (39.573) | 97.1 (39.744) | (0.171) |
| Sth | 17.85 (25.033) | 22.5 (27.0437) | (2.011) |
| HHV | 17.758 (24.988) | 18.002 (25.106) | (0.118) |

Main effect plots for GRG indicated that the combination of 4 mm wheat straw residue with 10 % gelatin binder is the optimal combination of factors for the multiple performance characteristics under study. Fig. 4-3 and Fig. 4-4 are the main effect plots for means of grey relational grade. The dashed lines running in the middle represents the total mean of grey relational grade. The conformation tests showed improvements in the S/N ratios and corresponding increase in GRG for the optimal parameter.

## CONCLUSION

Therelative effects of parameters on the processor yield are as follows: Binder Proportion> Binder type > Residue Type > Particle size. Thus, binder proportion has the largest effect followed by binder type, residue type, and the least effect from particle size. Similarly, the best combination of factor levels was $A_1B_1C_3D_1$ for enhancing pellet quality.

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