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Optimization of continuous microwave pre-milling process parameters for enhanced milling recovery of green gram

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ABSTRACT

Green gram (*Vigna radiata* L.) is a widely cultivated, protein-dense legume that plays a vital role in human nutrition and food security across the globe. Due to the presence of a tightly bound mucilage layer between the seed coat and the cotyledons, green gram is traditionally recognized as a difficult-to-mill pulse. Efficient pre-milling treatment is essential to weaken this seed-coat adherence, improve dehulling efficiency, enhance whole dhal recovery, preserve nutritional quality, and substantially lower energy consumption during commercial processing. This study investigates the optimization, and performance evaluation of a continuous pre-milling treatments tailored specifically for green gram. Treater operational parameters-including thermal exposure, moisture conditioning, treatment duration, and grain throughput rate-were systematically investigated to achieve uniform seed conditioning and optimal cotyledon hardness prior to mechanical dehulling. Response surface methodology (RSM) based on a central composite rotatable design was employed to assess the interactive effects of the independent variables on milling characteristics. The process optimization targeted maximum dehulling yield and high head dhal recovery while significantly reducing breakage, powder loss, and overall dehulling losses. Under the optimized operating conditions, the continuous treater effectively loosened the fibrous husk without inducing thermal degradation or fissures in the cotyledons. The optimized treatment yielded superior dehulling efficiency and lower energy input compared to conventional commercial milling methods. The findings validate the mechanical efficacy of the continuous pre-milling treater, offering an energy-efficient, scalable, and automated processing alternative for the modern pulse milling industry to enhance processing margins and product quality.

Keywords: Green gram, Optimization, Pre-milling treatment, Dhal yield, Dehulling efficiency

Introduction

Green gram (*Vigna radiata* L.) is a vital pulse crop renowned for its high protein content, digestibility, and essential micronutrients, making it indispensable for nutritional security. To maximize the recovery and quality of dhal, an efficient pre-milling treatment is essential. Dehulling green gram is notoriously challenging due to the presence of a strong, gummy mucilage layer binding the husk to the cotyledon. Traditional pre-milling techniques such as conventional sun drying, prolonged soaking, and batch heat treatments-often yield non-uniform moisture diffusion and inconsistent grain conditioning, resulting in high broken percentages, powder loss, and variable milling outcomes. India is the world's leading producer and consumer of green gram, contributing substantially to global output and domestic legume consumption. While earlier investigations have examined various pre-treatment approaches—including hot-air drying, hydrothermal conditioning, chemical application, and microwave heating—batch methods struggle to deliver uniform heat and mass transfer at commercial capacities. Continuous processing systems offer controlled residence times and uniform grain exposure, presenting a viable path to address these milling bottlenecks. This paper builds upon current processing technologies by proposing and optimizing a continuous pre-milling treater tailored specifically to green gram pre-milling process for improved dehulling efficiency and dhal yield with reduced broken.

Materials and methods**Experimental materials**

The continuous pre-milling treater is designed with a modular conveyor system that carries green gram onto a vibrating bed. The treater's design allows for adjustable residence times, enabling customization based on green gram variety and desired moisture content. The experimental methodology involves varying parameters such as flow rate, conveyor speed, and residence time to identify optimal conditions.

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Samples

The green gram was procured from the local market of Ludhiana, Punjab, India. The grains were cleaned using cleaner cum grader and Destoner to separate all foreign matter, dust, dirt, twigs, broken and mud balls.

Determination of moisture content

The moisture content of the sample was determined by the hot air oven method, drying at $102 \pm 2^\circ\text{C}$ for 24 h as per the AOAC method, and the average moisture content was found to be 12.98% (w.b.). Although green gram is conventionally dehulled at 11-13% moisture content (w.b.), the conditioning moisture content was deliberately varied over a wider range of 11-15% in this study to evaluate its interactive effect with microwave power level and treatment time on dehulling performance, since microwave-assisted conditioning may respond differently to moisture content compared to conven-

tional dehulling methods. For conditioning the samples to the required moisture levels, a 3 g portion of each sample was weighed on an analytical balance (Model: TB403, Dengver Instrument; accuracy 0.001 g) in triplicate, and the average value was recorded, following ASAE Standard S352.2 FEB03 for moisture measurement of un-ground grain and seeds (ASAE, 2003) [1]. The calculated amount of water required to raise the grain to each target moisture level was added to the samples using a sprayer, after which the samples were tempered overnight to allow uniform moisture distribution throughout the grain. The samples were then placed in a hot air oven at 130°C for three different time intervals (1, 2, and 3 h), and after each interval the samples were reweighed and their moisture content calculated using the formula below, to verify that the target conditioning moisture content had been achieved prior to conducting the designed experiments.

$$\text{Moisture content (\%)} = (W_1 - W_2 / W_1 - W) \times 100$$

Where,

W_1 = weight in g of the petri dish with the material before drying

W_2 = weight in g of the petri dish with the material after drying

W = weight in g of the empty petri dish.

Experimental run-on continuous microwave treatment

The continuous microwave treatment was performed in the developed system by Punjab Agricultural University, Ludhiana for continuous pre milling processing of green gram. Pre-milling treatments of green gram is labour and time-intensive batch operation, which is a big problem due to batch processing nature and results in excessive material handling, leading to increased processing duration with low final product recovery and chances of contamination in the handling process. For easy milling and to improve milling efficiency, pre-treatment of green gram is required. So far, only long and batch type pre-milling treatments have been developed, and no such continuous type pre-milling treater is available for this purpose. Hence this study was undertaken on continuous pre-milling treater of 10 kg/h capacity. The system consisted of a treatment section, frame, microwave system, conveyor system, driving mechanism, and controlling unit. The system was optimized for continuous pre-milling treatments of green gram to determine the best treatment condition for maximizing dehulling yield and dhal yield while minimizing the dehulling loss. The triplicate of each sample was taken in order to avoid an error. The samples were packed in plastic bags with proper coding of power level and time.

Dehulling parameters of green gram

Dehulling parameters were determined in terms of dehulling yield, dhal yield, and dehulling loss.

- Dehulling yield (DY) was defined as total whole dehulled kernels and broken kernels produced in the dehulling of pulses. The dehulling yield was calculated using the relation given by (Goyal *et al.* 2007) [2, 3].

Dehulling yield, (%) =

$$\frac{\text{Weight of dehulled kernel(g)} + \text{Weight of broken(g)}}{\text{Initial weight of selected pulse grains}} \times 100$$

- Dhal yield (DY) was defined as the yield of dehulled whole and split kernels as a percentage of initial seed weight. Dhal yield was calculated using the relation given by (Goyal *et al.* 2007) [2, 3].

Dhal yield, (%) =

$$\frac{\text{Weight of dehulled whole and split seeds(g)}}{\text{Initial weight of selected pulse grains}} \times 100$$

- Dehulling loss (DL) was calculated as the weight fraction of the powder and fine broken relative to the initial weight of green gram. It was calculated using the relation given by (Goyal *et al.* 2007) [2, 3].

Dehulling loss, (%) =

$$\frac{\text{Weight of powder(g)} + \text{Weight of fine broken(g)}}{\text{Initial weight of selected pulse grains}} \times 100$$

Statistical evaluation

All measurements were carried out in triplicate, and the results were expressed as the mean. To fit regression equations, Design expert software was utilized.

Results and discussions

The continuous pre-milling treater is designed with a modular conveyor system that carries green gram onto a vibrating bed within a microwave treatment chamber. The treater's design allows for adjustable treatment time, enabling customization based on green gram variety and desired grain conditioning. The experimental methodology involved varying conditioning moisture content, microwave power level, and treatment time to identify the optimal combination of processing conditions for maximizing dehulling efficiency.

Performance evaluation of continuous pre-milling treater

Green gram was pre-treated in the developed continuous pre-milling treater at different combinations of conditioning moisture content, microwave power level, and treatment time as listed in experimental design in table 1. The treated grain samples were analyzed for their response to dependent variables, i.e., dehulling parameters viz., dehulling yield, dhal yield, dehulling loss, and average grain surface temperature by varying the independent variables viz., moisture content of the grains, microwave power level, and treatment time were determined with the combination of various parameters used in design expert software. The quadratic model was fitted to the experimental data to check the adequacy of the model. The multiple regression techniques developed the response surface analysis of different response parameters as a function of process variables. Various three-dimensional response surfaces were developed to view a variance in processing variable responses and were drawn using Design Expert Software (design expert - 13.0.2).

Dehulling yield

The dehulling yield of green gram varied from 72.12% to 77.80% under different combinations of conditioning moisture content (CMC), microwave power level (MPL) and treatment time (TT) as presented in Table 1. The maximum dehulling yield (77.80%) was achieved at 14% CMC, 90% MPL and 105 s TT (Run 14), while the minimum (72.12%) was recorded at 13% CMC, 80% MPL and 60 s TT (Run 3). Therefore, the maximum dehulling yield was about 1.08 times compared to the minimum dehulling yield.

It was observed from Fig. 1 that the dehulling yield increased from 73.22% to 73.99% with an increase in conditioning moisture content across the entire range from 12% to 14%. It may be attributed to the fact that higher moisture contents probably led to a more uniform absorption and internal generation of microwave energy that, in turn, weakened the hull-cotyledon bond and, thus, facilitated an easy hull separation, a phenomenon similar to what was reported for mi-

crowave-assisted dehulling of pulses (Sokhansanj *et al.*, 2003; Ramakrishnaiah *et al.*, 1983) [5, 4].

The dehulling yield also increased from 73.22% to 74.59% with an increase in treatment time across the range of 75 to 105 s. Longer exposure to microwave probably helped to accumulate more energy within the grain for a longer period of time, further assisting the loosening of the hull-cotyledon structure for easier hull removal. A similar beneficial effect of longer treatment durations in microwave-assisted dehulling process was also reported by Joyner *et al.* (2015) [6] for continuous treatment of black gram.

It was observed from Fig. 2 that the dehulling yield increased from 73.23% to 74.28% with an increase in microwave power level across the range of 70% to 90% MPL. Higher powers resulted in a higher rate of internal energy input that caused enhanced internal heating and vapor pressure build-up within the seed, thus, accelerating the loosening of the hull as discussed above.

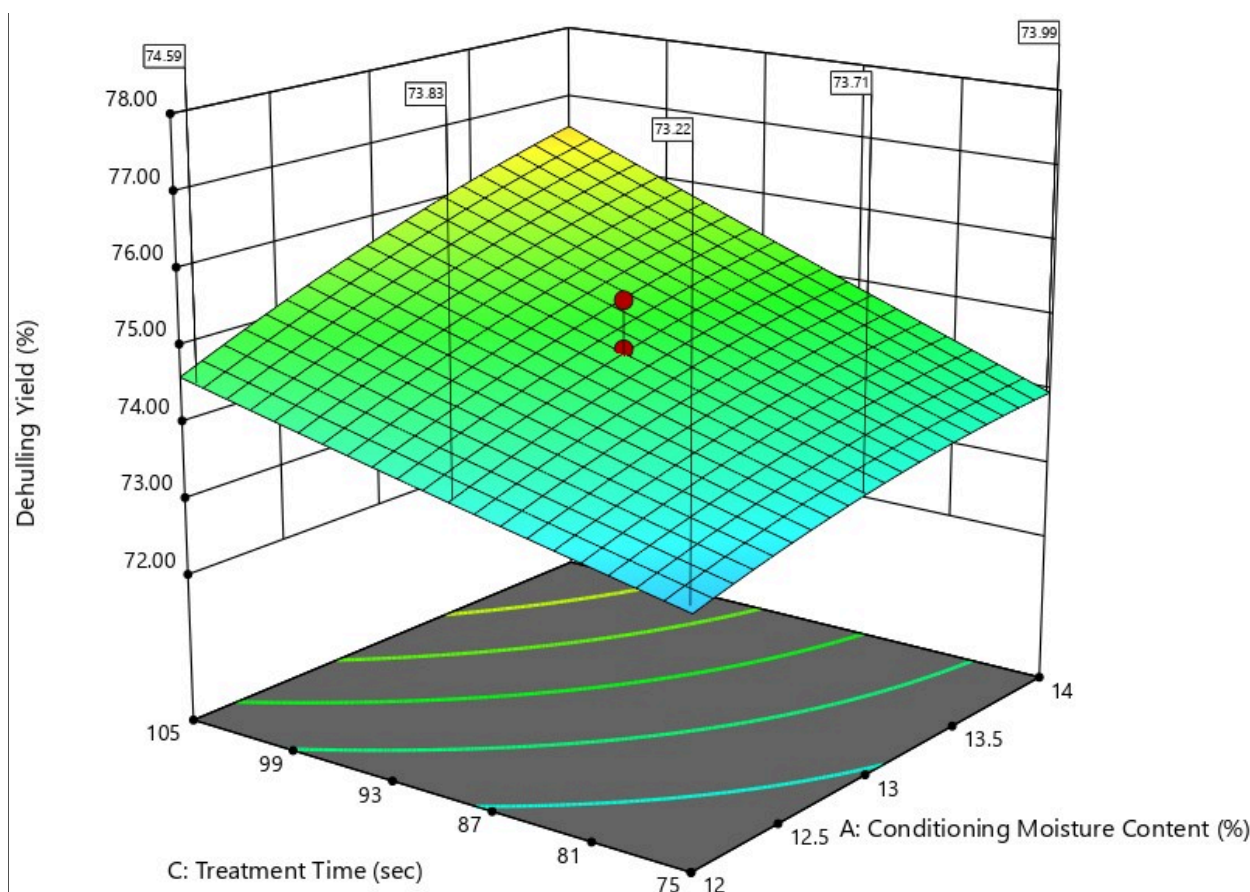


Figure 1. Cumulative effect of conditioning moisture content and treatment time on dehulling yield of green gram

Table 1. Combinations of various parameters used in design expert software for green gram

SI	Run	CMC (% w.b.)	MPL (%)	TT (sec)	Dehulling yield (%)	Dhal yield (%)	Dehulling loss (%)	Grain Surface Temperature (°C)
7	1	12	90	105	74.67	71.57	10.36	79.56
15	2	13	80	90	73.46	71.53	9.18	73.87
13	3	13	80	60	72.12	69.57	9.89	68.34
9	4	11	80	90	72.85	70.31	10.53	75.67
11	5	13	60	90	72.86	70.74	10.24	66.02
16	6	13	80	90	74.78	72.58	9.46	65.92
12	7	13	100	90	76.12	73.77	9.69	80.00
6	8	14	70	105	75.82	72.98	8.16	67.23
1	9	12	70	75	73.24	70.78	10.85	65.89
2	10	14	70	75	74.10	71.11	8.67	78.12
10	11	15	80	90	74.87	72.75	7.83	77.45

(continued on next page)

SI	Run	CMC (% w.b.)	MPL (%)	TT (sec)	Dehulling yield (%)	Dhal yield (%)	Dehulling loss (%)	Grain Surface Temperature (°C)
17	12	13	80	90	75.43	73.19	9.59	71.48
14	13	13	80	120	76.98	73.88	10.04	76.19
8	14	14	90	105	77.80	75.24	8.52	69.81
5	15	12	70	105	74.32	72.04	11.06	72.90
3	16	12	90	75	73.68	71.23	10.64	70.45
4	17	14	90	75	75.15	72.46	8.92	74.38

The dehulling yield also increased from 73.23% to 74.91% with an increase in treatment time across the range of 75 to 105 s. This could be explained by the same reasoning as in the previous paragraph and

was found to be in a good agreement with a similar finding of Joyner *et al.* (2015) [6] on enhanced dehulling effectiveness of continuous hydrothermal treatment of black gram in a dosage-dependent manner.

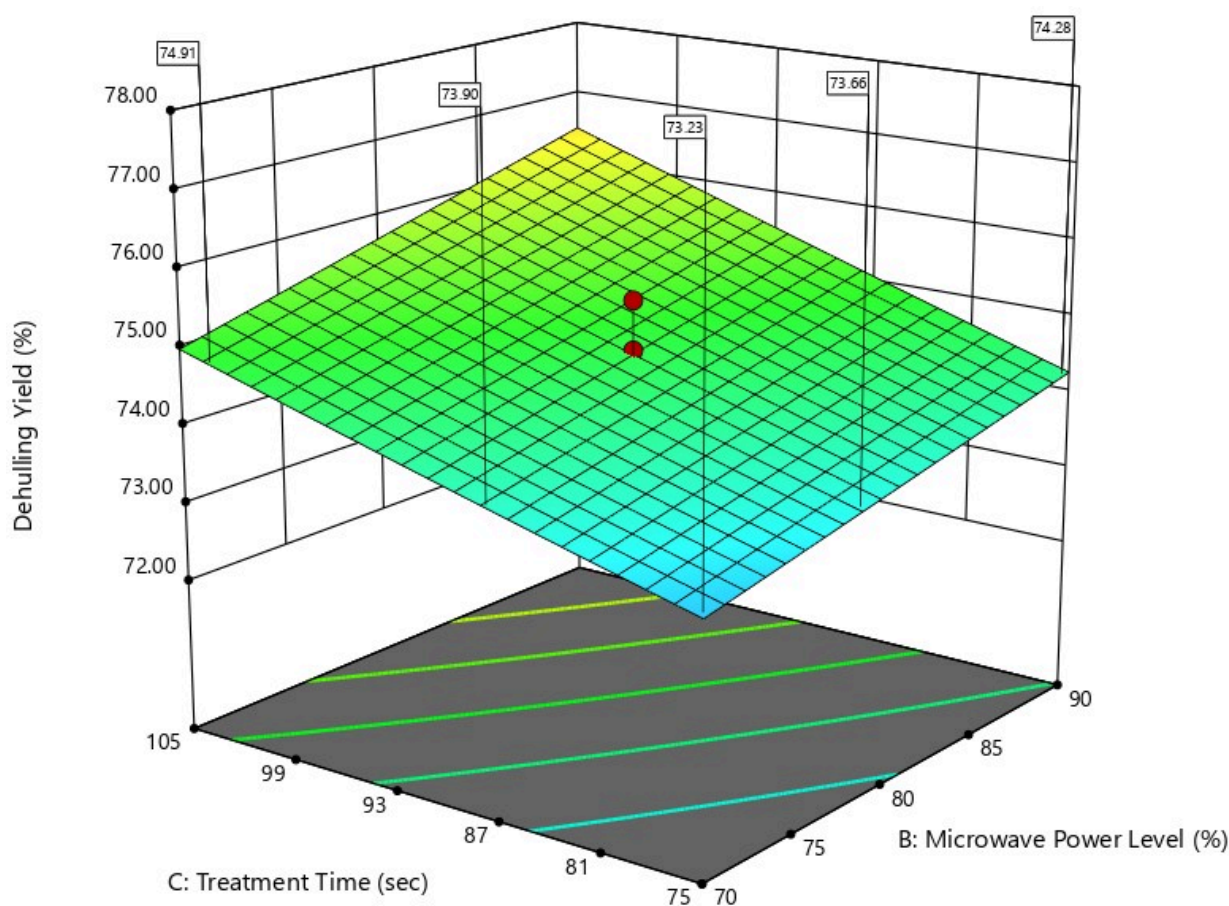


Figure 2. Cumulative effect of Microwave Power Level and Treatment Time on dehulling yield of green gram

The model equation in coded factors for dehulling yield was;

$$\text{Dehulling yield} = 74.7248 + 0.6875A + 0.64625B + 1.01C + 0.28AB + 0.2875AC + 0.105BC - 0.153152A^2 + 0.00434783B^2 + 0.0193478C^2 \quad (1)$$

Where A = CMC (% w.b.), B = MPL (%) and C = TT (s).

The ANOVA presented in Table 2 showed that the model was significant ($F = 5.30$, $p = 0.0194$) with an R^2 of 0.8721. The linear effects of CMC, MPL and TT were significant ($p < 0.05$), with TT showing the greatest influence ($F = 23.90$), followed by CMC ($F = 11.07$) and MPL ($F = 9.78$). The interaction and quadratic terms were non-signif-

icant, while the lack of fit was also non-significant ($F = 0.549$, $p = 0.7454$), indicating adequate model fit. Overall, the results suggested that increasing CMC, MPL and TT within the investigated range favoured dehulling yield, with treatment time being the most influential variable.

Source	Sum of Squares	df	Mean Square	F-value	p-value (Prob > F)
Model	32.59	9	3.62	5.30	0.0194 (significant)
Linear terms					
A – CMC	7.56	1	7.56	11.07	0.0126
B – MPL	6.68	1	6.68	9.78	0.0167
C – TT	16.32	1	16.32	23.90	0.0018
Interaction terms					

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Source	Sum of Squares	df	Mean Square	F-value	p-value (Prob > F)
AB	0.6272	1	0.6272	0.9182	0.3699
AC	0.6612	1	0.6612	0.9681	0.3579
BC	0.0882	1	0.0882	0.1291	0.7299
Quadratic terms					
A ²	0.4543	1	0.4543	0.6651	0.4416
B ²	0.0004	1	0.0004	0.0005	0.9822
C ²	0.0073	1	0.0073	0.0106	0.9208
Residual	4.78	7	0.6830	—	—
Lack of Fit	2.77	5	0.5532	0.5490	0.7454 (not significant)
Pure Error	2.02	2	1.01	—	—
Cor Total	37.37	16	—	—	—

Dhal yield (DY)

The dhal yield of green gram varied from 69.57% to 75.24% under different combinations of conditioning moisture content (CMC), microwave power level (MPL) and treatment time (TT) as shown in Table 1. The maximum dhal yield (75.24%) was achieved at 14% CMC, 90% MPL and 105 s TT (Run 14), whereas the minimum (69.57%) yield was recorded at 13% CMC, 80% MPL and 60 s TT (Run 3). Thus, the maximum dhal yield was approximately 1.08 times than the minimum value.

From Fig. 3, it was observed that, with an increase in conditioning moisture content, dhal yield increased from 70.93% to 71.52%, as

conditioning moisture content was varied from 12% to 14% CMC. This might be due to reduction of grain brittleness and mechanical damage, resulting in improved cotyledon recovery, thus, improved dhal yield. It was also observed from the Fig. 3 to improve the dhal yield from 70.93% to 72.07%, as treatment time was increased from 75 to 105 s. With an increase in treatment time, more amount of microwave energy might have been imparted onto the sample causing modification in grain structure, thus, resulting in improved hull removal, thus, improved dhal recovery. Improvement in dhal yield with an increase in dehulling yield was also observed with increase in treatment time.

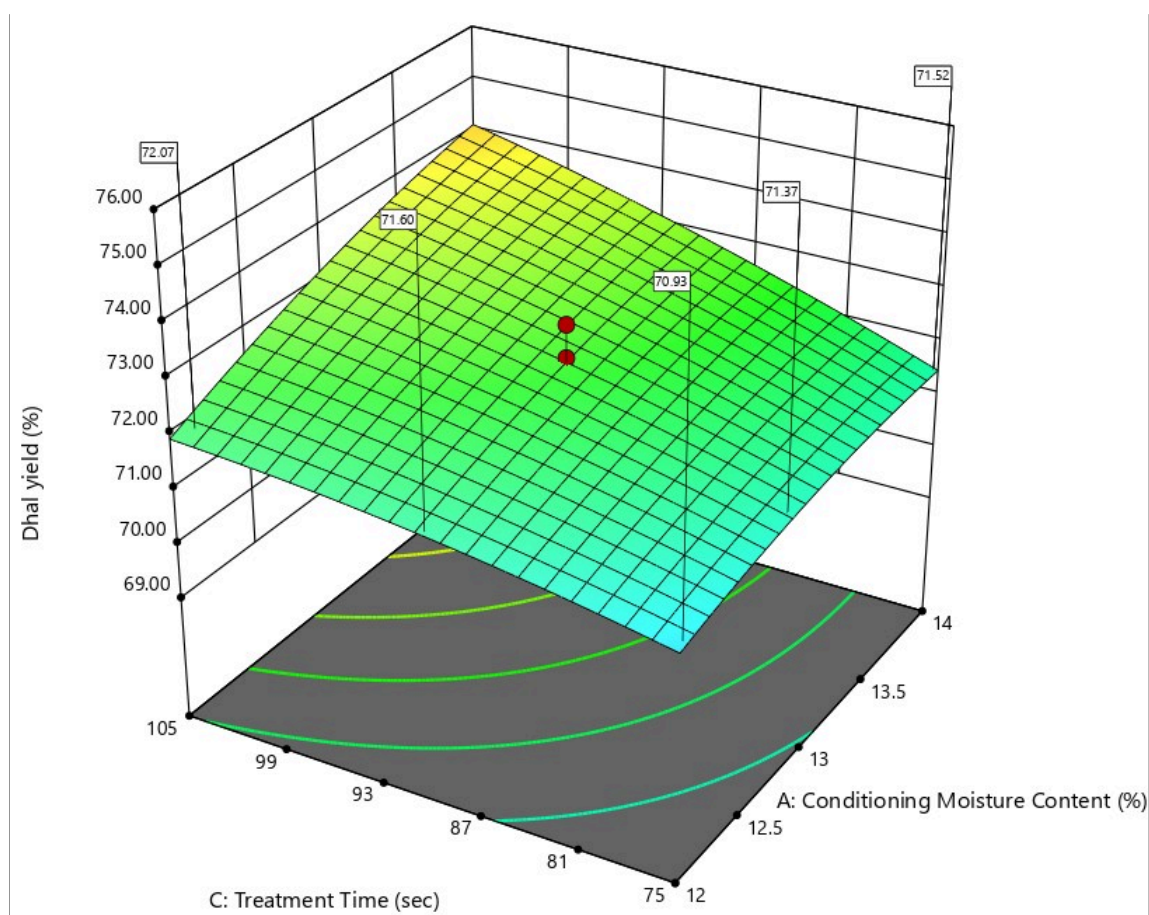


Figure 3. Cumulative effect of Conditioning Moisture Content and Treatment Time on dhal yield of green gram

As per Fig 4, with increase in microwave power level, an improvement in dhal yield from 70.78% to 71.99% was observed, as microwave power level was increased from 70% to 90% MPL. With an

increase in microwave power, more amount of microwave energy might have been imparted onto the sample causing modification in grain structure, thus, resulting in improved hull removal, thus, im

proved dhal recovery. It was also observed from the Fig. 4 observed to improve the dhal yield from 70.78% to 72.61%, as treatment time was increased from 75 to 105 s. Similar to the previous observation, combined effect of increase in microwave power and treatment time might have caused modification in grain structure, resulting in im-

proved hull removal, thus, improved dhal recovery. This agrees with the observation made by Joyner *et al.* (2015) [6] for continuous treatment of black gram, where with an increase in treatment time, improvement in dhal recovery was observed.

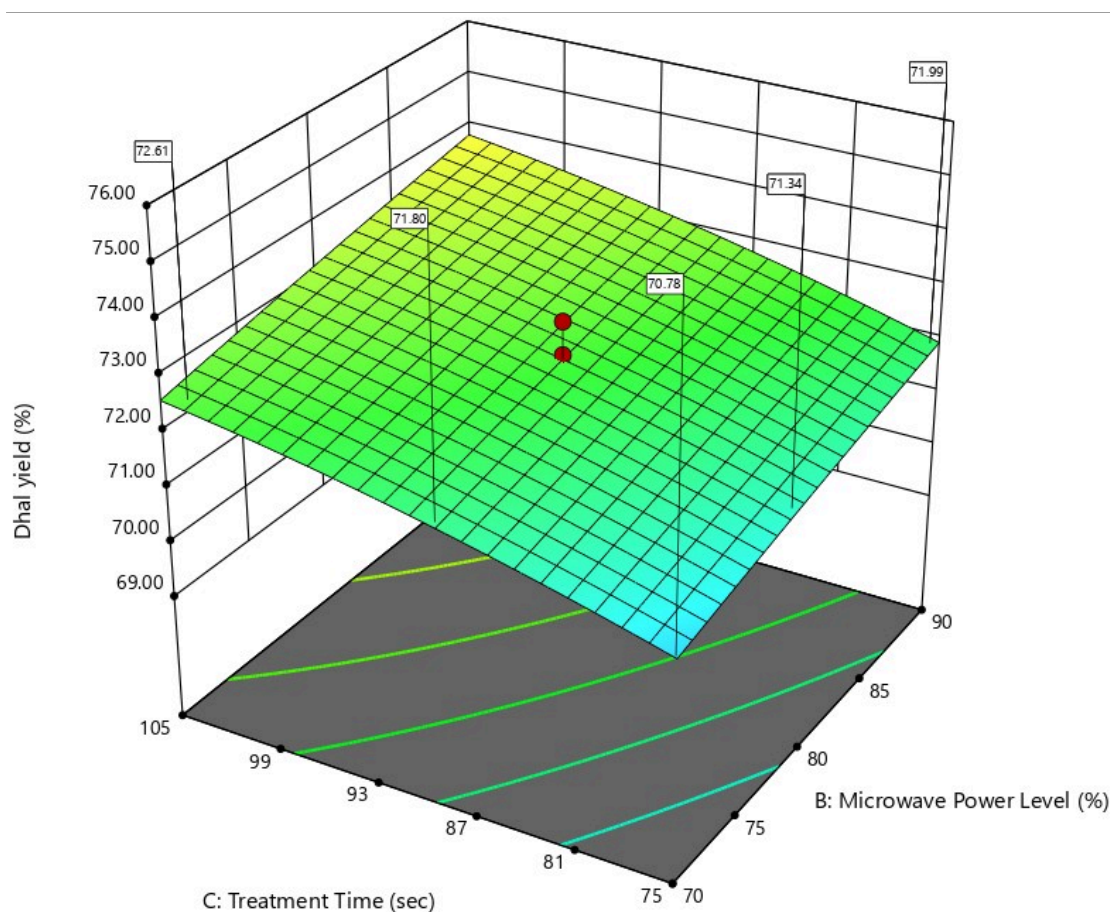


Figure 4. Cumulative effect of Microwave Power Level and Treatment Time on dhal yield of green gram

The model equation in coded factors for dhal yield was:

$$\text{Dhal yield} = 72.4996 + 0.690625A + 0.603125B + 0.929375C + 0.45375AB + 0.38125AC - 0.00125BC - 0.217554A^2 - 0.0363043B^2 - 0.168804C^2 \quad (2)$$

where A = CMC (% w.b.), B = MPL (%) and C = TT (s).

The ANOVA presented in Table 3 showed that the model was significant ($F = 8.64$, $p = 0.0048$) with an R^2 of 0.9173. The linear effects of CMC, MPL and TT were significant ($p < 0.05$), with TT showing the highest effect ($F = 34.35$), followed by CMC ($F = 18.97$) and MPL (F

$= 14.47$). The interaction and quadratic terms were non-significant, while the lack of fit was also non-significant ($F = 0.399$, $p = 0.8238$), indicating adequate model fit. Overall, the results showed that increasing CMC, MPL and TT within the investigated range benefited dhal yield, with treatment time being the most influential variable.

Table 3. Analysis of variance (ANOVA) for dhal yield

Source	Sum of Squares	df	Mean Square	F-value	p-value (Prob > F)
Model	31.29	9	3.48	8.64	0.0048 (significant)
Linear terms					
A – CMC	7.63	1	7.63	18.97	0.0033
B – MPL	5.82	1	5.82	14.47	0.0067
C – TT	13.82	1	13.82	34.35	0.0006
Interaction terms					
AB	1.65	1	1.65	4.09	0.0827
AC	1.16	1	1.16	2.89	0.1329
BC	0.0000	1	0.0000	0.0000	0.9957
Quadratic terms					
A ²	0.9167	1	0.9167	2.28	0.1749
B ²	0.0255	1	0.0255	0.0634	0.8084
C ²	0.5519	1	0.5519	1.37	0.2798

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Source	Sum of Squares	df	Mean Square	F-value	p-value (Prob > F)
Residual	2.82	7	0.4023		
Lack of Fit	1.41	5	0.2813	0.3989	0.8238 (not significant)
Pure Error	1.41	2	0.7050		
Cor Total	34.11	16			

Dehulling loss

The dehulling loss of green gram varied between 7.83% and 11.06% for different combinations of conditioning moisture content (CMC), microwave power level (MPL) and treatment time (TT) as illustrated in Table 1. The minimum dehulling loss (7.83%) was achieved at 15% CMC, 80% MPL and 90 s TT (Run 11), while the maximum dehulling loss (11.06%) was recorded in 12% CMC, 70% MPL and 105 s TT (Run 15). Therefore "the maximum dehulling loss was about 1.41 times higher than the minimum.

It was observed from Fig. 5 that the dehulling loss reduced from about 10.60% to 8.59% with increase in conditioning moisture content over the range of 12% to 14% CMC due to conductance for mi-

crowave treatment. This might be due to water acting as a plasticizer, which lowers grain's brittleness thus minimizing cracking and consequently reduction in fine powder during dehulling. Similar observation was reported by Sunil *et al.* (2018) [3] while working on processing of pulses, where they observed reduction in grain breakage with an increase in moisture content. Dehulling loss only reduced marginally from about 10.60% to 10.09% with an increase in the power level over the range of 70% to 90% MPL as shown in Fig. 5. This can be attributed to the fact that the linear effect of MPL on the dehulling loss was not significant ($F = 0.92$, $p = 0.3695$). Therefore, the power level did not have a considerable effect on the dehulling loss compared to the effect of moisture content.

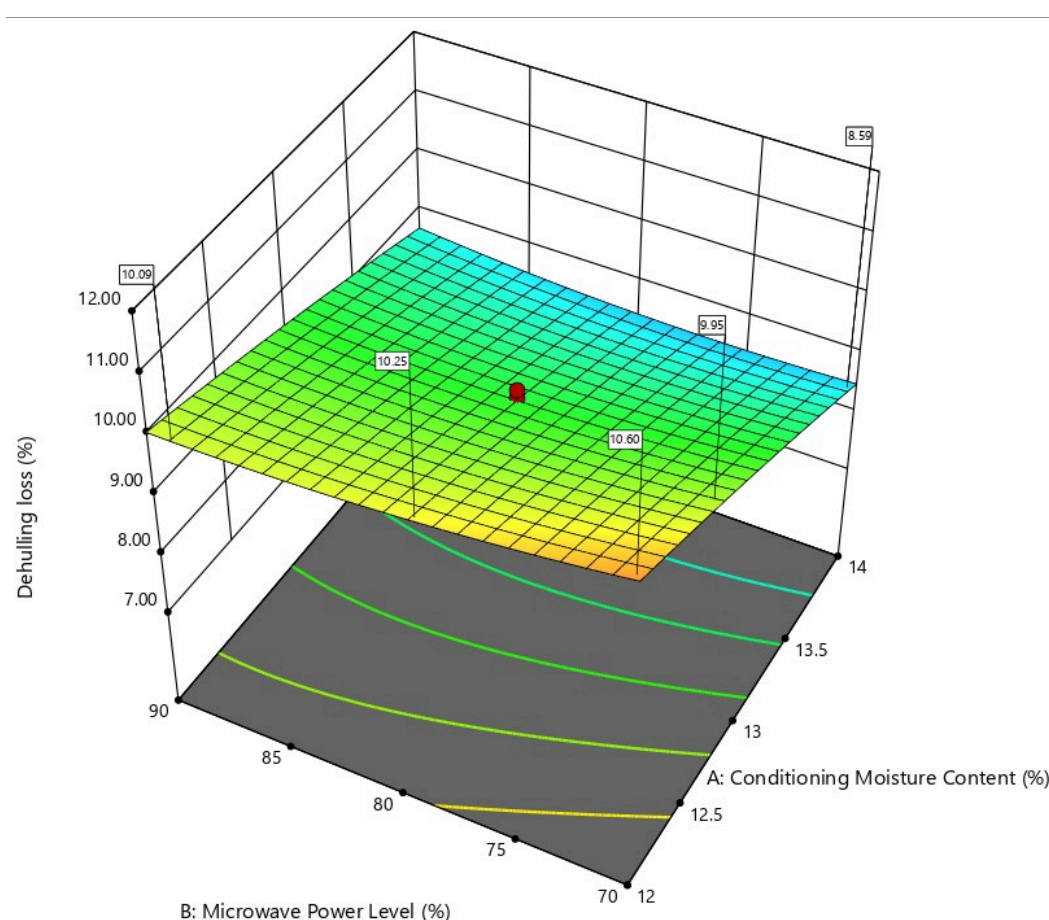


Figure 5. Cumulative effect of Conditioning Moisture Content and Microwave Power Level on dehulling loss of green gram

As observed from Fig. 6, the dehulling loss reduced from about 10.24% to nearly 9.5% as the conditioning moisture content increased from 12% to 14% CMC due to conductance for microwave treatment as discussed earlier. It was also observed that as the treatment time increased from 75 to 105 s, the dehulling loss only changed marginally from about 10.28% to 10.39% as shown in Fig. 6. This suggests that

there was no significant linear effect of TT on the dehulling loss ($F = 0.22$, $p = 0.6555$). From the discussion above, it can be concluded that out of the three variables evaluated, the conditioning moisture content had the highest influence on the dehulling loss of the grains while TT and MPL had a minimal effect.

The model equation in coded factors for dehulling loss was:

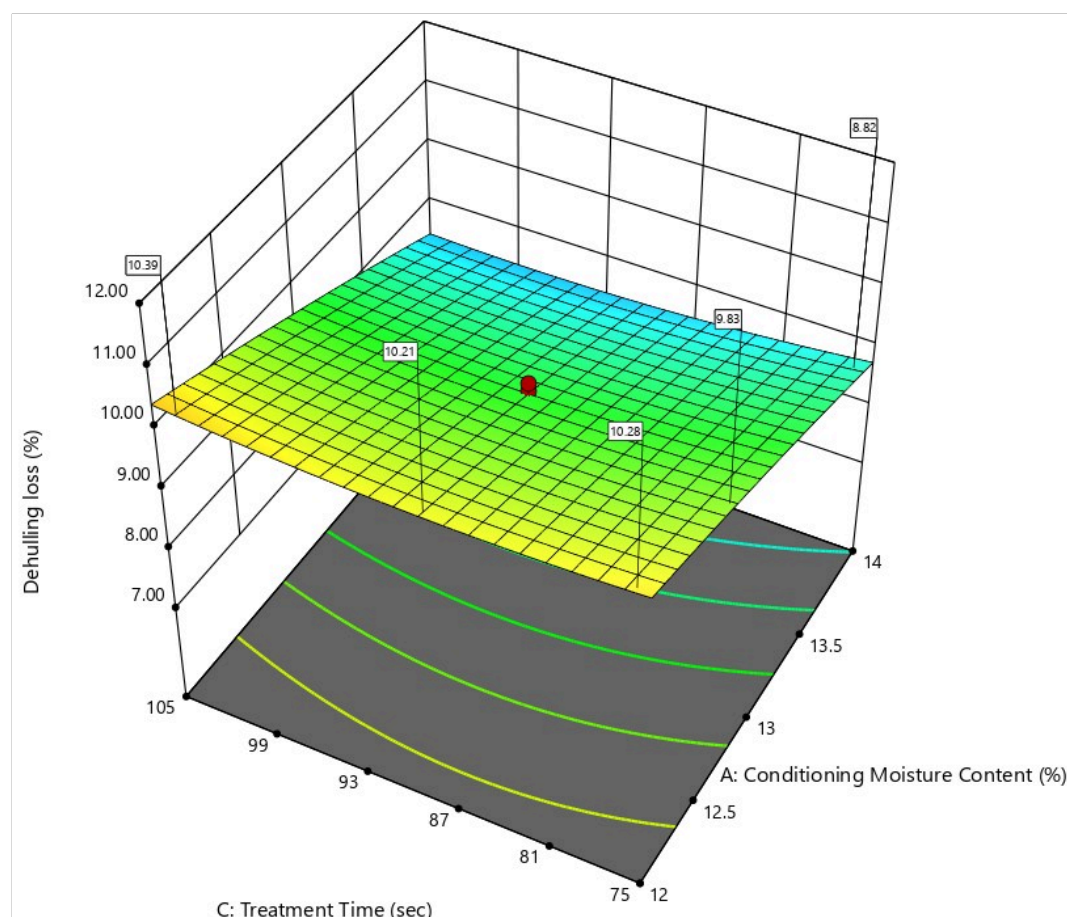


Figure 6. Cumulative effect of Conditioning Moisture Content and Treatment Time on dehulling loss of green gram

$$\text{Dehulling loss} = 9.41609 - 0.8775A - 0.0875B - 0.0425C + 0.19AB - 0.105AC - 0.0475BC - 0.0567391A^2 + 0.139511B^2 + 0.139511C^2 \quad (3)$$

where A = CMC (% w.b.), B = MPL (%) and C = TT (s).

The ANOVA presented in Table 4 showed that the model was significant ($F = 11.56$, $p = 0.0020$) with an R^2 of 0.9372. Among the processing variables, CMC had the greatest influence on dehulling loss ($F = 92.48$, $p < 0.0001$), whereas the linear effects of MPL and TT were non-significant ($p > 0.05$). The interaction and quadratic terms

were also non-significant. The lack of fit was non-significant ($F = 3.85$, $p = 0.2190$), indicating adequate model fit. Overall, the results indicated that increasing CMC within the investigated range reduced dehulling loss, with CMC being the most influential processing variable.

Table 4. Analysis of variance (ANOVA) for dehulling loss

Source	Sum of Squares	df	Mean Square	F-value	p-value (Prob > F)
Model	13.87	9	1.54	11.56	0.0020 (significant)
Linear terms					
A – CMC	12.32	1	12.32	92.48	< 0.0001
B – MPL	0.1225	1	0.1225	0.9195	0.3695
C – TT	0.0289	1	0.0289	0.2169	0.6555
Interaction terms					
AB	0.2888	1	0.2888	2.17	0.1844
AC	0.0882	1	0.0882	0.6620	0.4426
BC	0.0180	1	0.0180	0.1355	0.7237
Quadratic terms					
A^2	0.0624	1	0.0624	0.4680	0.5159
B^2	0.3770	1	0.3770	2.83	0.1364
C^2	0.3770	1	0.3770	2.83	0.1364
Residual	0.9326	7	0.1332		
Lack of Fit	0.8448	5	0.1690	3.85	0.2190 (not significant)
Pure Error	0.0878	2	0.0439		
Cor Total	14.80	16			

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Grain surface temperature

The grain surface temperature of green gram varied between 65.89 and 80.00 °C for different combinations of conditioning moisture content (CMC), microwave power level (MPL) and treatment time (TT) as reported in Table 1. The lowest surface temperature of the grain, 65.89 °C was recorded for 12% CMC, 70% MPL and 75s TT whereas the highest temperature of 80.00 °C was observed for 13% CMC, 100% MPL and 90s TT. Hence, the highest

recorded temperature value was about 1.21 times the lowest recorded temperature value.

It was observed from Fig. 7 that the grain surface temperature increased with an increase in microwave power level and consequently rose from about 68.15 °C at 70% MPL to around 75.28 °C at 90% MPL, suggesting that more microwave energy was being absorbed and consequently converted to thermal energy at higher power levels. The effect of conditioning moisture content on this surface was comparatively less pronounced and not significant ($F = 0.11$, $p = 0.7484$).

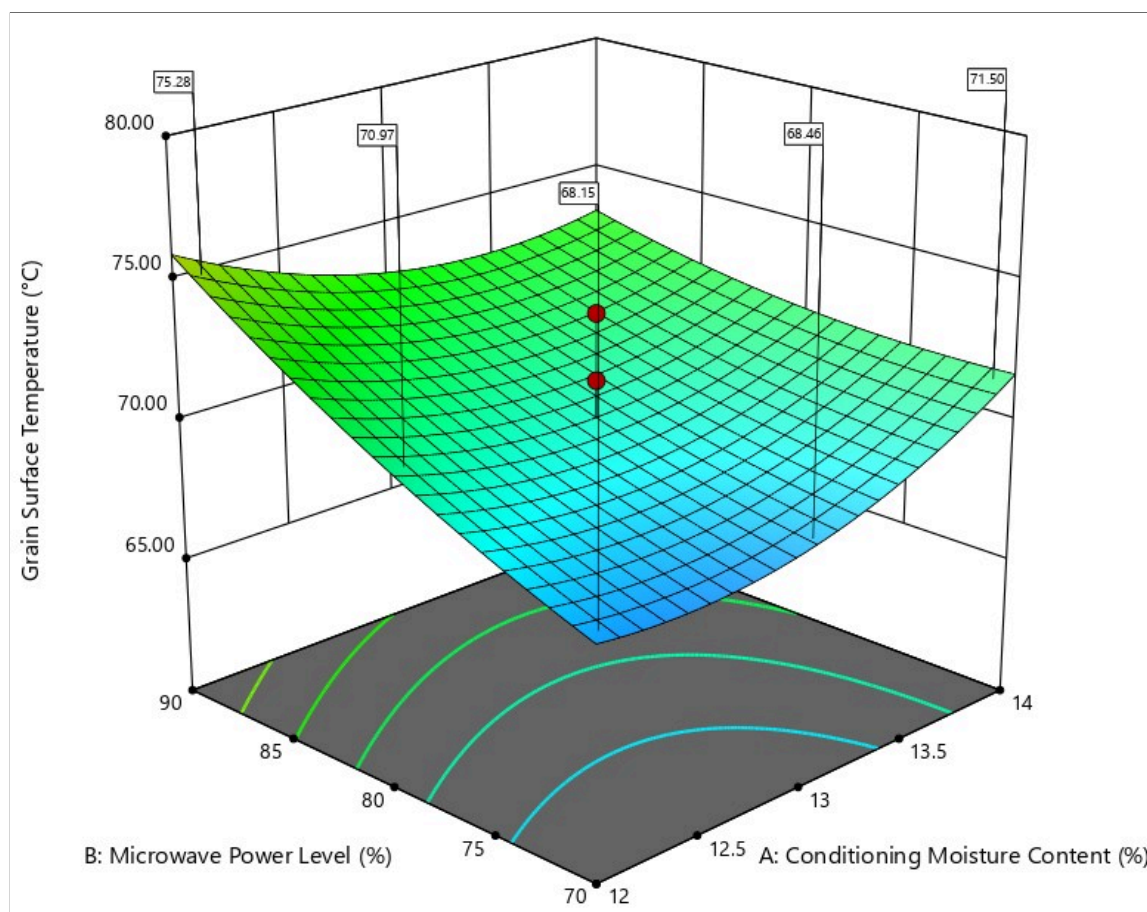


Figure 6. Cumulative effect of Conditioning Moisture Content and Microwave Power Level on grain surface temperature of green gram

It was observed from Fig. 8 that the grain surface temperature showed a distinctly curved response across conditioning moisture content and treatment time, with higher temperatures at the corners of the design space (75.77°C and 74.70°C) and a lower temperature near the central combination (67.06°C). This curvature is indicative of the significant interaction between CMC and TT ($F = 12.01$, $p = 0.0105$), suggesting

that the influence of treatment time on the grain surface temperature depended on the moisture level at which it was applied - rather than a simple additive affect, the two variables jointly determined the amount of thermal energy absorbed by the grain during microwave exposure.

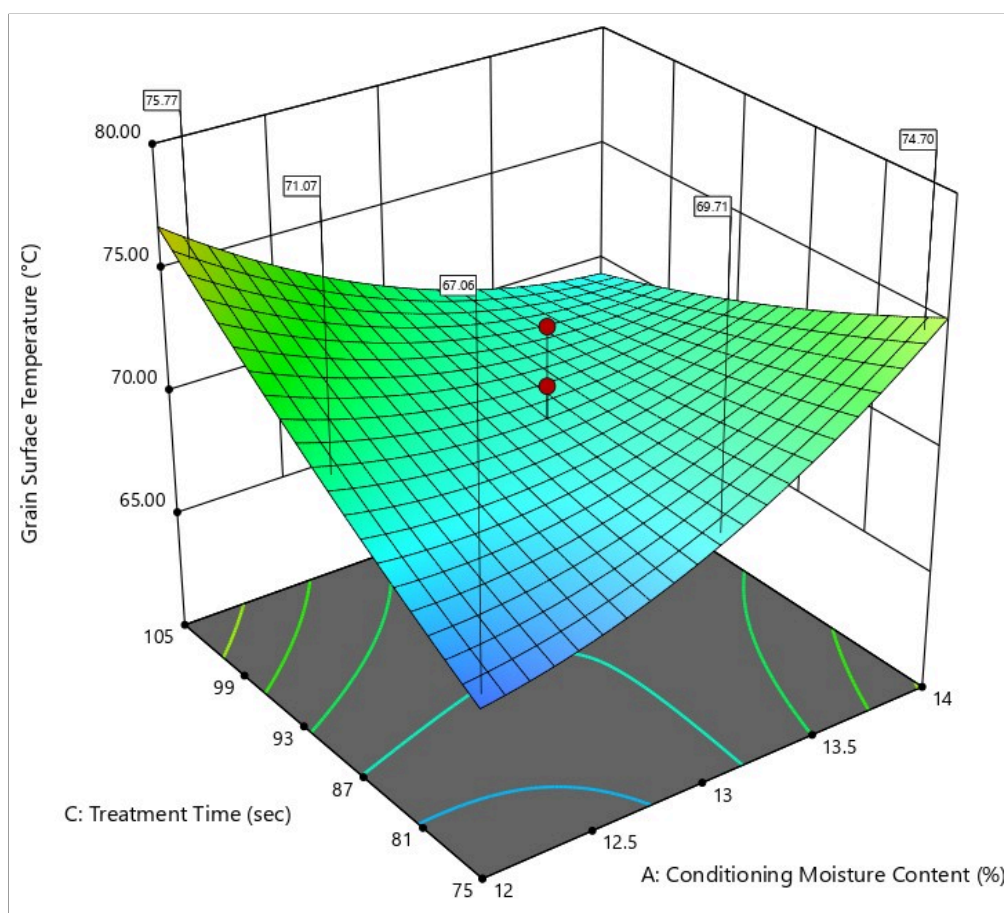


Figure 8. Cumulative effect of Conditioning Moisture Content and Treatment Time on grain surface temperature of green gram

The model equation in coded factors for the grain surface temperature was given as:

$$\text{Grain surface temperature} = 70.1548 + 0.26875A + 2.37625B + 1.0225C - 1.5475AB - 3.9475AC + 1.0525BC + 1.5006A^2 + 0.613098B^2 + 0.426848C^2 \quad (4)$$

Where A = CMC (% w.b.), B = MPL (%) and C = TT (s).

The ANOVA, presented in Table 5, showed that the overall model was not significant ($F = 3.27$, $p = 0.0663$), with an R^2 of 0.8077. Among the linear terms, the effect of MPL on grain surface temperature was significant ($F = 8.70$, $p = 0.0214$), whereas that of CMC and TT were non-significant. The interactive effect of CMC and TT (AC)

was also significant ($F = 12.01$, $p = 0.0105$), indicating that their combined effect influenced the grain surface temperature response. The rest of the interactions and quadratic terms were non-significant. The lack of fit was non-significant ($F = 0.473$, $p = 0.7838$), indicating there was no significant discrepancy between the model and experimental observations.

Table 5. Analysis of variance (ANOVA) for grain surface temperature

Source	Sum of Squares	df	Mean Square	F-value	p-value (Prob > F)
Model	305.27	9	33.92	3.27	0.0663 (not significant)
Linear terms					
A – CMC	1.16	1	1.16	0.1113	0.7484
B – MPL	90.35	1	90.35	8.70	0.0214
C – TT	16.73	1	16.73	1.61	0.2448
Interaction terms					
AB	19.16	1	19.16	1.85	0.2164
AC	124.66	1	124.66	12.01	0.0105
BC	8.86	1	8.86	0.8539	0.3862
Quadratic terms					
A^2	43.61	1	43.61	4.20	0.0795
B^2	7.28	1	7.28	0.7015	0.4300
C^2	3.53	1	3.53	0.3400	0.5781
Residual	72.65	7	10.38		
Lack of Fit	39.37	5	7.87	0.4733	0.7838 (not significant)
Pure Error	33.28	2	16.64		

(continued on next page)

Source	Sum of Squares	df	Mean Square	F-value	p-value (Prob > F)
Cor Total	377.92	16			

Numerical optimization of process parameters

Numerical optimization using Design-Expert software (version 13.0.2) revealed the optimum levels of conditioning moisture content (CMC), microwave power level (MPL) and treatment time (TT) for maximizing dehulling yield (%) and dhal yield (%) with minimum dehulling loss (%) of green gram. The grain surface temperature was excluded from the optimization study as their models were found to be non-significant. The optimum levels predicted by the design expert software were 14% CMC, 90% MPL and 105 s TT with desirability of 88.90%. The predicted values were 77.61% dehulling yield, 75.13% dhal yield, 8.67% dehulling loss.

Conclusion

The present study successfully optimized a continuous microwave pre-milling treater for green gram using response surface methodology based on a central composite rotatable design. Among the three process variables, treatment time exerted the greatest influence on both dehulling yield and dhal yield, followed by conditioning moisture content and microwave power level, while conditioning moisture content was the dominant factor governing dehulling loss. Increasing conditioning moisture content, microwave power level, and treatment time within the investigated range favored dehulling yield and dhal yield, while dehulling loss decreased with increasing moisture content, attributable to its plasticizing effect on the grain, which reduced brittleness and fine powder generation. Grain surface temperature increased primarily with microwave power level and its interaction with treatment time; however, since the overall model for this response was not statistically significant, it was excluded from the numerical optimization. Numerical optimization identified 14% conditioning moisture content, 90% microwave power level, and 105 s treatment time as the optimum combination, yielding a desirability of 88.90% with predicted responses of 77.61% dehulling yield, 75.13% dhal yield, and 8.67% dehulling loss. These findings demonstrate that the developed continuous microwave treater can achieve uniform grain

conditioning and effective hull–cotyledon separation without inducing excessive thermal degradation, offering a scalable, energy-efficient, and automatable alternative to conventional batch pre-milling methods for green gram processing. Future work could extend this optimization across different green gram varieties and assess the treater's long-term economic feasibility at commercial throughput.

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