Optimization of continuous hydrothermal treatment for improving the dehulling of black gram (*Vigna mungo* L)

J. Jerish Joyner¹ · B. K. Yadav¹

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Abstract Black gram kernels with three initial moisture contents (10, 14 & 18 % w.b.) were steam treated in a continuous steaming unit at three inlet steam pressures (2, 3 & 4 kg/cm²) for three grain residence times (2, 4 & 6 min) in order to determine best treatment condition for maximizing the *dhal* yield while limiting the colour change in acceptable range. The *dhal* yield, dehulling loss and the colour difference (Delta E*) of the dehulled *dhal* were found to vary respectively, from 56.4 to 78.8 %, 30.8 to 8.6 % and 2.1 to 9.5 with increased severity of treatment. Optimization was done in order to obtain higher *dhal* yield while limiting the colour difference (Delta E*) within acceptable range i.e. 2.0 to 3.5 using response surface methodology. The best condition was obtained with the samples having 13.1 % initial moisture treated with 4 kg/cm² for about 6 min to achieve a *dhal* yield of 71.2 % and dehulling loss of 15.5 %.

Keywords Black gram · Hydrothermal treatment · Dehulling · *Dhal* yield · Dehulling loss · Colour difference

Research highlights • Hydrothermal treatment (HTT) was studied w.r.t. edible oil method (EDM) for black gram dehulling

- The efficacy of pre-treatment was a function of initial moisture and hydrothermal dosage
- HTT optimized with RSM to maximize yield, minimize loss & colour change (DeltaE*) within 2–3.5
- Optimized HTPPT: grain moisture - 13.1 % (w.b.), steaming at 4 kg/cm² inlet pressure for 6 min
- Optimized case: *dhal* yield-71.2 %, loss-15.5 % compared to 71.0 % yield and 15.9 % loss for EDM

✉ B. K. Yadav
binodkyadav@yahoo.com

¹ Department of Food Packaging and System Development, Indian Institute of Crop Processing Technology, Pudukkottai Road, Thanjavur, Tamilnadu 613005, India

Notations

Delta E*	Total colour difference in CIELAB system
Dt	Relative change in the dehulling time, %
L_d	Dehulling loss, %
Y_d	<i>dhal</i> yield, %

Abbreviations

3D	Three dimension
ANOVA	Analysis of variance
C.V.	Coefficient of variation
GRT	Grain residence time, min
IMC	Initial moisture content, % w.b.
ISP	Inlet steam pressure, kg/cm ²
RSM	Response surface methodology
BSS	British standard screens

Introduction

It is a common practice to subject the black gram to dehulling to remove the hard seed coat which contains antinutrients and imparts a bitter taste, reducing its palatability. The dehulling process also improves appearance, texture, cooking quality and digestibility (Tiwari et al. 2007). Black gram is hard to dehull due to the presence of mucilage and gummy layer between seed coat and endosperm. Therefore, appropriate pre-treatment is essential to improve the milling of black gram. Current commercial process involves pitting and oiling the black gram, which is labour intensive, time consuming, prone to environmental contamination and needs a fair amount of edible oil. In addition, losses in the form of powder and broken grains have lead to lesser yields, which varies from 65 to 70 % in Indian pulse mills (Tiwari et al. 2011). This is far less than the theoretical yield of 87.5 % for black gram (Kurien 1977). Therefore, several methods were developed and proposed to replace the oil treatment method including chemical treatment,

enzyme treatment, soaking treatment etc., to name a few. But these methods have not achieved commercial success due to several drawbacks such as low yield, nutritional inferiority, non-viability of the technique, increased cooking time, batch mode of operation as well as scale-up limitation (Tiwari et al. 2008; Shrivastava et al. 1988; Singh 1995).

Hydrothermal treatment was observed to increase the dehulling efficiency, yield and reduce the powder losses in a batch mode operation tested in the laboratory (Tiwari et al. 2010). On this background, the current study was undertaken with an objective of determining optimum conditions of continuous hydrothermal treatment for maximizing the yields of dehulled black gram.

Materials and methods

Materials

Samples

Black gram of ADT5 variety purchased from the local market was cleaned to remove the extraneous matter and graded in a pulse grader with rectangular slots of dimensions 3×20 mm. First grade grains having size >3 mm were used for study.

Continuous steaming unit

A continuous steaming unit developed at Indian Institute of Crop Processing Technology, Thanjavur was used for continuous hydrothermal treatment of black gram (Fig. 1). The unit involves a horizontal auger mechanism that uses a rotating helical screw within a U-shaped trough, to move the grain. The length, diameter and pitch of the screw were 920, 150 and 150 mm respectively. The top of the trough was tightly closed. The screw was mounted on a hollow shaft of 33 mm diameter. The shaft of the screw was driven by a motor chain and sprockets unit. A variable speed drive was used to vary the rpm of motor in order to vary the grain residence time. Steam was supplied continuously into the chamber of screw conveyor in a parallel flow pattern through galvanized iron pipe of 15 mm diameter. The inlet steam pressure was monitored using a pressure gauge and adjusted by a valve installed at the grain inlet.

Methods

Moisture conditioning

Moisture content was measured by ASAE (2003) and the amount of water needed to mix and temper the grains to the desired moisture content was calculated using Eq. (1), when

Fig. 1 Schematic diagram of continuous steaming unit

the desired moisture content is more than the initial moisture content (AACC 1995).

$$W_w = \left(\frac{100 - M_o}{100 - M_d} - 1 \right) \times W_s \quad (1)$$

Where W_w is the weight of water to add (g), W_s is the weight of the grain sample (g), M_o is the initial moisture content of the grain sample (% w.b.) and M_d is the desired moisture content of the grain sample (% w.b.).

The black gram grains were dried at a constant temperature of 50°C in an electric tray drier (Industrial and laboratory tools corporation, Chennai, India) to obtain the moisture content below the initial moisture content.

Steaming

About 15 kg of black gram sample was loaded in the hopper of the continuous steaming unit preset at a particular inlet steam pressure level and rpm corresponding to desired grain residence time. Once the set conditions stabilized, the feed inlet shutter was opened fully. The steamed grains were collected in a strainer vessel to drain the condensate water. The samples for analysis were collected from the middle. The procedure was repeated for all experiments.

Drying and dehulling

The steamed grains were dried in an electric tray drier (Industrial and laboratory tools corporation, Chennai, India) at 50°C till a final moisture content of 12 % (w.b.) after tempering for about 1 h in ambient condition. The dried samples were packed in air-tight polyethylene bags, tempered in desiccators and stored at room temperature for dehulling experiments.

Dehulling was performed in emery roll polisher (Model: TM05, Satake Corporation, Japan) till complete removal of husk (hull). The different fractions were weighed and graded as head, broken, powder and fine broken. The head is defined as dhal retained on sieve no. 10 (BSS mesh), while the fraction that pass sieve no. 10 and retained on sieve no. 30 (BSS mesh)

is broken and fraction passing sieve no. 30 is graded as fine broken and powder. The dhal yield and dehulling loss were calculated as explained below.

Dhal yield was defined as the yield of dehulled whole and split (*dhal*) as a percentage of the initial weight of pulse used for dehulling (APQ Method 104.1 in BurrIDGE et al. 2001) and expressed by Eq. (2).

$$Y_d = \frac{W_{td}}{W_i} \times 100 \quad (2)$$

Where, Y_d is the *dhal* yield (%), W_{td} is the weight of total dehulled pulse obtained (g) and W_i is the initial weight of pulse (g).

Dehulling loss was defined as the weight fraction of the powder and fine broken relative to the initial weight of the pulse used for dehulling and calculated by Eq. (3) (Goyal et al. 2007).

$$L_d = \frac{W_p + W_f}{W_i} \times 100 \quad (3)$$

Where, L_d is the dehulling loss (%), W_p is the weight of powder obtained (g) and W_f is the weight of fine broken (g).

Control samples

The untreated samples and samples pretreated by oil treatment method were taken as control samples in the study. The oil treatment processing was done as recommended by Kurien (1987). In this method, about 200 g black gram was subjected to polisher to cause 75–80 % pitting of the seed coat and 0.5 % peanut oil was mixed. The mixed samples were sun dried for 2 to 3 days followed by adding and mixing about 2.5 % water and heaped overnight before milling.

Determination of efficacy of the treatment for ease of dehulling

In earlier studies the efficacy of a treatment for ease of dehulling were evaluated by keeping the dehulling time constant for all samples and determining the dehulling efficiency. However, the dehulling time is bound to change for different grains at different moisture content. Hence, in the present study, the efficacy of the treatment in providing an easier dehulling was assessed in terms of the relative change in the dehulling time.

Dehulling time was defined as the duration of dehulling black gram for complete removal of hull (seed coat) from the cotyledons, i.e., 100 % dehulling of the grains. The relative change in the dehulling time is the percentage increase or decrease in the dehulling time of

the pretreated sample as compared to the untreated sample given by Eq. (4).

$$dt = \frac{t_p - t_u}{t_u} \times 100 \quad (4)$$

Where dt is the relative change in the dehulling time (%), t_p is the dehulling time of the pretreated sample (s) and t_u is the dehulling time of the untreated sample (s).

This approach is unique in that this methodology can be used for all grains at different moisture contents.

Colour

Colour was determined by Hunter colour lab colorimeter (Model: Colour Quest XE, USA) in terms of CIELAB L^* , a^* , and b^* values and change in colour due to the hydrothermal treatment as compared to the oil treated sample was determined in terms of Delta E^* , using Eq. (5) (Francis and Clydesdale 1975).

$$\Delta E^* = \left[(L_o^* - L^*)^2 + (a_o^* - a^*)^2 + (b_o^* - b^*)^2 \right]^{1/2} \quad (5)$$

Where Delta E^* is the color difference in comparison to control and suffix o indicate the value for control sample.

It has been reported that a casual viewer can notice a difference between two colours when $\Delta E^* > 2-3.5$, which is an acceptable range. A colour difference of $\Delta E^* > 3.5$ would not be normally accepted, as the colour change is apparent for consumers (Krapfenbauer et al. 2006).

Experimental design

A 3-level factorial design was employed to analyse the experiments using Response Surface Methodology (RSM) performed in Design Expert 8.0.7.1 software. There were three independent variables viz., initial moisture content (IMC), inlet steam pressure (ISP) and grain residence time (GRT). The values of independent variables were coded as shown in Table 1. The design layout of RSM included 32 experiments with five replications at the centre points.

Optimization of the parameters for maximum yield

Numerical optimization was carried out using desirability function in RSM, performed using Design Expert 8.0.7.1 software. The goal was maximising the dhal yield, while keeping colour difference within acceptable range and minimising dehulling loss in order to predict the optimum process condition. Further confirmatory experiments were carried out at the optimized condition to validate the results.

Table 1 Coded levels of independent variables and their values

Independent variable	Symbol	Coded level		
		−1	0	+1
Initial moisture content (% w.b.)	IMC	10	14	18
Inlet steam pressure (kg/cm ²)	ISP	2	3	4
Grain residence time (min)	GRT	2	4	6

Results and discussions

Grain temperature and moisture during hydrothermal treatment

The grain temperature varied from 85.0 to 96.6 °C for samples having IMC of 10 to 18 % (w.b.) and treated with ISP ranging from 2 to 4 kg/cm² for 2 to 6 min. The grain temperature increased with increasing IMC, ISP and GRT in the continuous steaming unit. The increase in grain temperature with increasing IMC might be attributed to the higher thermal conductivity of grains at higher moisture (Tavman and Tavman 1998; Dutta et al. 1988); higher temperature of steam at higher ISP; and the longer exposure time for grains to absorb moisture for higher GRT. It was obvious that all the treatments allowed the grain to attain temperatures above 80 °C, required for denaturation of the gum and mucilage layer between cotyledon and hull. However, the extent of the denaturation varied according on the severity of the hydrothermal treatment.

The moisture content of the grains increased from 13.2 to 46.6 % (w.b.) for samples having IMC of 10 to 18 % (w.b.) when treated with ISP from 2 to 4 kg/cm² for 2 to 6 min. The increase in moisture content with increasing IMC, ISP and GRT might be due to change in the structure of the kernels. The kernels expand with moisture content thereby increasing the porosity and facilitating the higher diffusion of moisture into the grains. Also, condensation of steam into the steaming chamber helped adding moisture to the grains.

Efficacy of the hydrothermal treatment in ease of dehulling

The effects of continuous hydrothermal treatment on various responses are shown in Table 2. The relative change in dehulling time (Dt) of black gram samples with IMC of 10, 14 and 18 % (w.b.) decreased from

−4.98 to −50.25 %, −19.40 to −59.20 % and −56.21 to −76.11 % respectively with steaming at ISP from 2 to 4 kg/cm² for GRT from 2 to 6 min (Fig. 2). The negative sign indicates a decrease in dehulling time of the pretreated sample with increasing severity of hydrothermal treatment. The relative change in dehulling time of the control samples viz., untreated sample and oil pretreated sample were 0 and −76.12 % respectively.

The decreasing trend could be attributed to the increasing temperature and moisture contents of the grains helping in disruption of the bonds of gums and mucilages between the seed coat and the cotyledon. This effect provides ease of dehulling (Dorrel 1968; Kurien 1981; Phirke et al. 1994; Phirke et al. 1996; Sokhansanj and Patil 2003). Also, the grains swell to a bigger size, with increasing moisture and the cotyledons shrink more than the seed coat after drying resulting in loosening of husk enabling easier dehulling. Similar effect was observed by Kurien and Parpia (1968) while preheating pigeon pea with hot air.

Effect of hydrothermal treatment on the dehulling variables

Dhal yield

The *dhal* yield of black gram samples with IMC of 10 % (w.b.) increased from 56.4 to 68.9 % when steamed at an ISP from 2 to 4 kg/cm² for 2 to 6 min. The corresponding values of *dhal* yield for black gram with IMC of 14 and 18 % (w.b.) increased respectively from 62.3 to 73.1 % and 72.6 to 78.8 % under similar conditions. The *dhal* yield increased gradually with increasing levels of hydrothermal treatment with the maximum of 78.8 % observed for samples with an IMC of 18 % (w.b.) subjected to steaming at an ISP of 4 kg/cm² for 6 min (Fig. 3). The *dhal* yield of the control samples viz., untreated sample and oil pretreated sample were 52.3 and 71.0 % respectively.

The increasing *dhal* yield with increasing hydrothermal treatment conditions could be due to the increasing temperature and moisture of grain, as explained in earlier sections. The results are in agreement with the reported studies where heat treatment of soybeans at 93 °C for 15 min by hot air was observed to break the bond between hull and cotyledon (Sokhansanj and Patil 2003; Daniella 2010) and exposure of black gram at a temperature of 92 ± 2 °C for 10–15 min in steam resulted in increased *dhal* yield to a maximum of 70.2 % (Tiwari et al. 2008). The *dhal* yield obtained in the present study was greater than

Table 2 Experimental design matrix showing the observed parameters with different combinations of coded and actual values of IMC, ISP and GRT

Run	IMC (% w.b.)	ISP (kg/cm ²)	GRT (min)	Dt (%)	Dhal yield (%)	Dehulling loss (%)	Delta E*
1	18(+1)	2(-1)	2(-1)	-56.22	72.55	13.85	4.730
2	10(-1)	4(+1)	4(0)	-37.81	63.45	23.10	2.575
3	10(-1)	3(0)	4(0)	-34.83	62.90	23.60	2.167
4	14(0)	3(0)	4(0)	-43.28	65.37	22.13	2.828
5	14(0)	3(0)	4(0)	-41.79	65.23	21.47	2.814
6	10(-1)	3(0)	6(+1)	-48.26	68.30	18.25	2.365
7	14(0)	3(0)	4(0)	-41.79	65.27	21.80	2.821
8	14(0)	4(+1)	6(+1)	-59.20	73.10	13.85	3.488
9	18(+1)	2(-1)	6(+1)	-75.13	78.05	8.70	7.812
10	14(0)	3(0)	4(0)	-41.79	65.30	21.50	2.819
11	10(-1)	3(0)	2(-1)	-6.96	57.60	30.10	2.156
12	14(0)	4(+1)	4(0)	-46.27	68.40	18.25	3.168
13	14(0)	3(0)	4(0)	-43.28	65.33	22.11	2.824
14	18(+1)	4(+1)	6(+1)	-76.12	78.75	8.55	9.495
15	14(0)	2(-1)	2(-1)	-19.40	62.30	24.20	2.259
16	18(+1)	2(-1)	4(0)	-66.17	75.25	11.40	5.958
17	18(+1)	4(+1)	4(0)	-71.64	77.25	9.90	6.690
18	14(0)	3(0)	2(-1)	-21.39	63.10	23.55	2.327
19	14(0)	2(-1)	4(0)	-34.83	66.25	20.65	2.491
20	10(-1)	4(+1)	2(-1)	-10.45	59.90	26.80	2.544
21	18(+1)	4(+1)	2(-1)	-58.21	74.35	12.60	5.513
22	18(+1)	3(0)	4(0)	-70.65	76.85	10.25	6.360
23	10(-1)	4(+1)	6(+1)	-50.25	68.85	17.65	2.686
24	10(-1)	2(-1)	2(-1)	-4.98	56.35	30.75	2.081
25	14(0)	2(-1)	6(+1)	-49.75	70.20	16.65	3.395
26	10(-1)	2(-1)	4(0)	-22.39	59.75	26.95	2.152
27	18(+1)	3(0)	6(+1)	-75.13	78.30	8.50	8.946
28	18(+1)	3(0)	2(-1)	-57.21	73.25	13.65	5.245
29	10(-1)	2(-1)	6(+1)	-33.33	63.05	23.90	2.312
30	14(0)	3(0)	4(0)	-41.79	65.30	21.70	2.821
31	14(0)	4(+1)	2(-1)	-22.89	65.10	21.85	2.390
32	14(0)	3(0)	6(+1)	-57.21	71.55	15.10	3.479
Oil pretreated sample				-76.12	71.30	15.90	0.000
Untreated sample				0.00	52.30	34.2	2.709

the reported value which might be attributed to the uniformity of temperature due to mixing of grains by the screw auger.

Dehulling loss

The dehulling loss of black gram samples with IMC of 10 % (w.b.) decreased from 30.8 to 17.7 % when steamed at an ISP of 2 to 4 kg/cm² for 2 to 6 min. The corresponding figure of dehulling loss of black

gram samples with IMC of 14 and 18 % (w.b.) decreased respectively, from 24.2 to 13.9 % and 13.9 to 8.6 % under similar conditions. The dehulling loss decreased gradually with increasing levels of hydrothermal treatment conditions (Fig. 4). The dehulling loss of the untreated sample and oil pretreated samples were 34.2 and 15.9 % respectively.

The decrease in the dehulling loss with increasing levels of hydrothermal treatment could be attributed to the decreasing dehulling time. This was in agreement with

Fig. 2 Response surface plots for relative change in dehulling time, dt (%) as a function of IMC (% w.b.), ISP (kg/cm^2) and GRT (min) keeping the third variable fixed at “0” level viz., **a** GRT – 4 min, **b** ISP – 3 kg/cm^2 , **c** IMC – 14 % (w.b.)

Fig. 3 Response surface plots for *dhal* yield (%) as a function of IMC (% w.b.), ISP (kg/cm²) and GRT (min) keeping the third variable fixed at “0” level viz., **a** GRT – 4 min, **b** ISP – 3 kg/cm², **c** IMC – 14 % (w.b.)

the results reported by Deshpande et al. (2007) where the percent dehulling loss decreased in conventional dehulling of pigeon pea, with reduction in dehulling time from 45 to 25 s.

Colour

The colour difference of *dhal* of the pre-treated black gram sample having IMC of 10 % (w.b.) with respect to

Fig. 4 Response surface plots for dehulling loss (%) as a function of IMC (% w.b.), ISP (kg/cm²) and GRT (min) keeping the third variable fixed at “0” level viz., **a** GRT – 4 min, **b** ISP – 3 kg/cm², **c** IMC – 14 % (w.b.)

that of the oil treated sample increased from 2.1 to 2.7 with increasing ISP from 2 to 4 kg/cm² and GRT from

2 to 6 min. Corresponding increase in the Delta E* of *dhal* of black gram samples with IMC of 14 and 18 %

Fig. 5 Response surface plots for Delta E* (compared to oil pretreated sample) as a function of IMC (% w.b.), ISP (kg/cm²) and GRT (min) keeping the third variable fixed at “0” level viz., **a** GRT – 4 min, **b** ISP – 3 kg/cm², **c** IMC – 14 % (w.b.)

(w.b.) were respectively from 2.3 to 3.5 and 4.7 to 9.5 under similar conditions (Fig. 5).

The increase in the Delta E* values with increasing levels of hydrothermal treatment could be due to the diffusion of the

pigment from the seed coat into the cotyledon during steaming. It is in line with the previous research report indicated the changes in colour value due the higher temperatures above $92 \pm 2^\circ\text{C}$ (Tiwari et al. 2008).

Optimization of the hydrothermal process variables for dehulling black gram

It was observed that the dehulling parameters were improving with increasing levels of hydrothermal treatment, whereas the colour of the *dhal* was darkening with increasing levels of hydrothermal treatment. Hence, optimum hydrothermal treatment was determined to restrict the colour change (ΔE^*), as compared to that of the commercial oil processing method in the range of 2 to 3.5 while other variables such as dhal yield set to be maximized and dehulling loss and relative change in dehulling time to be minimized keeping IMC, ISP and GRT in the ranges, respectively, 10–18 %, 2–4 kg/cm^2 and 2–6 min. A set of solutions were obtained based on the set criteria. The solution having highest desirability value was selected as optimal with IMC of 13.1 % (w.b.), ISP of 4 kg/cm^2 , and GRT of 6 min for the dehulling of black gram using the continuous hydrothermal treatment technology to yield 71.2 % with loss of 15.5 %. Figure 6 depicts overlay plot showing the optimum region (shaded) obtained by superimposing contour plots of all the responses.

The optimum conditions were validated with the data obtained by independent experiments in triplicates and found that the observed *dhal* yield, dehulling loss and ΔE^* were respectively, $72.1 \pm 11\%$, $14.5 \pm 0.46\%$ and 3.5 ± 0.01 . Thus the experimental values were in close agreement with the predicted optimum values, which confirmed the adequacy of the models developed by RSM.

Fig. 6 Overlay plot showing optimum condition for dehulling black gram

Effect of hydrothermal process on the quality of the black gram dhal

The quality of the dhal produced by recommended hydrothermal process in the study was evaluated in terms of cooking time and batter volume rise. It was found that the cooking time of hydrothermally processed dhal reduced to 11.8 min as compared to 16.7 min for control whereas the batter volume rise reduced to 51 % as compared 70 % in case of control. Though, there was reduction of about 19 % in batter volume rise, the *vada*, a traditional south Indian dish, prepared from the treated black gram was having comparable sensory acceptance as compared to that of the *vada* prepared from commercial dhal sample.

Conclusion

The dehulling parameters of black gram were significantly improved by the continuous hydrothermal treatment. The best values were observed for the samples with IMC of 18 % w.b., subjected to steaming at an ISP of 4 kg/cm^2 for 6 min. However, the colour difference values compared to oil treated *dhal* sample increased abruptly. Using RSM, the optimum hydrothermal treatment condition was estimated to be with an IMC of 13.1 % (w.b.), ISP of 4 kg/cm^2 , and GRT of 6 min. The yield obtained was close to the oil pretreated sample and far better than the untreated sample.

The continuous hydrothermal treatment technology reduces the total processing time and eliminates the application of oil thus saving the non-renewable and scanty natural resource. Also, the moisture content of the black gram commonly available in the market is around 13 % (w.b.). Hence, these grains can be put into processing without need for any pre-conditioning procedures. Thus continuous hydrothermal treatment technology as compared to the current commercial practice of edible oil treatment method ensures ease of operation, saves manpower, drudgery and ensures higher productivity, and can be used as viable treatment method to replace the commercial oil treatment method.

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