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Optimization of extrusion processing conditions for preparation of an instant grain base for use in weaning foods

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Abstract

The purpose of this study was to investigate the effect of process conditions on the properties of instant grain base. A blend of wheat, mungbean and groundnut was used in the study. The effects of feed moisture, barrel temperature and screw speed on product responses viz. specific mechanical energy (SME), expansion ratio (ER), density (D), water absorption index (WAI) and water solubility index (WSI) was studied using response surface methodology.The blend was extruded at different moisture content (12.6 -19.4%), screw speed (349 - 601 rpm) and barrel temperature (116 - 184°C). The regression models for SME, expansion ratio, bulk density, WAI and WSI were highly significant. SME has been found to decrease with increase of moisture and temperature and increased with increase in screw speed. Expansion ratio and density were significantly affected by feed moisture and temperature. WAI and WSIwere found to decrease significantly with increase in moisture content and increased significantly with increase in Screw speed and temperature.The optimum values for moisture content, screw speed and temperature were 14.08%, 521 rpm and 140°C respectively. The desirability was found to be 0.835 for this model.

Keywords: *Weaning, Optimization, Wheat, Mungbean, Groundnut, Extrusion*

1. Introduction:

Weaning is a transition period when the diet changes from breast feeding to the normal family food. During the weaning period (from the age of three months to three years), there is a need for special type of weaning foods. Various food processing techniques are in use for preparation of weaning foods including roasting, germination, milling, baking, cooking, drying and fermentation [1].

Extrusion cooking is a feasible alternative for manufacturing water reconstitutable weaning foods [2-5].It is a modern high temperature-short time process and is being adopted to replace traditional food processing techniques which work at low temperatures and pressures and with long residence times, such as drum dryer, batch cookers, mixers, formers, stirred tank reactors and ovens [6]. The results of extrusion are gelatinization of starch, denaturation of proteins, partial dextrinization of starch, inactivation of many native enzymes, reduction of microbial counts, and improvement in digestibility and biological value of proteins as well as reduction of the activity of some anti-nutritional factors [7].

Generally, weaning foods are made from corn, wheat, rice, sorghum, oats or with combination of legumes and oilseeds. High protein (16.5-18.7%) weaning foods were developed using blends of peanuts, maize and soybean by Plahar et al.[8]. In an another study, Mouquet et al.[7] formulated and extruded several blends of rice, sesame and soybean to provide nutritious instant flour as complementary food for infants and young children. Cereal based traditional foods were fortified with legume protein and extruded to improve their nutritional value and shelf life [9].

In India, wheat is a second major cereal crop after rice with a production of 84.27 million tons in 2010-11. Extrusion cooking of wheat results into moderate expansion but the most of the population is well adapted to the taste of wheat and its products and can be used in the preparation of acceptable instant foods. Legumes are particularly high in protein, mineral, cholesterol-free, high in dietary fibers and low in saturated fat. The production of pulses in India was 17.29 MT during 2010-11. India is the largest producer of mungbean (*Vigna radiata*) and is 3rd most important pulse crop of India [10] which is rich in quality proteins, minerals and vitamins. It is an inseparable ingredient in the diets of vast majority of population in the Indian subcontinent [11]. Combination of wheat and mungbean could be blended with an oilseed to enhance the energy density of the product. Groundnut is an important oilseed crop of India. An effort has been made to optimize the extrusion process for making weaning food base from a combination of wheat, mungbean and groundnut.

II Material and methods

2.1 Sample preparation

Wheat (var.PBW 343), mungbean (SML 668) and groundnut pods (var. SG 99) were procured from Department of Plant breeding, PAU, Ludhiana, India. Wheat and mungbean were ground to pass through 200 µsieve using lab mill (Perten Instruments, Sweden). Roasted groundnuts were decorticated manually and were ground after removing the red skin. Several preliminary experiments were done to select the proportion of wheat, mungbean and groundnut.Composition of the blend and sensory quality was used as criteria for selection of proportion of each food grain.The wheat flour, mungbean flour and groundnut flour were blended in the ratio of 76.5:13.5:10 for 15 minutes to ensure uniform mixing in a ribbon blender (G L Extrusion systems, New Delhi, India). The blended grain flour had 12.66%, moisture, 13.92% protein, 6.6 % fat, 1.87 % fibre, 3.1 % ash and 68.86 % carbohydrates.

2.2 Experimental design

Statistical software Design-Expert 8 (Stat-Ease Inc, Minneapolis, MN, USA) was used to design the experiment. The central composite rotatable design for the three independent variables was performed. The independent variables considered were moisture, screw speed and temperature. Dependent variables were specific mechanical energy (SME), expansion ratio, density, water absorption index (WAI) and water solubility index (WSI). Response surface methodology was used to investigate the effect of extrusion condition on the product responses. The independent variable levels like feed moisture content (12.6-19.4%), screw speed (349-601 rpm) and barrel temperature of the last zone (108-192°C) considered for study were selected on the basis of the results of earlier experiments. The design required 20 experimental runs with eight factorial points, six star corner points and six centre points. Experiments were randomized in order to minimize the systematic bias in observed responses due to extraneous factors.

2.3 Extruder and processing conditions

Extrusion was performed on a co-rotating and intermeshing twin-screw extruder Model BC 21 (Clextral, Firminy, France). The barrel diameter and its length to diameter ratio (L/D) were 2.5 mm and 16:1, respectively. The extruder had 4 barrel zones. Temperature of the first, second and third zone were maintained at 40, 70 and 100^{o}C respectively throughout the experiments, while the temperature at last zone (compression and die section) was varied according to the experimental design. The diameter of die opening was 6mm. the extruder was powered by 8.5 KW motor with speed variable from 0 to 682 rpm. The screw configuration is shown in Table 1 and Fig 1. The extruder was equipped with a torque indicator, which showed percent of torque in proportion to the current drawn by the drive motor. Raw material was metered into the extruder with a single screw volumetric feeder (D.S. and M, Modena, Italy). The extruder was thoroughly calibrated with respect to the combinations of feed rate and screw speed to be used. The feed rate was varied for optimum filling of the extruder barrel corresponding to the screw speed. The moisture content of feed was varied by injecting water (approximately 30^{o} C) into extruder with water pump. A variable speed die face cutter with four bladed knives was used to cut the extrudates.

2.4 Determination of product responses

Specific Mechanical Energy (SME)

Specific mechanical energy(Wh/kg) was calculated from rated screw speed, motor power rating (8.5 KW),actual screw speed, % motor torque and mass flow rate (kg/h) using the following formula [12].

$$SME\left(\frac{Wh}{kg}\right)=\frac{Actualscrewspeed(rpm)}{Ratedscrewspeed(rpm)}x\frac{\%\,motor\ torque}{100}x\frac{motor\ power\,rating}{mass\ flow\ rate\left(\frac{kg}{h}\right)}x1000$$

Expansion ratio

The ratio of the diameter of the extrudate and the diameter of the die was used to express the expansion of the extrudate [13]. The diameter of the extrudate was determined as the mean of random measurements made with a Vernier caliper. The extrudate expansion ratio was calculated as

$$Expansion\ \ Ratio=\frac{Extrudate\ \ Diameter}{Die\ Diameter}$$

Density

Density (g/cc) of extrudates was determined by a volumetric displacement procedure as described by Patil et al. [14]. The volume of the expanded sample was measured by using a 100-mL graduated cylinder by rapeseed displacement. The volume of 20g randomized samples was measured for each test. The ratio of sample weight and the replaced volume in the cylinder was calculated as density (w/v).

Water absorption index (WAI) and water solubility index (WSI)

The water absorption index (WAI) measures the volume occupied by the granule or starch polymer after swelling in excess of water. While water solubility index (WSI) determines the amount of free polysaccharide or polysaccharide release from the granule on addition of excess water. WAI and WSI were determined according to the method developed for cereals [15-17]. The ground extrudates were suspended in water at room temperature for 30 min, gently stirred during this period, and then centrifuged at 3000 g for 15 min. The supernatants were decanted into an evaporating dish of known weight. The WAI was the weight of gel obtained after removal of the supernatant per unit weight of original dry solids. The WSI was the weight of dry solids in the supernatant expressed as a percentage of the original weight of sample.

$$\text{WAI}\left(\frac{g}{g}\right)=\frac{\text{Weight of sediment}}{\text{Weight of dry solids}}$$

$$\text{WSI}(\%)=\frac{\text{Weight of dissolved solid in supernatent}}{\text{Weight of dry solids}}\text{x}100$$

Statistical analysis and optimization

Responses obtained as a result of the proposed experimental design were subjected to regression analysis in order to assess the effects of moisture content, screw speed and temperature. Second order polynomial regression models were established for the dependent variables to fit experimental data for each response using statistical software Design-Expert 8 (Stat-Ease Inc, Minneapolis, MN, USA).

$$y_i = b_0 + \sum_{i=1}^{3} b_i x_i + \sum_{i=1}^{3} b_{ii}\ x_i^2 + \sum_{i=1}^{3}\sum_{i=1}^{3} b_{ij} x_i x_j$$

Where x_i (i=1, 2, 3) are independent variables (Moisture, screw speed and temperature) respectively, and b_o, b_i, b_{ii} and bijare coefficient for intercept, linear quadratic and interactive effects respectively. Data was analyzed by multiple regression analysis and statistical significance of the terms was examined by analysis of variance (ANOVA) for each response. The adequacy of regression model was checked by correlation coefficients. The lack of fit test was used to judge the adequacy of model fit. To aid visualization of variation in responses with respect to processing variables, series of contour plots were drawn. Numerical optimization was performed to obtain minimum density and maximum expansion, WAI and WSI whereas SME was not considered for optimization being a process parameter.

Validation:

Samples were extruded using optimized condition. Predicted and actual value of product response was compared.

3 Results and Discussion

The data on values of physical properties of extruded is presented in table 2. Results of analysis of variance and regression coefficients are shown in table 3 & 4 respectively. The regression models for SME, expansion ratio, bulk density, WAI and WSI were highly significant ($P < 0.0001$), with a high correlation coefficient (R^2 = 0.99, 0.97, 0.95, 0.98 and 0.92 respectively). None of the models showed significant lack of fit ($P > 0.01$), indicating that all the second-order polynomial models correlated well with the measured data. The predicted R-square was found in reasonable agreement with the adjusted R-square for all the parameters. Adequate precision (signal to noise ratio) greater than 4 is desirable. All the parameters showed high adequate precision (Table 3). Results and observations with respect to the relationship of independent variable with individual dependent variable are being presented as follows:

Specific mechanical energy (SME)

The calculated SME ranged from 19.82 to 64.34 Wh/kg (Table 2). Moisture, Screw speed and temperature had significant effects on SME ($P < 0.01$). The negative coefficients of the linear terms of moisture and temperature level indicated that SME decreases with increase of these variables, while positive coefficients for screw speed (Table 4) indicated that SME increases with increase in screw speed. The interactions among moisture and temperature ($P < 0.01$); screw speed and temperature ($P < 0.05$), were found to have significant negative correlation with SME values (Fig 2).

The specific mechanical energy (SME) is used as a system parameter to model extrudate properties. A lubricating effect is produced by high moisture resulting in less energy use and subsequently reduced SME. Increase in screw speed results in higher shear which gives higher SME. Similar results were observed by Ryu and Ng [18] and Altan et al. [19] in wheat, corn and barley extrudates. The starch gelatinization of extrudates has been found to increase with increased SME during extrusion [20]. Higher temperature facilitates the transformation from solid flow to viscoelastic flow and starch gelatinization and reduces the melt viscosity, which resulted in decrease in SME. Similar finding were reported by Dogan and Karwe [21].

Expansion Ratio and density

The expansion ratio of extrudates varied between1.69 and 2.43 g/cm^3 where as density of extrudates varied between 0.335 and 0.665 g/cm^3 (Table 2). The expansion ratio increases significantly with decrease in feed moisture content and increase in screw speed and barrel temperature. However, the effect of the independent variable on density was opposite as that of expansion ratio. The interaction between moisture and screw speed (P

<0.01) had significant negative correlation with the expansion values and densityof the product. However,feed moisture and temperature; screw speed and temperature had a positive correlation with the expansion ratio ($P < 0.05$). Density was significantly affected due to the interactions among moisture and temperature; among screw speed and temperature ($P < 0.01$)(Fig 3).

Feed moisture has been found to be the main factor affecting extrudate density and expansion [22-25] which is consistent with this work. Increased feed moisture leads to a sharp decrease in the expansion of extrudate. The high dependence of bulk density and expansion on feed moisture would reflect its influence on elasticity characteristics of the starch-based material. Increased feed moisture content during extrusion may reduce the elasticity of the dough through plasticization of the melt, resulting in reduced SME and therefore reduced gelatinization, decreasing the expansion and increasing the density of extrudate.

Wheat flour was reported to require high temperature to achieve a significant expansion and reduced density during extrusion cooking [26].The presence of wheat proteins has been shown to have an effect on the expansion of wheat starch. It could be expected that the presence of protein (12.6%) in the wheat flour and fat used in this study would have an influence on the density and expansion observed in the extrudate [27]. Hagenimana et al. [28] showed that increase in moisture increased the bulk density of rice flour based extrudates. It was observed that an increase in screw speed resulted in an extrudate with lower density. Higher screw speeds may be expected to lower melt viscosity of the mix increasing the elasticity of the dough, resulting in a reduction in the density of the extrudate. This effect has been reported previously Fletcher et al.[23]. An increase in the barrel temperature will increase the degree of superheating of water in the extruder encouraging bubble formation and also a decrease in melt viscosity [23] leading to reduced density, which was observed in this work. Similar results have been observed by Lawton et al. [29] and Mercier and Feillet [27].

Water absorption index (WAI)

WAI values for the extrudates ranged between 3.08 and 4.28 g/g (Table 1). All the independent variables had significant effect on WAI ($P < 0.01$). Increasing moisture significantly decreased WAI. However, increase in screw speed and barrel temperature significantly decreased WAI ($P < 0.01$). It is worth to note that starch granules should undergo a certain degree of conversion to initiate water absorption. WAI measures the water holding by the starch after swelling in excess water, which corresponds to the weight of the gel formed. WAI depends on the availability of hydrophilic groups and on the capacity of gel formation of macro molecule [30]. Gelatinization, the conversion of raw starch to a cooked and digestible material by application of water and heat is one of the important effects that extrusion has on the starch component of food. The interactions among independent variables significantly affected the WAI values ($P < 0.01$) except interactions among moisture and Screw speed (Fig 4).

WAI has been generally attributed to the dispersion of starch in excess water, and the dispersion is increased by the degree of starch damage due to gelatinization and extrusion-induced fragmentation, that is, molecular weight reduction of amylase and amylopectin [16]. Water acts as a plasticizer in the extrusion of starch; it reduces degradation resulting in products with a higher capacity of water absorption. The positive coefficients of the linear terms of screw speed and temperature (Table3) indicated that WAI increases with increase of these variables. The increase in water absorption index with screw speed may be attributed to high mechanical shear and higher expansion due to gelatinization. Water absorption index increased with the increase in temperature probably due to increased dextrinization at higher temperature [27, 31].

Water solubility index (WSI)

WSI, often used as an indicator of degradation of molecular components, measures the amount of soluble components released from the starch after extrusion [32]. WSI values for the extrudates ranged between 10.86 and17.73 %(Table 1). The WSI was influenced significantly by moisture, screw speed and temperature ($p < 0.01$). The positive coefficient of the linear term of screw speed and temperature (Table 3) indicated that WSI increases with increase in variables and decreased with increase in moisture. WSI, a measure for starch degradation, means that at lower WSI there is a minor degradation of starch and such conditions lead to less number of soluble molecules in the extrudate [5]. Interactions among feed moisture and temperature had significant positive correlation ($P < 0.01$) (Fig 5).

Results showed WSI had a negative correlation with feed moisture. Higher moisture content in extrusion process can diminish protein denaturation which subsequently lowers WSI values. Badrie and Mellowes [33] and Hernandez-Diaz et al. [5] reported similar findings. Higher WSI of extrudate with increasing screw speed may be related to increasing specific mechanical energy with screw speed. The high mechanical shear caused breakdown of macromolecules to small molecules with higher solubility.The increase in WSI withincreasing screw speed was consistent with the results reported by other researchers [21, 34].Increasing temperature would increase the degree of starch gelatinization that could increase the amount of soluble starch resulting in an increase in WSI. Positive relationship of WSI and temperature was also achieved by Ding et al. [35] in extruded products.

Optimization and validation

Data with respect to predicted and actual values of responses is presented in Table 5. The instant base was then prepared utilized the optimized conditions i.e., 14.08% moisture, 521 rpm screw speed and 140^0 C. variation in the predicted and actual values was found to be less than 5 per cent.

Conclusion:

RSM revealed the significant effect of all three important extrusion parameters (Screw speed, feed moisture and barrel temperature) on physical properties of twin screw extruded instant grain based weaning foods. Within the experimental range, temperature was the most important factor affecting the physical properties of the extrudate.
SME decreased with the increase in feed moisture and bulk density, whereas an increase was observed with an increase in screw speed. Expansion ratio increased with screw speed and temperature whereas density decreased as these factors increased. WAI and WSI values increased with the increase in screw speed and temperature and decreased with the increase in moisture. The interactive effect of feed moisture and temperature were found to be significant on all the dependent variables. However, effect of interaction among feed moisture and screw speed was significant on expansion ratio and density. Effect on interactions among screw speed and temperature was significant on all the variables except WSI.

The optimum values for moisture content, temperature and screw speed were observed as 14.08%, 521rpm and 140°C respectively. It can be thus concluded that blends of wheat, mungbean and groundnut flour could be used as a base to prepare instant weaning foods.

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Table 1: Screw configuration in different sections of the extruder (From hopper to die)

Screw section	1	2	3	4	5	6	7	8	9	10
Screw element	BAGUE	C2F	C2F	C2F	C2F	C2F	INO 0	C1F	CF1C	C1F
Length (mm)	20	50	50	50	50	50	5	50	25	50
Pitch (mm)	-	50	33.33	25	25	16.66	-	16.66	12.5	12.5

Table: 2Effect of extrusion conditions on dependent variables

S. No	**Moisture content (%)**	**Screw speed (rpm)**	**Temp (°C)**	**SME**	**Expansion ratio**	**Density**	**WAI**	**WSI**
1	14	400	125	55.34	2.14	0.451	3.78	15.15
3	18	400	125	37.56	1.83	0.665	3.38	11.53
5	14	550	125	61.18	2.35	0.335	3.63	17.73
7	18	550	125	56.27	1.74	0.443	3.08	13.12
2	14	400	175	54.64	2.05	0.455	3.26	16.52
4	18	400	175	21.21	2.04	0.462	3.33	16.56
6	14	550	175	58.54	2.51	0.556	3.96	17.73
8	18	550	175	19.82	2.08	0.459	3.86	16.49
9	12.6	475	150	64.34	2.43	0.455	3.68	15.12
10	19.4	475	150	21.69	1.69	0.478	3.33	10.86
11	16	349	150	57.32	1.95	0.543	3.47	15.12
12	16	601	150	62.23	2.25	0.449	3.72	17.69
13	16	475	108	55.01	1.92	0.492	3.78	12.83
14	16	475	192	24.61	2.21	0.435	3.91	16.91
15	16	475	150	62.41	2.07	0.495	4.19	14.98
16	16	475	150	62.94	2.22	0.495	4.28	15.44
17	16	475	150	60.02	2.23	0.443	4.27	15.95
18	16	475	150	57.23	2.21	0.456	4.26	15.12
19	16	475	150	63.19	2.19	0.501	4.26	15.13
20	16	475	150	63.57	2.21	0.472	4.26	14.03

Table 3 ANOVA and model statistics for the dependent variables

Term		Response			
Model	SME (Wh/Kg)	Expansion Ratio	Density (g/cc)	WAI (g/g)	WSI (%)
F value	212.45	45.19	23.63	74.85	13.12
P > F	0.0001	0.0001	0.0001	0.0001	0.0001
Mean	42.89	1.69	0.62	3.24	13.18
Standard deviation	1.83	0.043	0.031	0.069	0.63
C V	4.26	2.57	5.02	2.12	4.8
R Square	0.9948	0.9760	0.9551	0.9854	0.9222
Adjusted R square	0.9901	0.9544	0.9147	0.9722	0.8522
Predicted R square	0.9700	0.8815	0.7717	0.9357	0.6828
Adequate precision	43.546	24.695	16.086	31.400	13.100
Lack of fit	0.1945	0.4069	0.3481	0.5659	0.6585

Table 4Regression coefficients for fitted models

Parameter	**SME (Wh/Kg)**	**Expansion Ratio**	**Density (g/cc)**	**WAI (g/g)**	**WSI (%)**
Intercept	61.5959	2.187546	0.477	4.255808	15.08024
Feed Moisture	-12.1967**	-0.190712**	0.0198202**	-0.11486**	-1.2151**
Screw speed	2.586072*	0.0823424**	-0.0291494**	0.0879008**	0.705302**
Temperature	-7.85441**	0.08111109**	-0.00423686	0.0555496**	1.2178223**
Feed Moisture X Screw Speed	0.9475	-0.09**	-0.02625**	-0.04	-0.28375
Feed Moisture X Temperature	-6.1825**	0.06*	-0.0515**	0.115**	0.87875**
Screw Speed X Temperature	-2.755*	0.0475*	0.0545**	0.21**	-0.37875
Feed Moisture X Feed Moisture	-6.79141**	-0.040229*	-	-0.280747**	-0.565314**
Screw Speed X Screw Speed	-0.86585	-0.0260869	-	-0.248928**	0.642071**
Temperature X Temperature	-7.92454**	-0.0384612*	-	-0.160539**	0.099366

*Significant at $P < 0.05$
** Significant at $P < 0.01$

Table 5: Predicted response vs. actual response

Values	Response			
	Expansion Ratio	Density(g/cm^3)	WAI (g/g)	WSI (%)
Predicted	2.40	0.424	4.03	16.52
Actual	2.55	0.412	3.95	17.14
Variation %	0.06	0.0283	0.01	0.0375


Figure 1: Screw Profile

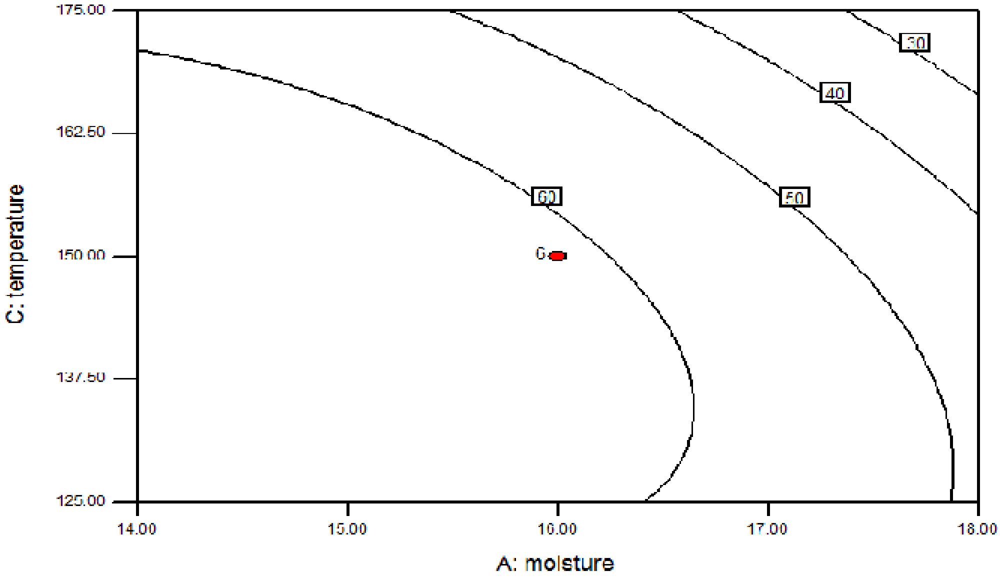

Figure 2: Contour plot showing effect of Temperature and moisture on SME

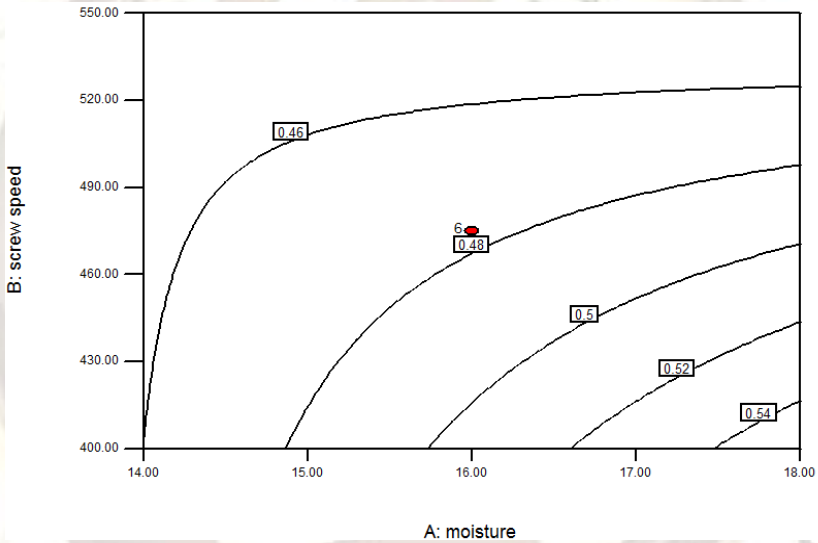

Figure 3: Contour plot showing effect of Screw speed and Temperature on Density

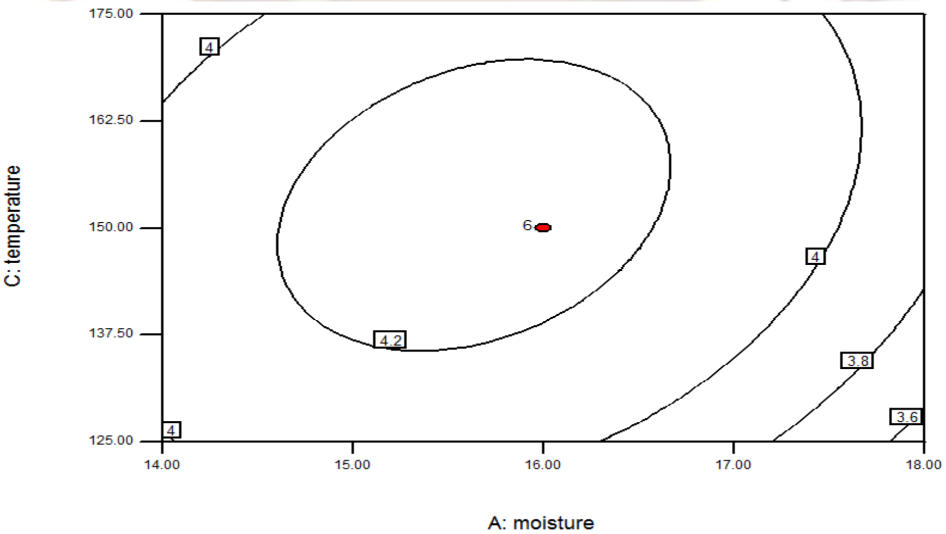

Figure 4: Contour plot showing effect of Screw speed and Temperature on WAI

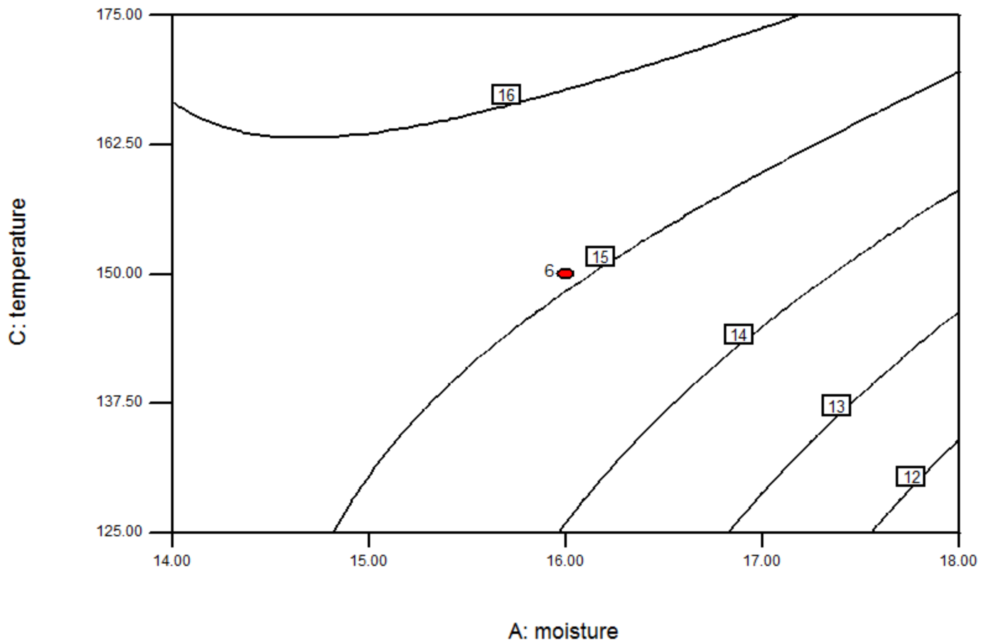

Figure 5: Contour plot showing effect of Temperature and Moisture on WSI