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Expansion ratio of extruded water yam (*Dioscorea alata)* starches using a single screw extruder

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The objective of this study was to develop predictive models that relate extrusion process variables to expansion ratio of five varieties of water yam starch. This was accomplished by varying the feed moisture content (FMC) and extruder parameters which include barrel temperature (BT), screw speed (SS) and determine their effects on resulting expansion ratio using response surface methodology. A single screw extruder (DCE 330, NJ) was used in evaluating the extrudate's physical property, expansion ratio of the starches that were processed using standard wet milling procedure. The expansion ratios of all the extrudates considered in this study ranged from 1.05 to 1.93. It was observed that changing the feed moisture content, barrel temperature and screw speed significantly (P<0.05) affected the expansion ratio of all the extrudates. Increasing the feed moisture content (18 to 28% db) and screw speed (80 to 180 rpm) resulted in a substantial decrease in expansion ratio of all the extrudates except that of TDa 98/01183. The screw speed and feed moisture content were found to be the major process variables showing significant (P<0.05) linear, quadratic and interaction influences on the expansion ratio.

Key words: Water yam, starch, extrusion variables, extrudate, expansion ratio.

INTRODUCTION

Economically, cocoyam and yam starchy tubers play a basic role in the diet of millions of people in areas of Africa, Asia and Oceania (Onwueme, 1999; FAO, 2008). Yams account for 50% of the total world production of tubers and several varieties of yam (*Dioscorea* species) are produced in many developing countries as subsistence food crops (Rodríguez-Miranda et al., 2011). Tropical tubers such as cassava, sweet potato, cocoyam and yam, are generally consumed after boiling, or sometimes after more or less elaborated processing, either home-made or manufactured on various scales. Yams provide, after cassava and cereals, the highest source of dietary energy in Nigeria's food system (Ukpabi et al., 2008; Oke, 2010).

Despite their nutritional and health values, the use and consumption of yam tubers are generally limited by the fact that they are subjected to extensive post harvest losses as a consequence of their high moisture content, sustained metabolism, and microbial attack, leading to damage during harvest and storage (Akinwande et al., 2004; Oluwole, 2008). These problems could be solved by converting the tubers from perishable to non- perishable

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products through food processing operations in order to manufacture new food products such as snack foods. These products have become a part of the feeding habits of the majority of the world population because they provide convenient portions and fulfill short-term hunger (Kuntz, 1996). One of the most important technologies which has shown great potential for the development of new snack products is extrusion cooking.

The application of extrusion technology is one of the most economic processes; being used increasingly in the food industries for the development of new products such as snacks, baby foods, breakfast cereals and modified starch from cereals and tubers (Harper, 1989; Anuonye et al., 2007; Rodríguez-Miranda et al., 2011). Thus, extruded yam products would be of economic assistance to the producing countries. Extrusion of snack foods demands close control of many variables such as feed moisture, feed composition, feed particle size, feed rate, barrel temperature, screw speed, screw configuration, and die geometry. These material and process variables determine the extent of macromolecular transformations during extrusion, which in turn influence the rheological properties of the food melt in the extruder and, consequently, the product characteristics of extrudates.

Extensive studies on extrusion processing of cereals, particularly corn and wheat, to generate ready-to-eat (RTE) breakfast cereals and snacks, have been carried out (Hsieh et al., 1990; Liu et al., 2000; Giri and Bandyopadhyay, 2000; Rampersad et al., 2003; Ding et al., 2005, 2006; Rodríguez-Miranda et al., 2011). A myriad of fabricated, cooked, flavored and shaped products is manufactured from cereals such as corn and wheat using single- and twin-screw extruders. For extruded snacks, one of the most desirable physical properties is the degree of expansion because it determines their structure and consequently their quality. Physical characteristics such as expansion, density, and hardness are important parameters to evaluate the consumer acceptability of the final product (Patil et al., 2007). It has been shown that specific mechanical energy (SME) correlates well with extrudate properties such as expansion, density and texture characteristics (Altan et al., 2008; Dogan and Karwe, 2003; Ilo, et al., 1996; Meuser and Van Lengerich, 1992; Onwulata et al., 2001a).

Expansion of extrudates can vary considerably depending on both processing conditions and feed composition. Starch based materials are preferred as raw materials to enhance the puffing of extruded snacks. Roots and tubers provide high quantity of starch but low nutritional value. Despite this information, fewer yam based extruded products are currently available compared to extruded cereal/grain products especially from corn, wheat and rice (Hsieh et al., 1990; Liu et al., 2000; Giri and Bandyopadhyay, 2000; Rampersad et al., 2003; Ding et al., 2006; Oluwole, 2008; Oke, 2010, Oke et al., 2012). This invariably means that little or nothing has been done on the effects of extrusion variables on the extrusion cooking of water yam starch in order to evaluate their expansion ratio properties. Therefore, the objectives of this work were to investigate the process-sability of starches produced from different varieties of water yam for extrusion process and also to establish the influence of some extrusion cooking variables on expan-sion ratio of the water yam (*D. alata*) starches extrudates.

MATERIALS AND METHODS

Yam specie, *D. alata* of five (5) varieties [TDa 98/01176; TDa 99/01169; TDa 297; TDa 98/01183; and TDa 00/00194] was used for all the experiments. The *D. alata* varieties selected were based on the output of the previous works of Ukpabi et al. (2008) and Baah et al. (2009). The *D. alata* were obtained from experimental plots of the yam breeding programme at the International Institute of Tropical Agriculture (IITA), Ibadan, Nigeria. Twenty five tubers per variety of *D. alata* were selected by simple randomization procedure from bulk of freshly harvested tubers.

Starch extraction

Starch extraction was done by the disruption of yam tissue to expose the starch according to the modified method of Walter et al. (2001). Each yam sample for starch extraction was peeled, cleaned of adhering soil particles. The tubers were later washed and grated to produce yam slurry. The grating was intermittently done to prevent the starch from heating up. The resultant slurry was placed in a muslin cloth and lowered into distilled water (DW) inside a bucket. The cloth was held at the mouth and the contents continuously squeezed to sieve out the starch into the water. The starch was allowed to settle and the supernatant decanted.

Further stirring of the starch with DW, settling of the starch granules and decantation of the supernatant removed soluble impurities. This process was repeated till the supernatant was as clear as the distilled water. The wet starch was spread out on trays and allowed to dry at 45ºC in a cabinet drier till the following day. Final weight of the dried starch was again noted before milling into very fine particle size by a micro mill, and kept in zip-lock bags in closed plastic containers till used for analyses.

The extrusion processes were performed on a single screw extruder (DCE 330, NJ). The screw has three distinct geometrical sections: the feed zone, where the channel depth is constant; the compression zone, where the channel depth changes along the axis; and the metering zone, where the channel depth is again constant but smaller. The temperature in the feed zone was constant (90ºC); barrel temperature at the metering zone ranged between 100 and 150ºC. The moisture content of the feed ranged between 18 and 28% and screw speed between 80 and 180 rpm.

Measurement of expansion ratio (ER)

Expansion ratio was determined using the method described by Conway and Anderson (1973) and Kannadhason et al. (2009). The diameter of the extrudates for each variety was measured with vernier caliper and then divided by the diameter of the die nozzle (5.0 mm) to determine its expansion ratio.

Statistical analysis

Response surface methodology (RSM) was used to build mathematical models that will make it possible to qualitatively interpret and describe the relationships between the extrusion

Table 1. Effect of feed moisture content (FMC), screw speed (SS) and barrel temperature (BT) on the expansion ratio of extruded water yam starches.

FMC (%d.b)	SS (rpm)	BT (°C)	TDa 98/01176	TDa 99/01169	TDa 297	TDa 98/01183	TDa 00/00194
18.00	80.00	100.00	1.67	1.62	1.44	1.49	1.68
18.00	80.00	125.00	1.65	1.61	1.39	1.41	1.67
18.00	80.00	150.00	1.65	1.60	1.36	1.34	1.67
18.00	130.00	100.00	1.76	1.72	1.49	1.58	1.79
18.00	130.00	125.00	1.73	1.69	1.41	1.56	1.73
18.00	130.00	150.00	1.71	1.67	1.35	1.55	1.70
18.00	180.00	100.00	1.80	1.76	1.54	1.70	1.93
18.00	180.00	125.00	1.79	1.75	1.51	1.59	1.87
18.00	180.00	150.00	1.78	1.74	1.50	1.51	1.82
24.00	80.00	100.00	1.55	1.51	1.26	1.28	1.54
24.00	80.00	125.00	1.55	1.51	1.25	1.27	1.49
24.00	80.00	150.00	1.55	1.50	1.25	1.26	1.46
24.00	130.00	100.00	1.58	1.54	1.27	1.28	1.55
24.00	130.00	125.00	1.55	1.51	1.23	1.27	1.53
24.00	130.00	150.00	1.53	1.48	1.18	1.26	1.51
24.00	180.00	100.00	1.62	1.57	1.32	1.34	1.58
24.00	180.00	125.00	1.58	1.53	1.26	1.26	1.56
24.00	180.00	150.00	1.54	1.50	1.19	1.19	1.55
28.00	80.00	100.00	1.35	1.31	1.12	1.06	1.24
28.00	80.00	125.00	1.34	1.30	1.08	1.06	1.19
28.00	80.00	150.00	1.32	1.28	1.05	1.05	1.15
28.00	130.00	100.00	1.46	1.42	1.16	1.14	1.31
28.00	130.00	125.00	1.38	1.34	1.11	1.10	1.18
28.00	130.00	150.00	1.32	1.28	1.06	1.07	1.11
28.00	180.00	100.00	1.49	1.44	1.21	1.21	1.35
28.00	180.00	125.00	1.43	1.39	1.17	1.19	1.34
28.00	180.00	150.00	1.38	1.33	1.14	1.18	1.34

dependent variables selected (expansion ratio) and the extrusion independent parameters/variables (feed moisture content, screw speed rate and barrel temperature). The generalized regression model fitted to the experimental data is given as follows:

$$Y = B_0 + b_1 FMC + b_2 SS + b_3 BT + b_{11} FMC^2 + b_{22} SS^2 + b_{33} BT^2 + b_{12}(FMC * SS) + b_{13}(FMC * BT) + b_{23}(SS * BT) + \varepsilon \quad (1)$$

Where, Y = Objective response, FMC = feed moisture content, SS = screw speed, BT = barrel temperature, ε = random error in which the linear, quadratic and interaction effects were involved.

The Statistical Analysis System (SAS) Version 9.1 (SAS Institute Inc., 2003) was used. The resulting models were tested for significance using analysis of variance (ANOVA) and coefficient of determination (R^2). Significant terms were accepted at $P<0.05$ (Jin et al., 1994). A minimum R^2 of 0.6 was accepted for predictive purposes. The terms that were not significant were deleted from the model equations (Joglekar and Hunt, 2002; Anuonye et al., 2007).

RESULTS AND DISCUSSION

The starch extrudates of all the five (5) varieties of *D. alata* studied are presented in Plates 1 to 5 while their expansion ratio is shown in Table 1. The estimated regression coefficients and analysis of variance (ANOVA) results of the effect of feed moisture content (FMC), screw speed (SS) and barrel temperature (BT) on the expansion ratio for the five (5) varieties were used for the mathematical modeling for the starch extrudates as summarized in Table 2. The expansion ratios of TDa 98/01176, TDa 99/01169, TDa 297, TDa 98/01183 and TDa 00/00194 extrudates ranged from 1.32 to 1.80, 1.28 to 1.76, 1.06 to 1.54, 1.05 to 1.70 and 1.11 to 1.93, respectively. Invariably, all the extrudates considered in this study had expansion ratio which ranged from 1.05 to 1.93. It increased with decrease in moisture content of the feeds. This is due to the fact that low moisture feeds can exhibit more drag and therefore exert more pressure at the die, resulting in greater expansion at the exit of the die than high moisture feeds (Ding et al., 2005; Oluwole, 2008; Rodríguez-Miranda et al., 2011). Moisture is the main plasticizer of cereal flours, which enables them to undergo a glass transition during the extrusion process

18% MC 24% MC 28% MC

Plate 1. The starch extrudates from TDa 98/01176 at different initial moisture contents (MC).

18% MC 24% MC 28% MC

Plate 2. The starch extrudates from TDa 99/01169 at different initial moisture contents (MC).

18% MC 24% MC 28% MC

Plate 3. The starch extrudates from TDa 297 at different initial moisture contents (MC).

18% MC 24% MC 28% MC

Plate 4. The starch extrudates from TDa 98/0118 at different initial moisture contents (MC).

18% MC 24% MC 28% MC

Plate 5. The starch extrudates from TDa 00/00194 at different initial moisture contents (MC).

Table 2. Estimated regression equations, coefficients and coefficient of determination (R^2) for expansion ratio of extruded water yam starches.

Variety	Regression Equation	RMSE	Coefficient	R^2
TDa 98/01176	$Y = 1.5502 - 0.002FMC^2$	0.0287	1.5502	0.980
TDa 99/01169	$Y = 1.5082 - 0.002FMC^2$	0.0287	1.5082	0.980
TDa 297	$Y = 2.7154 - 0.055FMC + 1E\text{-}05SS^2$	0.0299	2.7154	0.966
TDa 98/01183	Y= 2.6295	0.0495	2.6295	0.950
TDa 00/00194	$Y= -0.105 + 0.1644FMC + 0.0095SS - 0.003FMC^2 + 1E\text{-}05SS^2 - 5E\text{-}04FMC*SS - 5E\text{-}04FMC*BT - 8E\text{-}05SS*BT + 4E\text{-}6FMC*SS*BT$	0.0392	-0.105	0.979

RMSE, Root mean square error.

and thus facilitates the deformation of the matrix and its expansion. According to Ilo et al. (1996), an increase in moisture content during extrusion decreases the SME, apparent viscosity, and radial expansion ratio during extrusion of maize grits.

Parsons et al. (1996) reported a decrease in the expansion ratio of cornmeal when the extrusion moisture content was increased from 19.5 to 21.5% (w/w). The reduction of expansion at high moisture content was later confirmed by the findings of Chinnaswamy and Hanna (1990), Garber et al. (1997), Liu et al. (2000), Onwulata et al. (2001b), Onwulata and Konstance (2006). Screw speed generally has a positive effect on extrudate expansion due to the increase in shear, and thus decrease in melt viscosity induced by high screw speeds (Kokini et al., 1992; Ali et al., 1996; Ding et al., 2005; Rodríguez-Miranda et al., 2011). This was confirmed by this study.

In the study of Bhattacharya (1997), screw speeds of 100 to 400 rpm imparted curvilinear effects on the characteristics of rice and green gram extrudates. For that particular formulation, high barrel temperatures combined with low screw speeds were suitable for obtaining expanded products. However, at higher screw speed, radial expansion is expected to reduce while axial expansion increases due to reduced residence time (Hsieh et al., 1990), reduced degree of gelatinization of starch and hence reduce expansion (Chinnaswamy and Hanna, 1988; Padmanabhan and Bhattacharya, 1989; Onwulata and Konstance, 2006; Oluwole, 2008). Other researchers have reported, however, that screw speed had little or no significant effect on expansion ratio: Liu et al. (2000) for extruded oat-corn puff, and Giri and Bandyopadhyay (2000) for fish muscle-rice flour extrudates. Such differences may be explained by significant differences in the extrusion conditions, such as type of extruder, screw configuration, temperature, and composition of the feed.

Regression analysis indicated that barrel temperature as an independent variable had little significant ($P<0.05$) effect (Table 2), and only at the interactions (FMC*BT; SS*BT; FMC*SS*BT) on the expansion ratio of TDa 00/00194 extrudates, while other extrudates did not exhibit significant barrel temperature effect.

From the regression equation, it was observed that the barrel temperature did not have any effects (linear, quadratic and interaction) on TDa 98/01176, TDa 99/01169, TDa 297 and TDa 98/01183 extrudates, whereas it had an interaction effect on TDa 00/00194 extrudates. The feed moisture content had linear (TDa 297; TDa 00/00194), quadratic (TDa 98/01176; TDa 99/01169; TDa 00/00194) and interaction (TDa 00/00194) effects ($P<0.05$) on the expansion ratio. Expansion ratio showed a significant influence of feed moisture content and screw speed in the process whereas no effect of barrel temperature was detected except for TDa 00/00194 extrudates. It should be noted that all the process variables did not have any significant effect ($P<0.05$) on TDa 98/01183 extrudates The analysis of variance, however, showed significant ($P<0.05$) model fitnesses. The response surface and contour plots generated for the expansion ratio of the extrudates with feed moisture content, barrel temperature and screw speed are shown in Figures 1 to 5.

Figures 1 to 5 show the effects of feed moisture content, screw speed and barrel temperature on the expansion ratio of extruded water yam starches of all five varieties considered.

In general, lowering the feed moisture content from 28 to 18% and increasing the screw speed (from 80 to 180 rpm), increased the expansion, while no significant contents (18%), barrel temperatures (100ºC) and highest screw speed (180 rpm), whereas the lowest expansion value (1.05 for TDa 297 and TDa 98/01183) were for the highest moisture contents (28%) and barrel temperatures (150ºC).

The extruded products were softer and crispier after puffing. Sebio and Chang (2004) and Oke et al. (2012) reported maximum expansion ratio for fine yam flour and water yam flours, respectively, at the highest barrel temperature (120 to 150ºC) and the lowest moisture content (8 to 18%). An inverse relationship between barrel temperature and feed moisture content has been previously reported (Sebio and Chang, 2004) Hagenimana et al., 2006; Oluwole, 2008; Oke, 2010). Expansion volume is the primary quality parameter associated with product crispiness, water absorption, water solubility and crunchiness (Onwulata and Konstance, 2002; 2006; Rodríguez-Miranda et al., 2011). Gujska and Khan (1990) and Sebio and Chang (2004) have suggested that the degree of expansion affects the density, fragility and softness of extruded products. Hence, the degree of expansion is an important factor to monitor, especially if the extruded product is to be used as a snack.

At high screw speeds, the increase in expansion was less accentuated. At greater moisture contents, the expansion showed low values, independent of the screw speed variation (Figures 1 to 5). The moisture present in the samples becomes super-heated as it moves through the extruder. This circumstance, combined with the high shearing action of the screw, creates a high pressure build-up in the barrels. As the product emerges, the sudden drop in pressure and temperature causes vaporization of the superheated moisture. The higher the barrel temperature and the slower the speed screw, the greater the vaporization in the product, resulting in an increase in expansion and a loss in moisture. Ali et al. (1996) extruded corn grits with a Brabender single-screw laboratory extruder and found that the overall and radial expansion increased with temperature and screw speed, whereas the axial expansion decreased.

The expansion ratio of starch (or cereals) depends mainly on its degree of gelatinization (Chinnaswamy and Bhattacharya, 1983; Hagenimana et al., 2006; Rodríguez-Miranda et al., 2011) which in turn is determined by temperature, shear rate and moisture content of the feed material (Chinnaswamy and Hanna, 1988; Padmanabhan and Bhattacharya, 1989; Ding et al., 2005; Oluwole, 2008).

Low moisture contents of the starch may restrict the material flow inside the extruder barrel, increasing the shear rate and residence time, which would perhaps increase the degree of starch gelatinization, and thus, the expansion. However, when the moisture content of the starch is too low (below 14% d.b.), it may create very high shear rates and longer residence times, thus increasing the product temperature. Such conditions are known to cause starch degradation and dextrinization (Colonna et al., 1983; Onwulata and Konstance, 2002).

Diverse authors have cited that lower feed moisture contents and barrel temperatures favoured the expansion

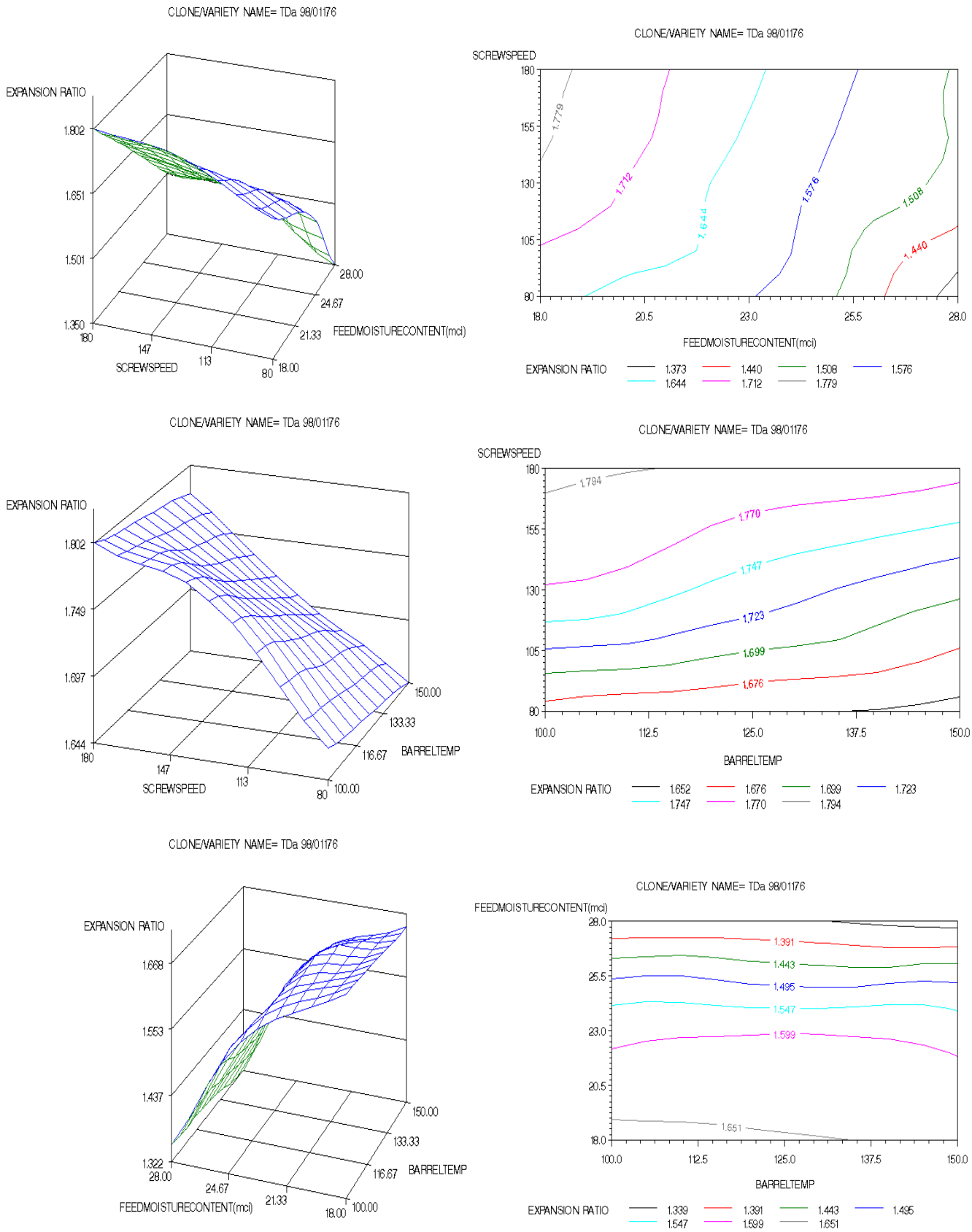

Figure 1. Response surface and contour plots of effect of feed moisture content (%), screw speed (rpm) and barrel temperature (^{o}C) on TDa 98/01176 starch extrudate expansion ratio.

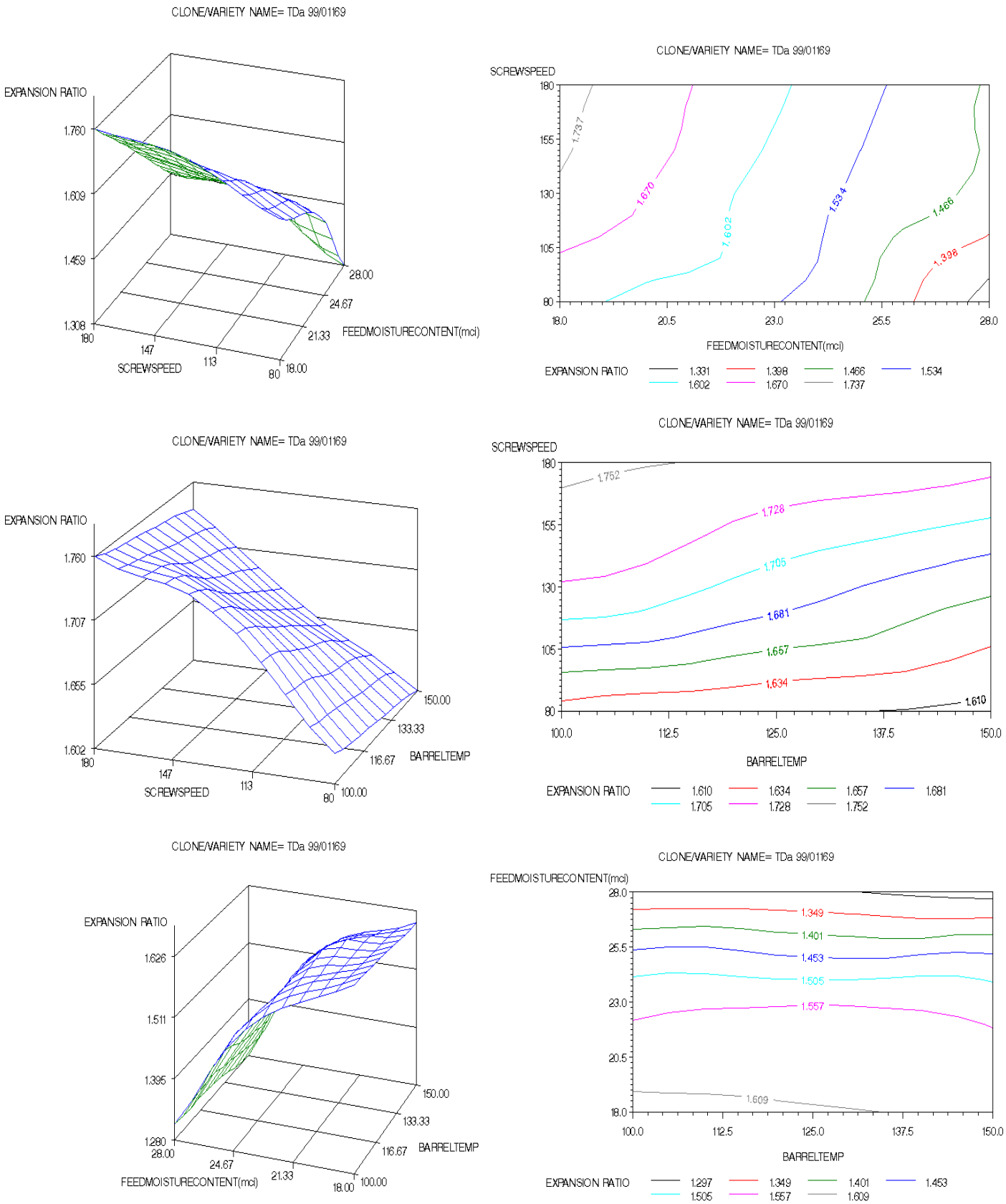

Figure 2. Response surface and contour plots of effect of feed moisture content (%), screw speed (rpm) and barrel temperature (^{o}C) on TDa 99/01169 starch extrudate expansion ratio.

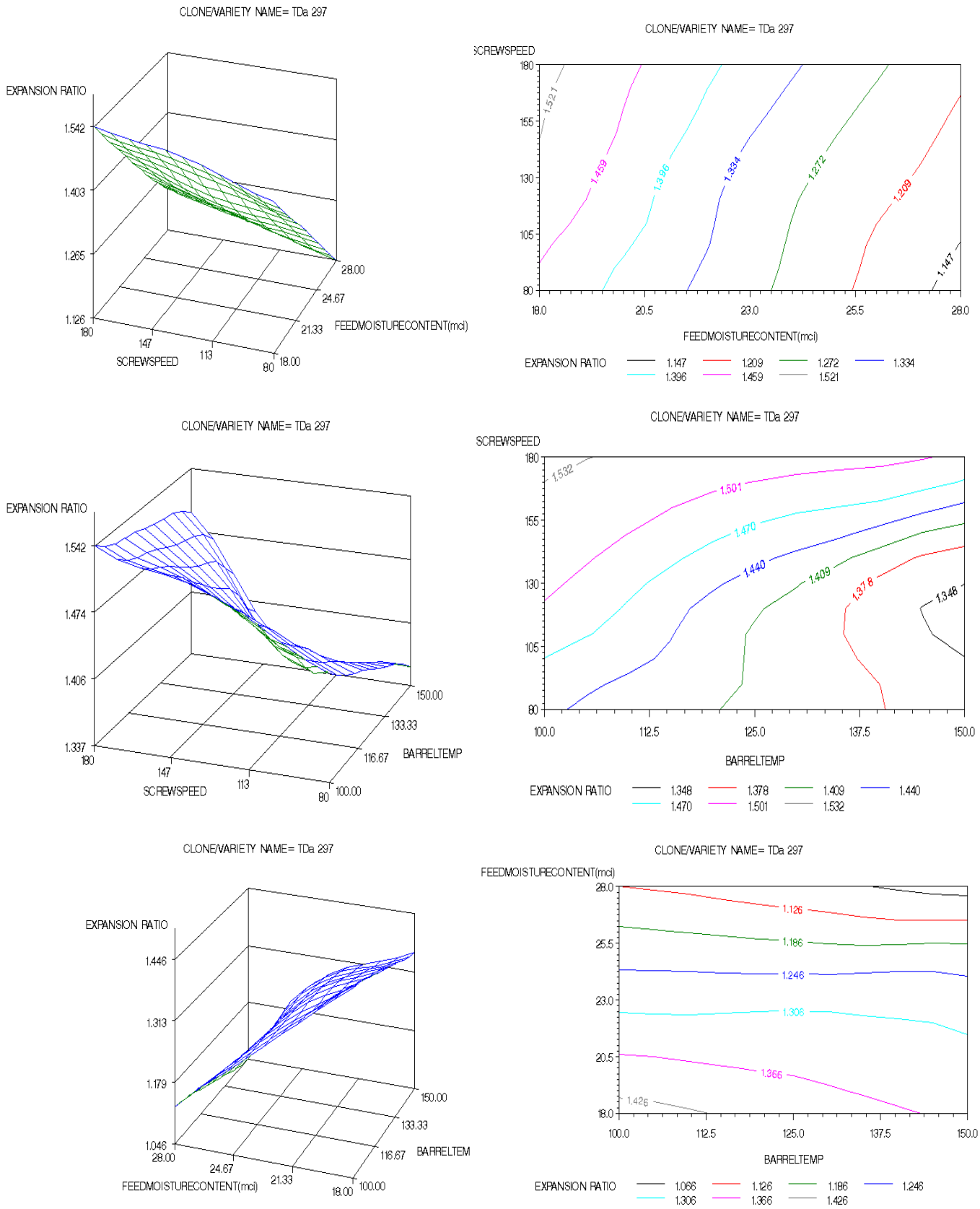

Figure 3. Response surface and contour plots of effect of feed moisture content (%), screw speed (rpm) and barrel temperature (°C) on TDa 297 starch extrudate expansion ratio.

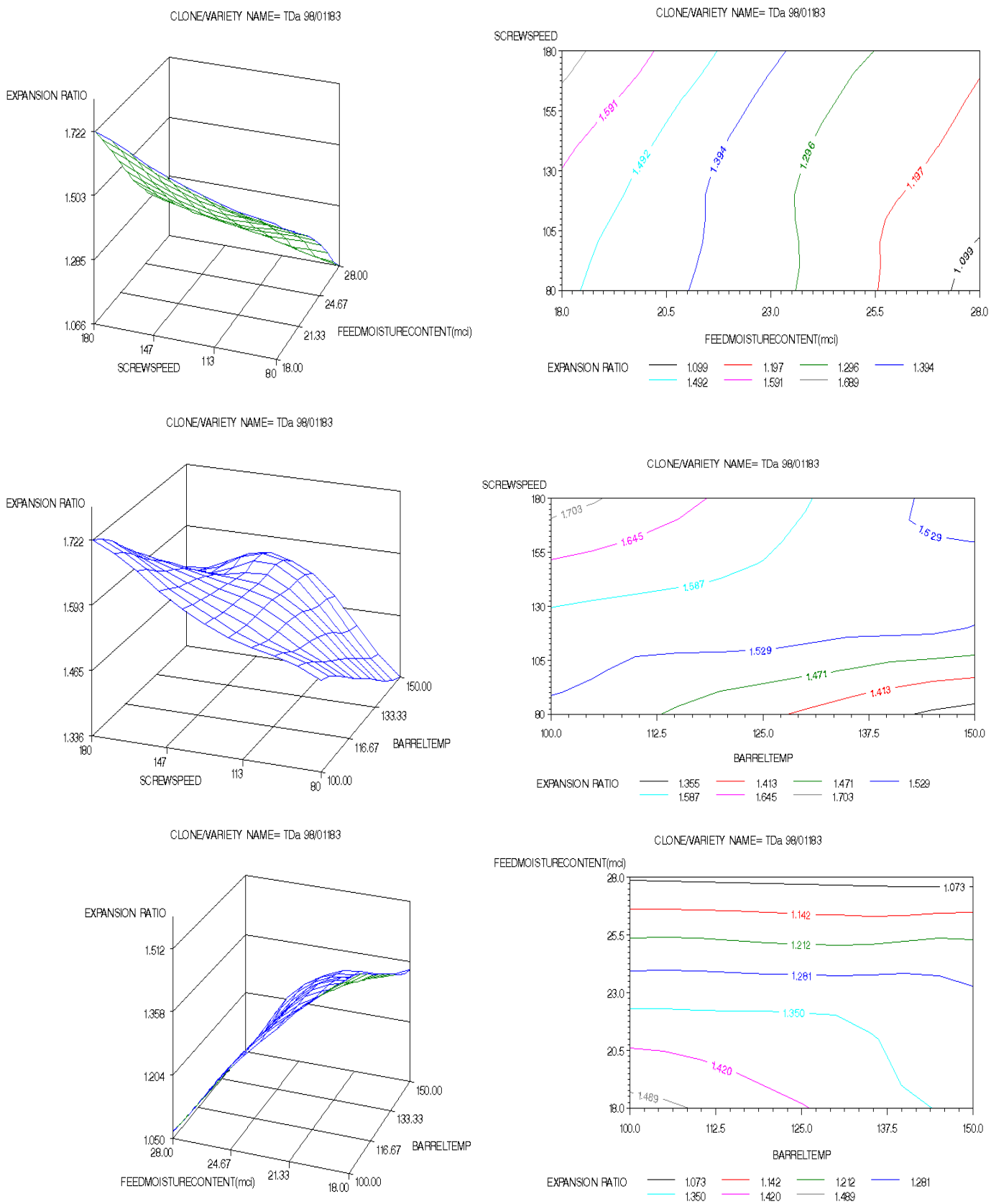

Figure 4. Response surface and contour plots of effect of feed moisture content (%), screw speed (rpm) and barrel temperature (^{o}C) on TDa 98/01183 starch extrudate expansion ratio.

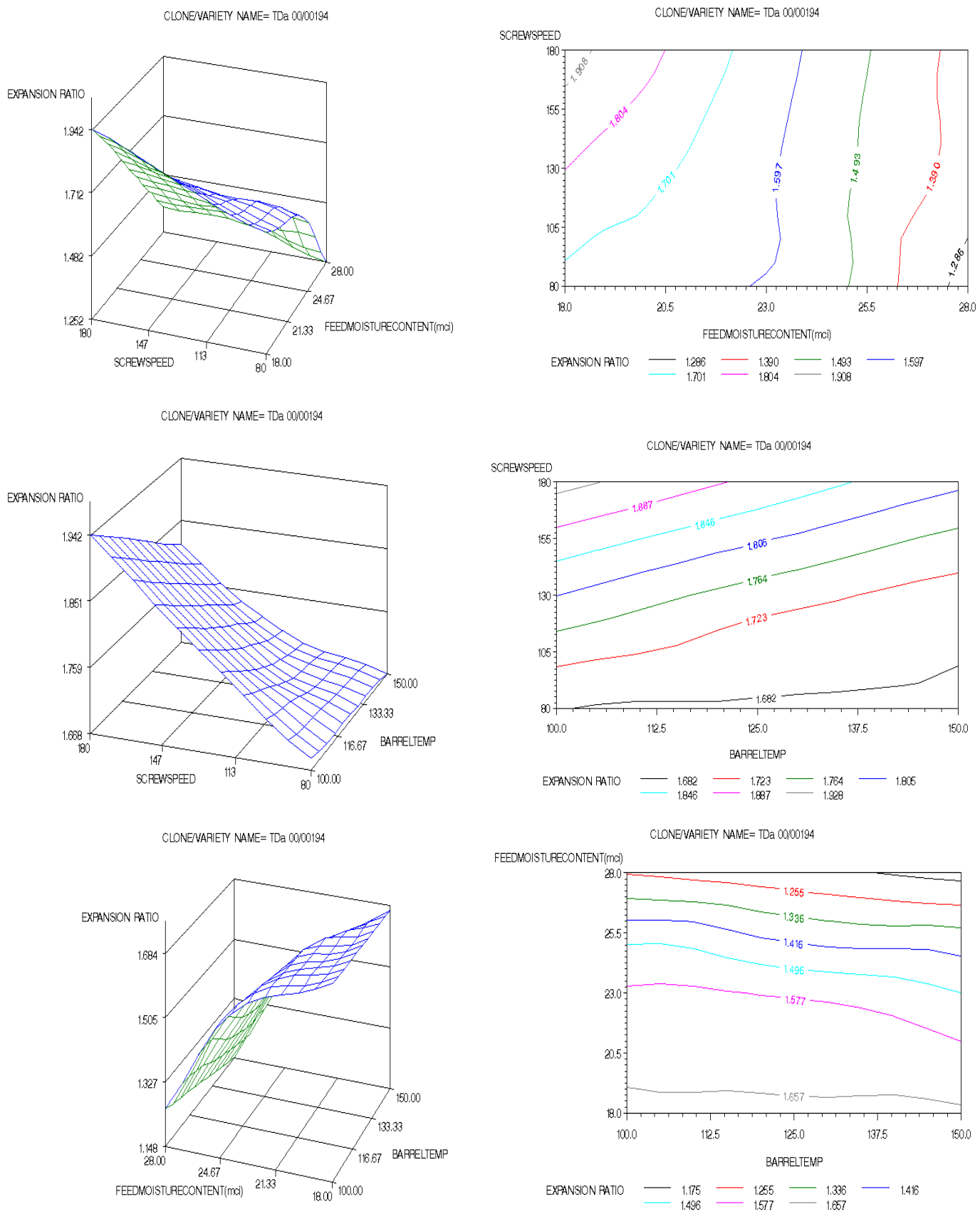

Figure 5. Response surface and contour plots of effect of feed moisture content (%), screw speed (rpm) and barrel temperature (^{o}C) on TDa 00/00194 starch extrudate expansion ratio.

of materials such as corn grits, corn starch (Gomez and Aguilera, 1984; Onwulata and Konstance, 2002; Onwulata and Konstance, 2006; Hagenimana et al., 2006), potato starch (Mercier, 1977) and corn germ flour (Sebio and Chang, 2004; Rodríguez-Miranda et al., 2011). Expansion generally decreases rapidly when the moisture content increases (Guy and Horne, 1988; Ding et al., 2006; Hagenimana et al., 2006; Oke et al., 2012). It was generally observed that changing the feed moisture content, barrel temperature and screw speed significantly ($P<0.05$) affected expansion ratio of all the extrudates studied except the TDa 98/01183 extrudates. Increasing the feed moisture content and screw speed resulted in a substantial decrease in expansion ratio of all the extrudates except that of TDa 98/01183.

Conclusion

Response surface analysis and contour graphs revealed that extruded water yam (*D. alata*) starch product characteristics were related to feed moisture content, barrel temperature and screw speed. The physical properties of the extruded products showed that at lower feed moisture contents and high screw speed, the expansion index was greater. Processing variables and their effect on product quality may be analysed by process models, which establish dependency of extrudate quality on input variables. Due to its high starch content, water yam starch has a great potential as a food ingredient in extruded products and can be successfully used in the preparation of snacks, pre-gelatinized flours and breakfast cereals.

Abbreviations: RTE, Ready-to-eat; **SME,** specific mechanical energy; **DW,** distilled water; **ER,** expansion ratio; **FMC,** feed moisture content; **SS,** screw speed; **BT,** barrel temperature.

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