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Hulled varieties of Barley showed better expansion characteristics compared to hull-less varieties during twin-screw extrusion

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Abstract

Background and Objectives: Consumption of food barley is increasing due its health and nutritional benefits. Whole grain flours of two hulled barley varieties, Lyon and Muir and three hull-less barley varieties, Havener, 09WA-265.12, and Meg's Song were extruded with a co-rotating twin-screw extruder. The impacts of feed moisture, screw speed and die temperature on functional properties of extrudates were investigated.

Findings: Expansion ratio (ER) of barleys were slightly lower compared to the reported numbers for cereals like corn. Hulled varieties showed significantly higher ER compared to the hull-less varieties. Havener was the only hull-less variety having comparable ER with hulled varieties and moderate levels of ß-glucan. ER correlated positively with water solubility index (r = 0.680, P < 0.01), specific mechanical energy (r = 0.633, P < 0.01), and negatively with unit density (r = -0.729, P < 0.01).

Conclusions: Hulled varieties are better suited for extrusion expansion. Feed moisture and die temperature had strong influence on expansion while screw speed showed marginal effects.

Significance and novelty: Understanding the properties of hulled and hull-less barley extrudates will enable process industry to utilize them for development of novel extruded foods, while taking advantage of their nutritional values.

KEYWORDS: hulled barley, hull-less barley, extrusion processing, ß-glucan

1.0 INTRODUCTION

Barley (*Hordeum vulgare* L.) is a cereal grain containing high ß-glucan (dietary fiber), phenolic compounds, and antioxidants proven to be beneficial for human health (Madhujith, Izydorczyk, & Shahidi, 2006). It is a staple food in North Africa, the Middle East, and Northern and Eastern Europe (Newman & Newman, 2006). However, in the rest of the world, barley is used differently. At present, only 2% of world barley production is used for human food (Sharma & Kotari, 2016); while the majority is used for malting and animal feeding . Barley became unpopular for food use because of the difficulty of its husk removal, and absence of gluten protein content, making it less desirable for leavened bakery products (Sullivan, Arendt, & Gallagher, 2013). Further, discoloration of products made from barley has been observed due the presence of polyphenol oxidases (Baik, 2016). The recent endorsement of soluble barley ß-glucan health claims by the Food and Drug Administration (FDA) in the United States (US) for lowering blood cholesterol level, could increase consumer interest in barley food products and incorporation of barley in food product development (Baik & Ullrich, 2008). The search for food barley varieties with enhanced human health qualities is therefore on the rise. Thus, there is an ever increasing need to understand their processing characteristics for their effective utilization in the development of food products.

Barley grains differ in composition leading to their different processing properties and end-use applications. Barley is classified in one way as either hulled or hull-less depending on the type of husk surrounding the grain perisperm. Hull-less barley is sometimes referred to as naked barley and defined by the existence of a thin hull tightly adhering to the to the grain perisperm (Baik & Ullrich, 2008) while the hulled type has a fibrous husk. Honců et al., (2016) reported that hull-less barley is a good source of fiber in contrast to hulled barley varieties. It has also been demonstrated that amylose-free hull-less barley may have some unique food and industrial applications including low pasting properties, high paste clarity and increased freeze-thaw stability(Zheng, Han, & Bhatty, 1998).

Cereals such as wheat, maize, and rice have been processed using extrusion cooking. The process imparts desirable textural and sensory qualities to the products. Other cereals such as oats, rye, and buckwheat are primarily used to improve flavor or as functional characterizers or nutritional enrichment to extrudates due to their bioactive components useful for human nutrition (Mościcki & Wójtowicz, 2011). Extrusion processing is a continuous cooking and shaping process designed to produce food products with unique physical and chemical characteristics (Gu, Kowalski, and Ganjyal, 2017; Kowalski, Morris, and Ganjyal, 2015). It has many advantages including high productivity, versatility, retention of nutrients due to short residence time, high quality, and the ability to make products with unique shapes and forms (Gaosong & Vasanthan, 2000). Some of the operating parameters that can be varied in extrusion processing include screw speed, barrel temperature, and die geometry. These variables can alter important extrusion system response parameters such as mechanical and thermal energy input (Godavarti & Karwe, 1997; Kowalski et al., 2015), and in turn affect the functional properties of final products. Sensory quality of extruded products is dependent on the structure and texture which is highly correlated to the expansion during extrusion. This makes expansion of extrudates a very important quality parameter of interest for direct expanded snack industries (Alvarez-Martinez, Kondury, & Harper, 1988).

Literature review on barley extrusion processing (Table 1) show that majority of researchers studied hulled or hull-less varieties separately; though in a few cases both types were studied, Altan et al., 2009, , Huth et al., 2000). Some these studies do not mention the type of hulled varieties in their reports. There are additional reports that involve whole flours of hull-less and hulled barley (Altan et al., 2009; Köksel, Ryu, Başman, Demiralp, & Ng, 2004), however the focus was not on extrusion direct expansion characteristics.

Presently, little knowledge exists that directly compare processing of hulled and hull-less barley by extrusion and particularly, with whole grain flours. Barley whole flours possess soluble dietary fiber components such as ß-glucan, which is reported to offer beneficial impacts on human health; for example reducing coronary heart disease risk, blood glucose, and cholesterol (Chau, Chen, & Lee, 2004). Flours with high fiber and lipids have been found to reduce expansion of products during extrusion (Wang et al., 2017). To increase our understanding on the extrusion of whole hulled and hull-less barley flours, five varieties comprising hulled and hull-less barleys were evaluated. The main objective of this study was to understand the extrusion characteristics of whole flours derived from select hull-less and hulled barley. Results of this study could be useful for barley varietal selection as well as for the food industry in developing products with nutritious whole barley flours.

2.0 MATERIALS AND METHODS

2.1 Materials

Five barley varieties were acquired from the Sustainable Seed Systems Lab at Washington State University, Pullman, WA (Murphy, Ullrich, Wood, Matanguihan, Guy, et al., 2015; Murphy, Ullrich, Wood, Matanguihan, Jitkov, et al., 2015). They included three hull-less varieties (Havener – designated as HL1, 09WA-265.12 as HL2 and Meg’s Song as HL3) and two hulled (Lyon designated H1 and Muir as H2) varieties. These were developed by breeders to serve as food types, and have superior agronomic qualities, such as high yield compared to existing barley varieties grown by farmers. The samples were cleaned to remove foreign materials and milled into flour through a 2 mm screen using a hammer mill (Model # BSC-DF-15, Yiwu, China) followed by a UDY cyclone milling (Model # 3010-030, UDY Corp., Fort Collins, Colo., U.S.A.) using a 0.5 mm screen.

2.2 Chemical composition of raw materials

2.2.1 Proximate Analysis

Proximate analysis of the barley flours was determined using AACC approved standard methods (AACC International, 2012) with all measurements performed in triplicate. Moisture (AACC 44-15.02) and ash (AACC 08-01.01a) were analysed by a thermogravimetric analyzer (TGA-601, Leco Corporation, St. Joseph, MI, USA). Crude protein was determined with a nitrogen analyzer (FP-528, Leco Corporation, St. Joseph, MI, USA) following AACC method 46-30.01 with the nitrogen conversion factor of 6.25. Crude fat was analyzed with Soxhlet apparatus utilizing petroleum ether as solvent following AACC method 30-25.01.

Crude fiber content was determined with an Ankom 2000 fiber analyzer (Ankom Technology, NY, USA), based on AOCS approved method Ba 6a-05 (AOCS, 1996). 0.95-1.00 g of flour milled through a 2 mm screen was weighed into filter bags and sealed with a heat sealer. Two blank bags were added to determine blank bag correction. The filter bags were placed in a 250 ml beaker containing copious volume of petroleum ether for 10 min to extract fat. The bags were drained and placed into the vessel of the machine with the bag suspender, while putting the bag suspender weight on top, to keep the bags suspended. Bags were digested with 2 L of 0.255 N H_2SO_4 with heating and agitation for 40 min. The vessel was then drained and rinsed with 2 L of distilled water at 50-90^{o}C for 5 min with agitation. The process of digestion was repeated with 2 L of 0.313 N NaOH and rinsed with 2 L of distilled water at 50-90^{o}C for 5 min. The bags were removed and drained by gently pressing out excess water and immersed in acetone for a duration of 5 min. The bags were placed on a wire screen to dry. Complete drying was achieved with an oven (VWR Symphony Air Flow Oven model # 414004-568, VWR International, LLC, NJ, USA) at 102^{o}C for 4 hr. The filter bags were immediately placed in a desiccator to cool to ambient temperature. Ashing of filter bags was done by placing bags in pre-weighed crucibles and heated to 600 ± 15^{o}C for 2 h using a furnace (Sybron Thermolyne model # 6020-12325, Dubuque, Iowa, USA). The crucibles were placed in a desiccator to cool and weighed to find the loss of organic matter. Percentage crude fiber was calculated as:

$$\%\, Crude\ fiber = \frac{100\big(w3 - (w1xc1)\big)}{w2}$$

Where *w1* is bag tare weight, *w2* is sample weight, *w3* is weight of organic matter and *c1* is the ash corrected blank bag. All samples were tested in triplicates.

2.2.2 Amylose

The amylose content of the barley flour was determined using an Amylose/Amylopectin Assay Kit (K-AMYL 06/17, Megazyme International Ltd, Bray, Ireland). The method involves specific precipitation of amylopectin using concanavalin A-lectin as described by Gibson, Solah, & McCleary, (1997)

2.2.3 Extractable ß-glucan

Extraction and quantification of ß-glucan in barley flour was conducted using a modified method described by Temelli, (1997). 50 g of flour was suspended in 500 ml of distilled water and pH was adjusted to 7.0, using 20% w/v sodium carbonate. Water bath used for heating was (VWR International LLC, Radnor, PA, USA) while centrifugation was done with a Beckman J2-HS, (Palo Alto, CA, USA). Filtration was carried out with Whatman # 1 paper. Extractable ß-glucan was reported as a percentage of initial weight of flour. All measurements were conducted in triplicate.

2.3 Pasting properties of barley flours

Pasting properties were determined using Brabender Micro Visco-Amylo-Graph (Model # 803221-050096 Brabender, S. Hackensack, NJ, USA), following the AACCI method 76-21.01. 10 g of barley samples and 100 ml distilled water was mixed in a cup to form a slurry. The slurries were swirled to mix well and heated, following a 23-min temperature profile using a constant bowl rotation speed of 250 rpm. Samples were heated from 50°C to 95°C at the rate of 6°C/min then kept at 95°C for 5 min. Samples were cooled down to 50°C and held for another 2 min. The peak and final viscosities were determined from the curves generated. All measurements were conducted in triplicates.

2.4 Sample preparation and extrusion processing

Prior to extrusion cooking, moisture content of flours was adjusted to the desired levels using a Hobart mixer (Model A-200, The Hobart MFG.CO., Troy, OH, USA) with gradual addition of calculated amounts of distilled water to bring the final flour moisture content to 15.0±0.5%, 20.0±0.5% and 25.0±0.5% wb (Kowalski et al., 2015) and equilibrated overnight in a walk-in refrigerator. Moisture contents of the adjusted flours were confirmed next day before processing. Extrusion experiments were conducted using a laboratory co-rotating twin screw extruder (Model TSE 20/40, CW Brabender, South Hackensack, NJ, USA), having a clam shell barrel system made up of a feed zone and four independent temperature-controlled zones (Li, Kowalski, Li, & Ganjyal, 2017). The temperature profile from the feed zone and the next three zones were kept constant at 50, 50, 100, and 120°C. The temperature of the last zone, hereafter referred to as die temperature, was varied between 120, 140, and 160°C according to the experimental design. The length and diameter of the screws were 400 and 20 mm respectively, giving a length to diameter (L/D) ratio of 20:1. Screw speeds of 150, 200, and 250 rpm and a die with an internal diameter of 3.0 mm were used. The screw profile used (Fig. 1) included one reverse mixing element (KP-45/5/20/R) to impart shear to the product. Flour was fed into the extruder using a pre-calibrated twin-screw volumetric feeder (DDSR20-5, CW Brabender, S. Hackensack, NJ, USA) at a constant mass flow rate of 100 g/min. Extrudates were collected at steady conditions of pressure and torque. Product samples were dried in a convection oven (VWR Symphony Air Flow Oven model # 414004-568, VWR International, LLC, NJ, USA) at 45°C overnight. Samples were transferred to air tight plastic zip lock bags and stored at 4°C until further analysis.

2.5 Experimental design

A central composite response surface design with three factors and three replicates was utilized in this study. The factors included feed moisture (X1) at levels of 15, 20 and 25% (wb), extruder die temperature (X2) with levels of 120, 140 and 160^{o}C, and screw speed (X3) at levels of 150, 200 and 250 rpm. The number of runs were condensed to an 18-D optimized selected points. The ranges of the factors were selected based on our preliminary tests conducted with the barley flours.

2.6 Extrusion System parameters

2.6.1 Specific Mechanical Energy (SME)

Specific mechanical energy (SME) is the amount of energy required to extrude a unit mass of product. It was calculated according to the method reported by Godavarti and Karwe, (1997) and expressed as kJ/kg.

2.6.2 Back Pressure (BP) and Motor torque (T)

Data on motor torque and back pressure were collected continuously at intervals of 20 s during extrusion with a data acquisition system designed for use with an Intelli-Torque extruder (CW Brabender, S. Hackensack, NJ, USA). Five data points were selected for calculation of data (Li et al., 2017).

2.7 Product characteristics

2.7.1 Expansion ratio (ER)

ER was calculated as the ratio of average extrudate diameters to the die diameter (3.0 mm), using a modified method described by Wang et al., (2017). This is the measure of the radial expansion of the extrudates. Extrudate diameters were measured using a caliper (Mitutoyo America Corp., Aurora, IL, USA) at two random positions on each of five randomly picked extrudates for a total of 10 data points per sample.

2.7.2 Unit Density (UD)

UD is a measure of the density of the extrudate and calculated by dividing displaced volume over mass of extrudate. Samples were placed in 1.0 mm diameter glass beads (General Laboratory Supply, Pasadena, TX, USA) with 10 g of extrudates using a volumetric cylinder in three replicates (Li et al., 2017).

2.7.3 Water Absorption Index (WAI) and Water Solubility Index (WSI)

WAI and WSI were measured using a modified method described by (Anderson, et al. 1969). Barley extrudates were milled with a UDY cyclone mill (Model # 3010-030, UDY Corp., Fort Collins, Colo., U.S.A.) fixed with a 2 mm screen.

2.7.4 Color

The color of barley flour and milled extrudates was measured in triplicates using a Minolta Chroma Meter (CR-210, Ramsey, NJ, USA) in terms of Hunter Lab values (L, a, b)

(Kowalski, Medina-Meza, Thapa, Murphy, & Ganjyal, 2016). The total color change (ΔE) was calculated using the following equation:

$$\Delta E = \sqrt{(\Delta L^2) + (\Delta a^2) + (\Delta b^2)}$$

Where $\Delta L = L - L_0$, $\Delta a = a - a_0$, and $\Delta b = b - b_0$. L_0, a_0, and b_0 represent the color of the flour before extrusion at the corresponding moisture levels.

2.8 Statistical Analysis

All data was analysed with Minitab 17.3.0 statistical software (Minitab Inc., 2016, PA, USA). Chemical composition data was subjected to one-way ANOVA and Fisher's LSD. The process response variables (BP, T and SME) and product functional properties (WAI, WSI, ER, UD and Color) were subjected to regression analysis. This was done to determine the effects of process conditions on the process and product characteristics during extrusion. Correlation analysis of process and product parameters were also conducted to understand their interrelationships.

3.0 RESULTS AND DISCUSSION

3.1 Chemical Composition

The chemical composition data is shown in Table 2. Moisture contents of barley flours were all less than 10% wb. The hulled varieties (H1 and H2) showed significantly ($P < 0.05$) higher ash contents of 2.08 and 2.01% respectively compared to hull-less varieties which recorded a maximum of 1.49%. This could be due to the nature of the grains and method of flour preparation as they were milled without pearling with the hull intact. Protein contents were all significantly different from each other ($P < 0.05$) and there was no relationship with the barley type. HL3 and HL2, hull-less types, had the highest protein contents while H1, a hulled variety, recorded the least. Crude fat contents showed significant differences between hulled and hull-less varieties at $P < 0.05$ with hulled varieties showing higher fat contents. Crude fiber contents of hulled varieties were significantly higher ($P < 0.05$) than the hull-less varieties. Similar findings on fiber and fat contents between hulled and hull-less barley was reported by Aman & Newman, (1986). Results of amylose contents indicated that all the barley samples were of the waxy type according to definition of Morrison, Milligan, & Azudin, (1984) who showed that waxy barley amylose ranged from 2.1- 8.3%. The highest amylose content of 5.65% (H1) was significantly different ($P < 0.05$) from the rest. Extractable ß-glucan contents revealed significantly ($P < 0.05$) lower values for hulled varieties compared with hull-less varieties with HL3 showing the highest of 5.54%.

3.2 Pasting Properties

The pasting properties of the barley flours is presented in Fig. 2. The amylographs generated were typical of common cereals, such as rice and corn. The peak viscosities were in the range of 467 (H2) to 1025 mPas (HL3). Differences were observed between amylographs of hulled and hull-less barley varieties. Peak times for hulled and hull-less varieties were significantly different at $P < 0.05$, with hulled varieties pasting later than hull-less varieties. This is likely attributed to the higher levels of the fiber in the hulled varieties. Presence of fiber results in the disruption of the starch matrix, leading to delayed pasting time (Kallu, Kowalski, & Ganjyal, 2017; Wang et al., 2017).

Two hull-less varieties (HL2 and HL3) showed the highest peak viscosities but were not significantly different ($P < 0.05$). HL1 and H1 had similar peak viscosities significantly lower ($P < 0.05$) than HL2 and HL3, while the least peak viscosity was shown by H2. The variations could be attributed to differences in chemical composition between hulled and hull-less barley; particularly the amylose content. Starch granules absorb water, swell, and rupture during constant heating and constant shear rate. This results in increase in viscosity of the starch, thus increased peak viscosity. Our results supports the finding that low amylose produces high pasting viscosity (Ming, Morris, Batey, & Wrigley, 1997). Lower amylose denotes greater swelling during cooking of starch, as it consumes a greater amount of water that leads to an increased peak viscosity.

The final paste viscosity values ranged between 687 to 995 mPas with H2 and HL1 showing the least values, while H1 recorded the highest values and was significantly different ($P < 0.05$) from the other varieties. This suggests that H1 has the potential for use in food applications that require high cooked viscosity and stability upon cooling.

3.3 Process Responses

SME values ranged between 5.13 (for HL3) to 25.39 kJ/kg (for H1). This was significantly lower than the values ranging from 978.6-1242 kJ/kg reported by Altan et al., (2009) when they studied the effect of raw material and screw configuration on barley extrudates. This difference may be due to the extruder type and screw configuration used. SME input for hulled varieties were in the range of 5.87 kJ/kg (H2) to 25.39 kJ/kg (H1), slightly higher compared to the hull-less barley at 5.13 kJ/kg (HL3) to 17.4 kJ/kg (HL2). This could be due to the variation in chemical composition between hulled and hull-less barleys leading to differences in melt viscosities. For instance, hulled varieties were found to contain significantly high ash and fiber contents (Table 2). The presence of a thin pericarp tightly adhered to seeds of hull-less varieties contributed to the lowering of fiber and ash contents compared to hulled varieties. Additionally, hulled barley varieties have been reported to have a hard and dense outer covering which does not absorb moisture easily (Pomeranz, 1987) compared to the hull-less varieties which are more soft and mealy. This must have contributed to higher resistance of the melt with hulled varieties, thus increasing residence time, and higher energy requirement to pump the material through the extruder.

Regression coefficients for SME (Table 4) revealed significant linear effects with die temperature for HL1($P < 0.01$) and HL2 ($P < 0.05$) and feed moisture content for HL3 ($P < 0.05$). Further, die temperature showed quadratic effects on SME in HL1 ($P < 0.01$) and HL2 ($P < 0.01$), while interaction between feed moisture and die temperature showed significance on SME in HL3 ($P < 0.05$). Screw speed has been reported by some authors to have a positive relationship to SME (Baik, Powers, & Nguyen, 2004; Kowalski et al., 2016) and our results are in agreement. SME was observed to be positively correlated to T ($r = 0.851$, $P < 0.01$) and BP ($r = 0.860$, $P < 0.01$) signifying that an increased SME resulted in increased back pressure and motor torque. Contour plots showed that increasing moisture contents reduced the SME for all barley extrudates. High SME was observed at low feed moisture contents of 15% wb, decreasing drastically with small increase in the moisture contents (Supplementary Fig.1). A similar finding from the effect of moisture and die temperature on SME (Supplementary Fig. 2) signified that feed moisture was a strong determinant of SME than die temperature or screw speed. On the other hand, the contour plots (Supplementary Fig. 2) also showed that high screw speeds contributed to high SME in H2 and HL2. This could be attributed to the reduced viscosities in the abundant moisture, thus making it easier for the screws to push the melt through the die. Increasing die temperature and screw speed would both cause a decline in the melt viscosity, consequently a decrease in SME. Increased motor torque led to increased SME as more energy is needed to turn the screws due to an increased dough viscosity. This was found to be consistent with other reports (Akdogan, 1999; Kowalski et al., 2015). Additionally, Dogan & Karwe, (2003) reported that high feed moisture produces a lubricating effect, resulting in less energy usage, and subsequently reduced SME. T values ranged from 8.16 Nm (HL3) to 31.86 Nm (H2), while BP values ranged between 166 psi (HL3) to 2468 psi (H2). BP, T, and SME all behaved similarly throughout the extrusion as illustrated (Table 5), with high correlation coefficients among them (BP/T r = 0.957, BP/SME r = 0.860, SME/T r = 0.851).

3.4 Product responses

3.4.1 Expansion ratio (ER) and Unit density (UD)

High ER and low UD is a desired textural attribute of direct expanded products (Kowalski et al., 2016; Luyten et al., 2004). The lowest ER observed was 1.39 for H2. This was observed under extrusion conditions of high feed moisture content (25% wb), high barrel temperature (160°C) and low screw speed (150 rpm). The highest expansion ratio of 2.81 was observed in H1 with low feed moisture content (15% wb), low temperature (120°C) and high screw speed (250 rpm). These values are low compared to other cereals, for instance an expansion ratio of 4.0 has been reported in commercial corn starch extrudates (Chinnaswamy & Hanna, 1988). However, ER values were higher than what was reported by authors for barley extrudates using hulled and hull-less varieties (Table 1). ER of 2.17 and 1.70 of barley extrudates were reported by Altan et al., (2009) with hull-less whole flour and Huth et al., (2000) with hulled refined flour respectively. This could be due to the different extrusion conditions used in their studies, as well as the use of different varieties in their studies. The hull-less varieties recorded lower ER values compared to hulled varieties under most of the conditions studied. The levels of fiber contents (about 5%) present in hulled varieties (Table 2) must have been an important factor, as observed by Kaisangsri et al., (2016) when they added small quantities of carrot pomace to starch. They explained that about 5% of fiber helped with strengthening of starch matrix in the melt, thus improving with expansion, although higher level of fiber has been reported to be detrimental to expansion. Another contributory factor may be the fat content of the flours. Crude fat contents of the flours (Table 2) showed that hull-less varieties had significantly higher ($P < 0.05$) levels. This suggests that expansion was affected by a slippage of the melt in the barrel as fat was acting like a lubricant in the melt, leading to partial mixing and shearing and disturbed formation of bubbles which cause expansion.

ANOVA revealed that extrusion conditions that produced the highest expansion ratio in all varieties was at low feed moisture content (15% wb), low temperature (120 °C), and high screw speed (250 rpm) at $P < 0.05$. Contour plots of feed moisture and screw speed on ER (Fig. 3A-E), showed that in all varieties, increasing screw speed and lowering moisture content increased ER. This is because low feed moisture results in formation of high viscosity melts in the extruder barrel and in combination with high screw speed ensures breakdown of the starch granules leading to high expansion. Similar results have been reported (Köksel et al., 2004). Significant linear relationships were found through regression analysis (Table 3 and 4) between some dependent variables and ER. Feed moisture in H1 ($P < 0.01$), die temperature in H2 ($P < 0.01$) and HL1 ($P < 0.05$) as well as screw speed in H2 ($P < 0.05$). Feed moisture content and die temperature were revealed as stronger determinants of ER by regression analysis than screw speed. These were deducted from the number of times and level of significance observed from regression analysis of dependent variables on ER (Table 3 and 4).

Least UD of 0.20 g/cm^3 coincided with extrudates with high ER (H1) and the highest UD of 0.69 g/cm^3 (HL3) had lowest ER (Supplementary Table S1 and Table S5). Regression analysis developed from our model showed that UD was significantly affected by die temperature, only for HL3 ($P < 0.01$), while other main effects were not significant. There were however significant interaction effects for UD in hull-less varieties, including, die temperature and screw speed (HL2, $P < 0.01$; HL3, $P < 0.01$), feed moisture and die temperature (HL1, $P < 0.05$), feed moisture and screw speed (HL1, $P < 0.05$) (Table 4). This indicated that UD was significantly affected by different extrusion conditions and for different varieties because of their differences in chemical composition.

3.4.2 Water Absorption Index and Water Solubility Index

WAI ranged from 5.05 (H2) to 8.09 g/g (HL3), while WSI ranged between 5.82 (HL2) and 26.50% (HL1). ANOVA showed that WAI of hulled varieties were significantly lower than hull-less varieties ($P < 0.05$) while there were no significant differences ($P < 0.05$) in WSI among extrudates of the five varieties. A comparison of WAI and WSI before and after extrusion showed an increase, in the multiples of 3 and 2, for WAI and WSI respectively, (H1, H2 and HL1), while HL2 and HL3 were increased in multiples of only 2 and 1 respectively after extrusion (Supplementary Table S6). This suggests that H1, H2 and HL1 varieties went through higher degree of degradation by shearing, during the extrusion process. High WSI has been reported as a good measure of the degree of starch conversion into soluble polysaccharides during extrusion cooking, and is often used as an indicator to starch degradation (Kirby et al., 1988). The results also confirm their relatively higher ER observed for H1 and H2. Further, the results indicate that the hulled varieties H1 and H2 possess more potential in making ready-to-eat extruded products such as a breakfast cereals, because they can maintain a crispy texture over longer periods in water (Li et al., 2017).

3.4.3 Color

The color of food products is known to directly affect consumer perception and acceptability, because it is perceived as an indication to changes in quality of products due to processing and storage (Lawless & Heymann, 1999). This test is significant for processed barley because the color of barley products tend to be browned after processing and has been reported to be among the limiting factors for its utilization (Lagassé, Hatcher, Dexter, Rossnagel, & Izydorczyk, 2006). ΔE, which measures extent of extrudate discoloration was lowest (1.27) in H1 and highest (5.71) in HL2. ANOVA grouped discoloration of extrudates into three significantly different groups. H1, H2 and HL3 extrudates were mostly discolored in relation to color of their original barley flours used for extrusion and were significantly different ($P < 0.05$) from the least discolored (HL1). HL2 had an intermediate discoloration and significantly different ($P < 0.05$) from the rest. This could be attributed to the non-enzymatic browning reactions occurring at different rates according to the chemical composition of the varieties during the extrusion process. The significant correlation $r = -0.588$, $P < 0.01$ (Table 5), indicated that discoloration in extrudates was inversely related to WSI. This suggests that discoloration was present in extrudates with low WSI and with low radial expansion ratio ($r = -0.470$, $P < 0.05$) (Table 5).

4.0 CONCLUSIONS

Differences were observed in the extrusion process responses and functional properties of extrudates of hulled and hull-less barley. Hulled varieties Lyon (H1) and Muir (H2) generally expanded significantly more than hull-less varieties, 09OWA.265.12 (HL2) and Meg's Song (HL3). The overall radial expansion for HL1 (Havener) was not significantly different from the hulled variety, H2, even though HL1 had moderate ß-glucan content. Havener, therefore showed both good characteristics of hulled and hull-less varieties. The results suggest that the varieties, their chemical composition, and functional properties, influence their extrusion processing properties. The high ß-glucan content makes barley a potential important ingredient for making healthy and quality products. Barley could be recommended for making extruded products that do not require high expansion or be utilized in flour composites to make direct expanded products to take advantage of their high ß-glucan contents.

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Table 1. Summary of reported studies on barley extrusion

Raw material/source	Refined and hull status	Moisture content (%)	Length/ Diameter ratio	Feed Rate	T (^{o}C)	Screw Speed	Screw type	Die dimension	Expansion Ratio	Citation
Barley flour (Bob's Red Mill Natural Foods Milwaukie, OR, USA)	Refined flour	22	13:1	2.09 ± 0.05 kg/hr	140-160	150-200	Co-rotating twin-screw	Slit die 1.47 mm × 20 mm × 150mm.	-	Altan, McCarthy, & Maskan, 2008
Summer barley var Krona and Hini Ami Cherry, Germany	Hulled, refined flour	15-30	-	1.5scale units	110-170	130-200	Single screw	4-5 mm	0.9-1.7	Huth et al., 2000
Barley (six rowed) and (two rowed), India	Hulled, refined flour	15-20	16	20kg/hr	150-180	400	Co-rotating twin screw	6 mm	-	Sharma et al., 2012
Waxy barley (CDC Candle), regular barley (Phoenix) USA	Hulled, refined flour	20, 35, 50	20:1	50lb/hr	90-140	50	Twin screw	-	-	Vanasathan et al., 2001
Barley grits and barley flour (Bob's Red Mill USA)	Hulless whole flour	20.5	13:1	1.11kg/hr	150	175	Co-rotating twin-screw	Slit die 1.47 mm x20 mm x 150 mm.	1.88-2.17	Altan et al., 2009
Czech Spring barley	Hulled and hulless refined	20	2.3:1	150kg/hr	130	220	Single screw with turbo	10 round dies, 3 mm diameter each	-	Honců et al., 2016
USA cultivar-Merlin	Hulless waxy whole flour	22.3, 26.8, 30.7	25:1	2.5kg/hr	130-170	300	Co-rotating twin screw	Round; diameter 2mm	-	Koksel et al., 2004

Table 2. Chemical composition of hulled and hull-less barley varieties

Variety	Moisture (%)	Ash (%)	^{a}Protein (%)	Crude fat (%)	Crude fiber (%)	Amylose (%)	ß-glucan extract (%)
H1	6.79^{b}	2.08^{a}	11.31^{e}	1.55^{c}	4.56^{a}	5.65^{a}	2.36^{e}
H2	6.77^{b}	2.01^{a}	12.02^{c}	1.66^{c}	5.99^{a}	2.21^{b}	2.84^{d}
HL1	7.14^{a}	1.49^{b}	11.54^{d}	2.41^{b}	1.34^{b}	2.10^{bc}	3.76^{b}
HL2	6.81^{b}	1.28^{c}	12.56^{b}	2.57^{ab}	1.28^{b}	1.55^{c}	3.30^{c}
HL3	6.83^{b}	1.25^{c}	13.11^{a}	2.84^{a}	1.71^{b}	1.76^{bc}	5.54^{a}

a = N% x 6.25, b = by difference. Values correspond to mean ± SD; different letters in same column indicate significant differences at $p<0.05$. H: hulled varieties (H1=Lyon, H2=Muir): hull-less varieties (HL1=Havener, HL2=09WA-265.12, HL3=Meg’s Song).

Table 3. Regression coefficients for product and process response variables by extrusion factors of H1 and H2 barley varieties

		Motor torque (Nm)	Back pressure (psi)	SME (kJ/kg)	WAI (g/g)	WSI (%)	Radial Expansion ratio	Unit density (g/cm^3)	Color (∆E)
H1	Constant	-53.4	-1038	31.9	4.47^{o}	-3.6	5.43^{+}	2.16	-14.9^{o}
	M	-1.81	-288	-3.02	-0.349^{+}	-2.526^{+}	-0.4303*	0.1765	0.154
	SS	0.169	10.6	0.038	0.0064	0.0649	0.0059	-0.0011	-0.0113
	T	1.41	84.3	0.39	0.0777^{o}	0.640*	0.0154	-0.0511	0.231^{o}
	M x M	0.0207	2.01	0.0347	0.0037^{o}	0.0175	0.0079^{+}	-0.0035	0.0044
	SS x SS	-0.0002	-0.0032	0.00002	-0.00001	0.0002	0.000005	-0.00001	-0.00003
	T x T	-0.006	-0.417	-0.0034	-0.0003^{o}	-0.0028^{+}	-0.00004	0.0002	-0.0008^{+}
	M x T	0.0052	1.163^{o}	0.0138	0.0004	0.0095^{+}	0.0001	-0.0001	-0.0012
	M x SS	-0.0015	-0.136	-0.0048	0.0003^{+}	-0.0006	0.0001	-0.00003	0.0006^{o}
	T x SS	-0.0004	-0.0451	0.0005	-0.00006^{o}	-0.0007^{+}	-0.0001^{+}	0.00003	0.00008
	Adj. R^2	0.769	0.847	0.762	0.951	0.947	0.977	0.865	0.961
H2	Constant	236.5^{+}	30923*	117.5^{o}	-5.91	67.8^{o}	6.78*	-3.45	17.3
	M	0.88	-321	3.14	0.067	-1.66	-0.0756	0.0688	1.584^{+}
	SS	-0.416^{o}	-33.6	-0.118	0.0039	0.221	0.0143^{+}	-0.0075	-0.0583
	T	-2.294^{+}	-301.9*	-1.581	0.1694^{+}	-0.784	-0.0722*	0.0573	-0.373^{o}
	M x M	-0.1124^{+}	-4.78	-0.0733	-0.0036	0.0652^{+}	0.0042*	-0.0039	-0.045*
	SS x SS	0.0005	0.0198	0.0003	0.00002	-0.0002	-0.00001	0.000001	-0.00003
	T x T	0.0064^{o}	0.775^{+}	0.0054	-0.0007^{+}	0.0031	0.0003*	-0.0003	0.0011
	M x T	0.0111	2.289*	-0.0043	0.0007	-0.0044	-0.0007*	0.0005	0.0011
	M x SS	0.0061^{+}	0.534^{+}	-0.0016	-0.0003	-0.0042^{+}	-0.0003*	0.0002	0.0012^{o}
	T x SS	0.0003	0.0934	0.0002	-0.00005	-0.0004	-0.00002	0.00002	0.0003^{o}
	Adj. R^2	0.911	0.931	0.784	0.794	0.84	0.989	0.651	0.771

^{o} Significant at $p < 0.1$, $^{+}$ significant at 0.05, * significant at $p < 0.01$, Hulled varieties (H1=Lyon, H2=Muir): SME= specific mechanical energy, WAI= water absorption index, WSI= water solubility index

Table 4. Regression coefficients for product and process response variables by extrusion factors of HL1, HL2 and HL3 barley varieties

		Motor torque (Nm)	Back pressure (psi)	SME (kJ/kg)	WAI (g/g)	WSI (%)	Radial Expansion ratio	Unit density (g/cm^3)	Color (ΔE)
HL1	Constant	-36.8	-3888	-76.6	-17.5	35.7	2.50	0.86	-22.3*
	M	-5.06*	-329*	-1.33	1.68^{+}	-3.25	-0.327	0.0797	0.47
	SS	0.02	-3.2	-0.014	-0.007	0.389	0.0113	-0.007	-0.0179
	T	1.597	129.2*	1.527^{O}	0.109	-0.24	0.032	-0.0105	0.296
	M x M	0.0757	4.82	0.036	-0.034^{+}	0.0446	-0.0017	-0.00009	-0.0107
	SS x SS	-0.0004	-0.0228	-0.0002	0.00007	-0.0003	-0.00005	0.00002	0.000009
	T x T	-0.0057	-0.525^{+}	-0.006*	0.0001	-0.001	-0.0003	0.00009	-0.0008
	M x T	0.0008	0.269	-0.0049	-0.003*	0.0212^{+}	0.002^{+}	-0.0006^{+}	-0.0015
	M x SS	0.0066^{+}	0.279	0.0009	0.0009	-0.011^{+}	0.0003	0.0001^{+}	0.00105*
	T x SS	-0.0003	0.0393	0.0006	-0.0003*	-0.0001	0.00001	-0.00002	-0.00004
	Adj. R^2	0.692	0.744	0.558	0.519	0.665	0.471	0.817	0.422
HL2	Constant	259.5*	18515*	178.0*	8.9	125.3	8.38^{+}	-1.74	-2.0
	M	-3.99^{+}	-359^{+}	-1.53	-0.207	1.85	0.061	-0.038	0.348
	SS	-0.305*	-20.2	-0.208	-0.011	-0.23	0.0145	0.0032	0.1355*
	T	-2.465*	-168.3^{+}	-1.921^{+}	0.017	-1.42	-0.1144^{+}	0.0292	-0.191
	M x M	0.0176	2.56	0.0166	-0.0039	0.0522	-0.02	-0.0013	-0.011
	SS x SS	0.0003	0.0243	0.0002	0.00001	0.0002	0.00001	0.00001	-0.0002
	T x T	0.0066^{+}	0.443^{+}	0.0049*	-0.0002	0.0043	0.0004^{+}	-0.00006	0.0007
	M x T	0.017*	1.224^{+}	0.0098	0.0024	-0.018*	0.002	0.0004	0.0027
	M x SS	0.0026	0.251	-0.0038	0.0002	-0.007*	-0.0002	0.0002	-0.001
	T x SS	0.0011^{+}	0.0582	0.0018^{+}	-0.00001	0.0019*	-0.00008^{+}	-0.0001*	-0.0003
	Adj. R^2	0.831	0.84	0.737	0	0.651	0.899	0.382	0.408
HL3	Constant	67.2	4441	50.7	54.0^{+}	164.0*	0.32	-4.47^{+}	-37.32^{+}
	M	-6.18^{+}	-4885*	-4.88^{+}	- 0.579	-3.55^{+}	0.015	0.0116	0.891^{+}
	SS	-0.227	-13.45	-0.214	0.0644	0.149	-0.0033	0.0086	-0.0196
	T	0.554	40.9	0.514	-0.703^{+}	-1.797^{+}	0.0258	0.0576*	0.452^{+}
	M x M	0.0743	5.78^{+}	0.0567	0.0176	0.0926^{+}	0.0008	-0.0004	-0.0263^{+}
	SS x SS	-0.00005	-0.0041	-0.00006	-0.0002	0.00002	0.00003	-0.00002	0.00002
	T x T	-0.0037	-0.297*	-0.004	0.0027^{+}	0.0059^{+}	-0.00007	-0.0002	-0.0019^{+}
	M x T	0.0125*	1.208^{+}	0.013^{+}	-0.0014	0.0039	-0.0002	-0.0002	0.0029^{+}
	M x SS	0.0059	0.359^{+}	0.0032	0.0007	-0.006*	-0.0003*	0.0002*	0.00002
	T x SS	0.0007	0.0541	0.0012*	-0.0001	-0.0002	-0.00002	-0.00004*	0.0001
	Adj. R^2	0.691	0.854	0.684	0.497	0.877	0.77	0.62	0.928

^{o} Significant at $p < 0.1$, $^{+}$ significant at 0.05, * significant at $p < 0.01$, Hull-less varieties (HL1=Havener, HL2=09WA-265.12, HL3=Meg's Song). SME= specific mechanical energy, WAI= water absorption index, WSI= water solubility index

Table 5. Correlation matrix of process and product responses for h less barley extrudates.

Variable	T	BP	SME	WAI	WSI	ER	UD	Color
Tm	1							
BP	0.957*	1						
SME	0.851*	0.860*	1					
WAI	-0.230^{+}	-0.205^{o}	-0.256^{+}	1				
WSI	0.359^{+}	0.424*	0.434*	-0.029	1			
ER	0.542*	0.612*	0.633*	-0.116	0.680*	1		
UD	-0.388*	-0.429*	-0.539*	0.202^{o}	-0.769*	-0.729*	1	
Color	-0.181^{o}	-0.254^{+}	-0.165	-0.182^{o}	-0.588*	-0.470*	0.457*	1

^{o} Significant at $p < 0.1$, $^{+}$ significant at 0.05, * significant at $p < 0.01$, WAI-water absorption index, WSI-water solubility index, ER-radial expansion ratio, UD- unit density, T-motor torque

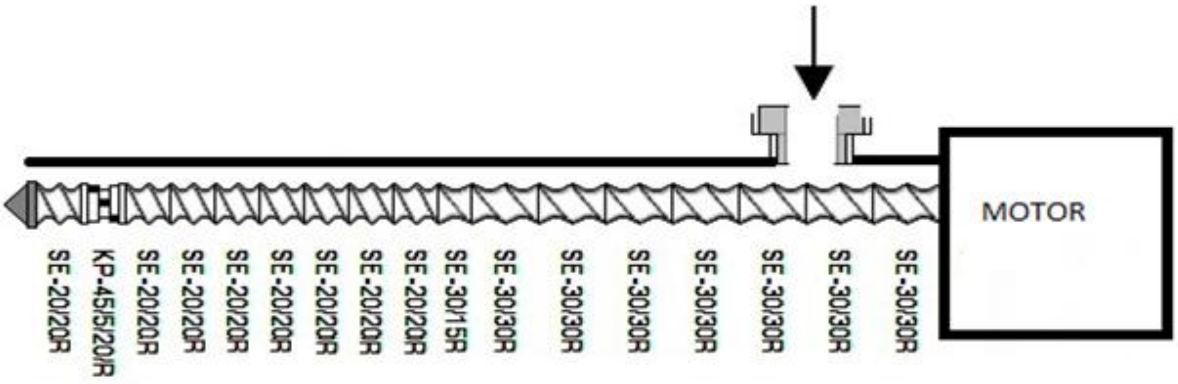

Fig. 1. Screw configuration used in the study. Screw elements are coded as (SE) or kneading plate (KP). SE is followed by screw pitch (degrees) and length of element (mm). KP is followed by plate offset angle in degrees. The last letter is the direction of rotation; right (R) or left (L).

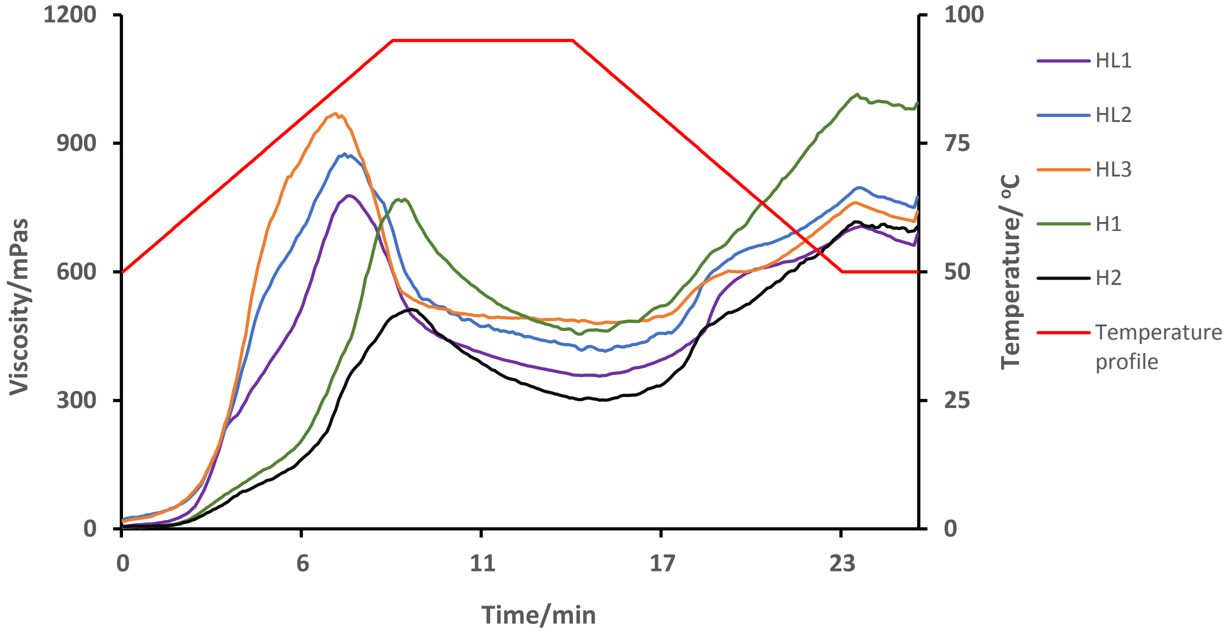

Fig. 2. Pasting properties (average of three replications) of hulled (H1 and H2) and hull-less (HL1, HL2, HL3) barley varieties. H1=Lyon, H2=Muir, HL1=Havener, HL2=09WA-265.12, HL3=Meg’s Song

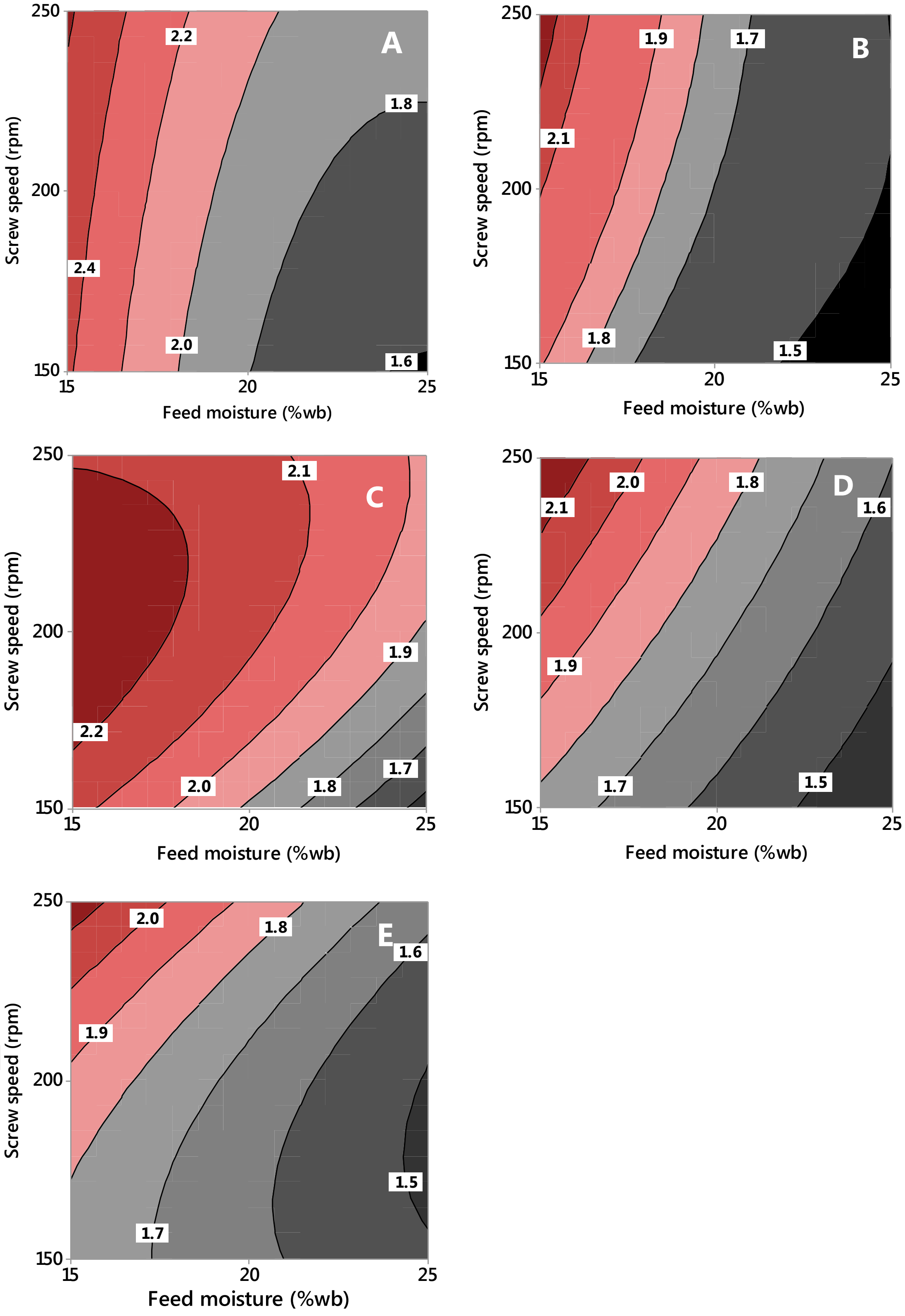

Fig. 3. Radial expansion ratio as a response of feed moisture and screw speed for H1(A), H2 (B), HL1 (C), HL2 (D) and HL3 (E) barley varieties. H1=Lyon, H2=Muir, HL1=Havener, HL2=09WA-265.12, HL3=Meg's Song